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What Does Physical Rotation Reveal About Mental Rotation?

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Abstract

In a classic psychological science experiment, Shepard and Metzler (1971) discovered that the time participants took to judge whether two rotated abstract block figures were identical increased monotonically with the figures' relative angular disparity. They posited that participants rotate mental images to achieve a match and that mental rotation recruits motor processes. This interpretation has become central in the literature, but until now, surprisingly few researchers have compared mental and physical rotation. We had participants rotate virtual Shepard and Metzler figures mentally and physically; response time, accuracy, and real-time rotation data were collected. Results suggest that mental and physical rotation processes overlap and also reveal novel conclusions about physical rotation that have implications for mental rotation. Notably, participants did not rotate figures to achieve a match, but rather until they reached an off-axis canonical difference, and rotational strategies markedly differed for judgments of whether the figures were the same or different.

Keywords

mental models, motor processes, spatial perception

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Shepard and Metzler's (1971) seminal experiments on mental rotation required participants to judge whether two rotated abstract block figures were the same or different. Results showed the angular disparity effect (ADE), a positive linear relationship between response time (RT) and the angular difference between the figures. Phenomenologically, this finding has been interpreted as indicating that people mentally rotate one figure to align with the other (i.e., to achieve a match). Central to this interpretation is the assertion that mental image manipulation involves motor processes (Kosslyn, 1994, Shepard & Cooper, 1982).

Behavioral research supports this assertion. Wexler, Kosslyn, and Berthoz (1998) suggested that mental rotation involves covert simulation of motor rotation. In their study, participants judged rotated 2-D figures while simultaneously rotating a joystick. Joystick rotations congruent with the mental rotation direction facilitated performance, whereas incongruent rotation impaired it. Subsequent research demonstrated that these interactive effects do not require spatially isomorphic manual actions (Schwartz & Holton, 2000). Wohlschläger and Wohlschläger (1998) compared RTs for a classic mental rotation task and a physical rotation task. Participants rotated 3-D figures by turning a dial. The tasks yielded statistically indistinguishable ADEs. Other studies have revealed that physical rotation training improves subsequent mental rotation (Wiedenbauer & Jansen-Osmann, 2008; Wiedenbauer, Schmid, & Jansen-Osmann, 2007) and that individuals with motor expertise (e.g., athletes) show impaired mental rotation when their hands are constrained (Moreau, 2013).

Neural evidence provides mixed support for the motor-mental link. Some studies found premotor and motor cortex activation during mental rotation, whereas

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others have found little or no motor activation (see Zacks, 2008, for a review). This variability likely reflects task differences and varying cognitive strategies. For example, mental rotation of drawings of hands (but not of abstract figures) yielded primary motor cortex (M1) activation (Kosslyn, DiGirolamo, Thompson, & Alpert, 1998). However, imagining mental rotation as a consequence of one's own physical rotation, rather than an external force, led to M1 activation for both hands and figures (Kosslyn, Thompson, Wraga, & Alpert, 2001). A motor strategy may also be implicitly induced. Mentally rotating drawings of hands leads to M1 activation during subsequent mental rotation of figures (Wraga, Thompson, Alpert, & Kosslyn, 2003). An object's manipulability also influences motor activation. Mental rotation of hand tools yielded premotor activation contralateral to the dominant hand (Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002). Neural evidence thus suggests that motoric simulation during mental rotation is context dependent.

The Present Research

Given that mental rotation may involve motor processes, it is important to directly compare mental rotation and physical rotation. This comparison allows the exploration of central assumptions in the literature on mental rotation, namely that mental rotation involves rotating mental images analogous to physical objects to match their orientations and that mental rotation and physical rotation are similar. We went beyond Wohlschläger and Wohlschläger's (1998) direct comparison between mental rotation and physical rotation by using virtual 3-D block figures, a novel tri-axis rotational apparatus, and real-time physical-rotation data collection. We predicted that mental rotation and physical rotation would show similarities. Specifically, RTs during physical rotation would show an ADE, and participants' real-time physical rotation would reflect rotation to a matching mental image.

Method

Participants

Thirty-two Tufts University undergraduates (mean age = 19.47 years; 16 male, 16 female) participated for monetary compensation.

Materials

Figures and stimuli presentation. We designed 3-D models of Shepard and Metzler's (1971) figures from Peters and Battista's (2008) stimulus library using Google SketchUp (http://google-sketchup.en.softonic.com/). The stimuli (15 figures and their mirror images) were presented using virtual-reality software (WorldViz Vizard 4.0, Santa Barbara, CA). Figure 1a depicts our experimental setup, showing how stimuli were presented. During physical rotation, participants rotated figures using a handheld rotational sensor with three degrees of freedom, the Intersense InertiaCube 2+ (Boston, MA), encased in a tennis ball. This spherical rotation apparatus (see Fig. 1b) minimized imposition of reference frames, although the data cable may have imposed some awkwardness. However, neither participant report nor experimenter observation suggested any impact of awkwardness.

Questionnaires and cognitive assessments. Questionnaires assessed factors that have previously shown a relationship to mental rotation performance: spatial ability; preferences for landmark-based (i.e., a focus on unique objects at constant locations), route-based (i.e., a

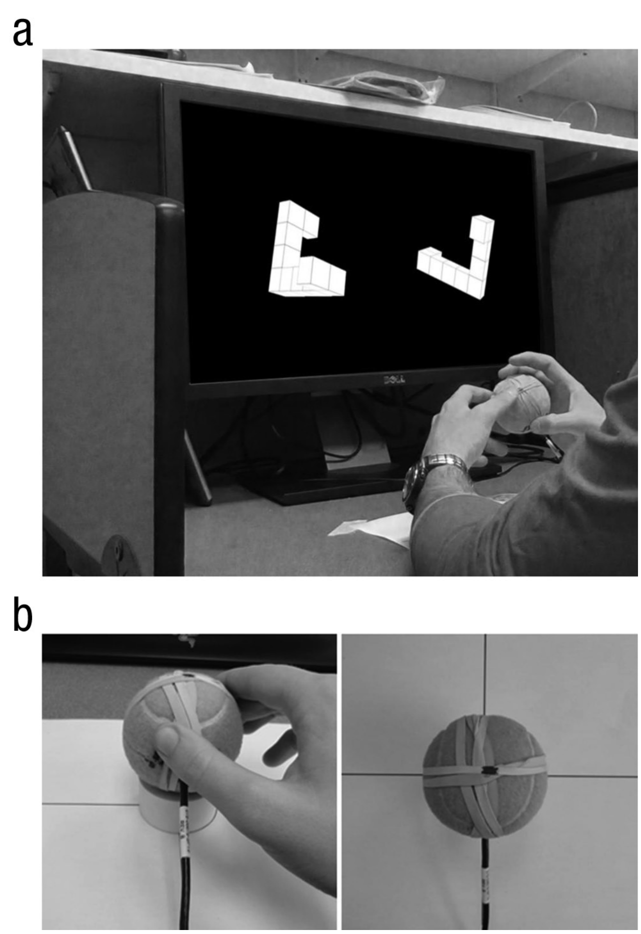

Fig. 1. Photos showing the experimental setup (a) and close-ups of the rotation apparatus (b). Participants saw two figures presented side by side on a monitor. They had to rotate one of the figures either mentally or with the handheld sensor, depending on the trial type, in order to judge whether the two figures were identical (*same*) or mirror images of each other (*different*).

focus on sequences of paths and turns), and survey-based (i.e., a focus on abstracting knowledge from sequences into a global model) spatial representation; spatial self-confidence; preferences for survey strategies; knowledge of cardinal directions; video game experience; and working memory capacity. Table 1 lists the measures used to assess each variable, as well as the results for our sample.

Procedure

Participants first completed the questionnaires and an operation span task. For the experimental task, participants saw two figures presented side by side on a monitor. One figure was designated the target and the other the response figure. The figures in each pair were presented in different rotations, and participants had to judge whether the two figures were identical (same) or mirror images of each other (different) by either mentally rotating the response figure or actually rotating it using the bimanually held sensor. Participants were instructed to respond quickly and accurately, saying "same" or "different" into a headset microphone. Microsoft Speech SDK voice-recognition software recorded their responses.

The mental rotation and physical rotation tasks and the rotated figure's screen position (left, right) were equally counterbalanced across male and female participants. Five practice trials that used figures distinct from those in the main experiment preceded each task. For the mental rotation task, participants practiced mentally rotating the response figure; for the physical rotation task, they practiced rotating the response figure with the sensor. The main task involved three trial blocks, each containing 15 *same* and 15 *different* trials in which the figures were randomly selected (without replacement) from the stimulus set. Each trial presented figure pairs in random rotations. The angular difference (in degrees) between the figures' quaternion rotations (see Hanson, 2006, for a review) was sampled from a uniform distribution between 0 and 180. A quaternion represents 3-D rotation as a vector between a sphere's center and a point on its surface, and the angular difference (henceforth referred to as the *angular disparity*) represents the angle required to rotate one figure into congruence with another. Using quaternions, instead of Euler angles, avoids aberrant triaxis rotational behavior (e.g., gimbal lock) and provides an easy-to-interpret measure of angular disparity (see Appendix A for equations used to calculate angular disparity). Trials were separated by a screen instructing participants to continue to the next trial; for physical rotation trials, the screen additionally instructed participants to return the sensor to the starting position. Saying "next" began a new trial. Error rates, RTs (time-locked to voice onset), and real-time angular disparities (for the physical rotation task; 50 Hz) were recorded.

Results

Central findings

We considered only correct responses in our analyses of RT and continuous physical-rotation data. We first examined mental-rotation and physical-rotation data for the classic ADE. For each participant, we correlated the initial angular disparities between figure pairs and RTs for *same* trials. Both mental rotation and physical rotation trials yielded ADEs. Pearson correlation coefficients (mental rotation: mean r = .36, physical rotation: mean r = .32)

Table 1. Measures of and Results for Individual Differences in Key Variables

Variable	Questionnaire/assessment	Results
Spatial ability	Santa Barbara Sense-of-Direction Scale (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006)	Moderate sense of direction (M = 4.1, scale range = 1–7)
Preferences for landmark-, route-, and survey-based spatial representation	Spatial Representation Questionnaire (Pazzaglia & De Beni, 2001)	Preference for landmark (M = 7.3) and route (M = 7.1) representation over survey (M = 5.8) representation (scale range = 2–10)
Spatial self-confidence, survey strategy, and knowledge of cardinal directions	English version of the Fragebogen Räumliche Strategien (Spatial Strategies Questionnaire; Münzer & Hölscher, 2011)	Moderate self-confidence in spatial abilities (M = 4.3, scale range = 1–7), moderate preference for survey strategies (M = 3.7, scale range = 1–7), and low knowledge of cardinal directions (M = 2.4, scale range = 1–7)
Video game experience	Video-game-experience questionnaire (Boot, Kramer, Simons, Fabiani, & Gratton, 2008)	Moderate frequency of video game play (M = 1.8 hr per week)
Working memory capacity (WMC)	Operation span task (Kaufman, 2007; Turner & Engle, 1989)	Moderate WMC (M = 38, hypothetical range = 0–64)

differed significantly from zero—mental rotation: $t(31) = 12.62$, $p < .001$, physical rotation: $t(31) = 10.79$, $p < .001$, and a paired t test comparing the correlation sets was not significant, $t(31) = 1.04$, $p > .1$, which suggests that ADEs were similar in both trial types.

We further examined how RTs and error rates varied at different initial angular disparities. We employed repeated measures analyses of variance (ANOVAs), with Greenhouse-Geisser correction in the case of sphericity violations (Geisser & Greenhouse, 1958), denoted by F_{GG}. We divided trials with different initial angular disparities into six 30° bins and submitted RTs to a 2 (task: mental rotation, physical rotation) × 2 (trial type: *same, different*) × 6 (initial-angular-disparity bin: 0°–30°, 30°–60°, 60°–90°, 90°–120°, 120°–150°, 150°–180°) ANOVA. No three-way interaction emerged, $F(5, 155) = 0.65$, $p > .1$, which suggests that RT patterns were similar for the mental and physical rotation tasks. Note that 3 of the 768 cells were empty as a result of participant error and replaced with averages of the same cell across participants. A two-way Trial Type × Initial-Angular-Disparity Bin interaction emerged, $F(5, 155) = 16.6$, $p < .001$, $\eta_p^2 = .349$, which reflects that *same*-trial RTs linearly increased with initial angular disparity but *different*-trial RTs did not vary. This analysis further revealed main effects of task and trial type. RTs for physical rotation trials were slower than RTs for mental rotation trials, $F(1, 31) = 59.62$, $p < .001$, $\eta_p^2 = .658$, and slower for *different* than for *same* trials, $F(1, 31) = 40.71$, $p < .001$, $\eta_p^2 = .568$. Figures 2a and 2b depict the ADEs and show that RT patterns were similar for mental and physical rotation trials.

The same ANOVA used to examine RTs was used to investigate error rates. This analysis yielded similar findings, with no three-way interaction, $F_{GG}(3.83, 118.6) = 1.09$, $p > .1$. For *same* trials, a two-way Trial Type × Initial-Angular-Disparity Bin interaction emerged, $F(5, 155) = 8.01$, $p < .001$, $\eta_p^2 = .205$, which reflects a positive linear relationship between initial angular disparity and error rate. For *different* trials, error rates did not vary with initial angular disparity. A main effect of task was also observed. Error rates for physical rotation were lower than error rates for mental rotation, $F(1, 31) = 111.97$, $p < .001$, $\eta_p^2 = .783$. In contrast to the results for RTs, no trial-type effect was observed, $F(1, 31) = 0.31$, $p > .1$. Figures 2c and 2d depict the observed ADEs and show that error-rate patterns for the mental and physical rotation tasks were similar. Taken together, the RT and error-rate data demonstrated a speed/accuracy trade-off. Mental rotation was faster but less accurate than physical rotation.

We next examined continuous real-time angular disparity between the figures in each pair during the physical rotation task. Data varied between trials (trials with longer RTs had more angular-disparity data). To address this, we first normalized the data into 100 samples using linear interpolation. Second, to discretize the continuous time variable, we created a time factor by dividing each trial into interpolated time quartiles (Sample 1–25, 26–50, 51–75, 76–100). Third, we divided trials by initial angular disparity (30° bins) as before. We then conducted a 4 (time quartile) × 6 (initial-angular-disparity bin) × 2 (trial type) ANOVA, which yielded a three-way interaction, $F(15, 465) = 5.99$, $p < .001$, $\eta_p^2 = .162$. Figure 3 depicts the continuous physical-rotation data underlying this interaction. Rotation initiating from varying initial angular disparities converged to stable and distinct comparatives. Averaging angular disparity at Sample 100 (angular disparity at response) demonstrated that *same*-trial rotation converged to 49°, whereas *different*-trial rotation converged to 113°. In neither case did rotation achieve a match between figures (i.e., 0°).

Finally, we examined how stimuli features relate to the speed/accuracy trade-off. One influential theory posits that mental rotation involves three stages: search, transformation and comparison, and confirmation (Just & Carpenter, 1976). The time-intensive transformation and comparison stage involves switching gaze between figure pairs' exterior "arms" (see Fig. 4a). Thus, figures' arm characteristics may influence RTs. We devised a dichotomous factor, *symmetry*, coding figures symmetric if the exterior arms had an equal number of blocks and asymmetric if they did not. We also devised a dichotomous factor, *arm weighting*. Figures in which the majority of blocks were contained in their arms (six or more) were coded as having high arm weighting, and figures with five or fewer blocks were coded as having low arm weighting. Figure 4a presents example figures depicting these factors.

We submitted RT data for *same* and *different* trials to a 2 (task: mental rotation, physical rotation) × 2 (symmetry: symmetric, asymmetric) × 2 (arm weighting: high, low) ANOVA, which revealed a three-way interaction (see Fig. 4b), $F(1, 31) = 9.45$, $p < .01$, $\eta_p^2 = .234$, as well as main effects of symmetry, $F(1, 31) = 17.23$, $p < .001$, $\eta_p^2 = .357$, and arm weighting, $F(1, 31) = 24.49$, $p < .001$, $\eta_p^2 = .441$. RTs were slower for both asymmetric (relative to symmetric) figures and figures with high (relative to low) arm weighting. Participants had the most difficulty responding to symmetric figures with high arm weighting during physical rotation.

Individual differences

To assess contributions of individual differences for each participant, we regressed RTs for correctly answered *same* trials with initial angular disparity, producing slopes of each participant's mental rotation and physical rotation ADE regression lines. We then regressed participants' individual-difference measures with their slopes. Neither gender effects nor significant relationships between other individual differences and slopes emerged for either mental or physical rotation (all ps > .1).

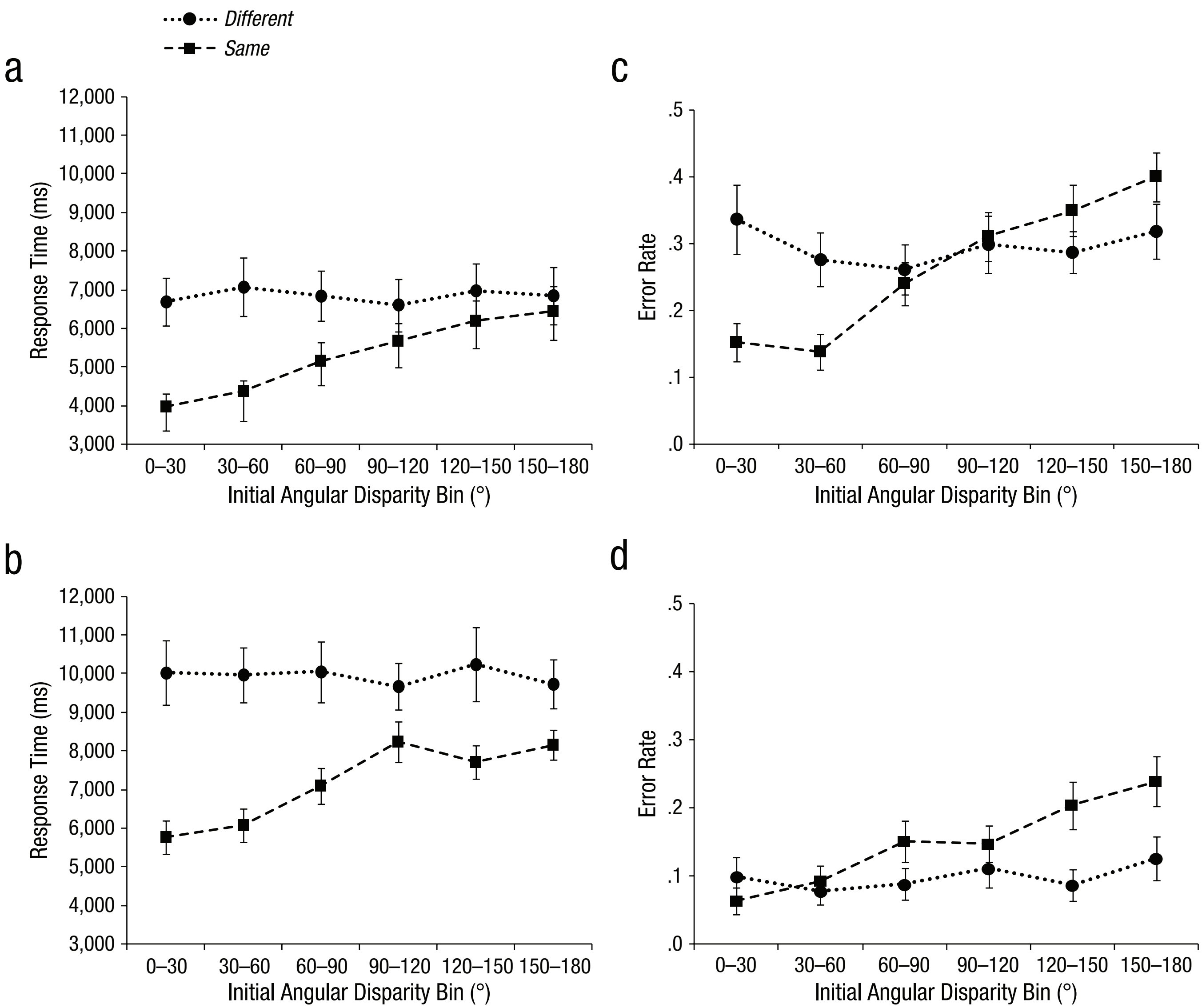

Fig. 2. Mean response time (a, b) and mean error rate (c, d) as a function of initial-angular-disparity bin and trial type. Results are shown separately for the mental rotation task (top row) and the physical rotation task (bottom row). Error bars show standard errors.

Discussion

In the present research, we directly compared mental rotation and physical rotation to explore central assumptions in mental rotation research. Mental and physical rotation showed predicted similarities, yielding statistically indistinguishable ADEs. This similarity was tempered by the speed/accuracy trade-off, with mental rotation being faster but less accurate than physical rotation. The prediction that participants would physically rotate figures within pairs on *same* trials to achieve a match was not supported. The data for continuous physical rotation challenge the assumption that mental rotation involves rotating figures to achieve a match and also suggest that participants use markedly different strategies for *same* and *different* trials.

Are mental rotation and physical rotation similar?

The observed ADEs and similar RT patterns for mental and physical rotation replicate the findings of Wohlschläger and Wohlschläger (1998), supporting their interpretations that mental rotation involves motoric processes and that mental and physical rotation are similar. However, those authors did not show a speed/accuracy trade-off. The items analysis provides a possible explanation. Figure 4b shows that RTs for symmetric figures with

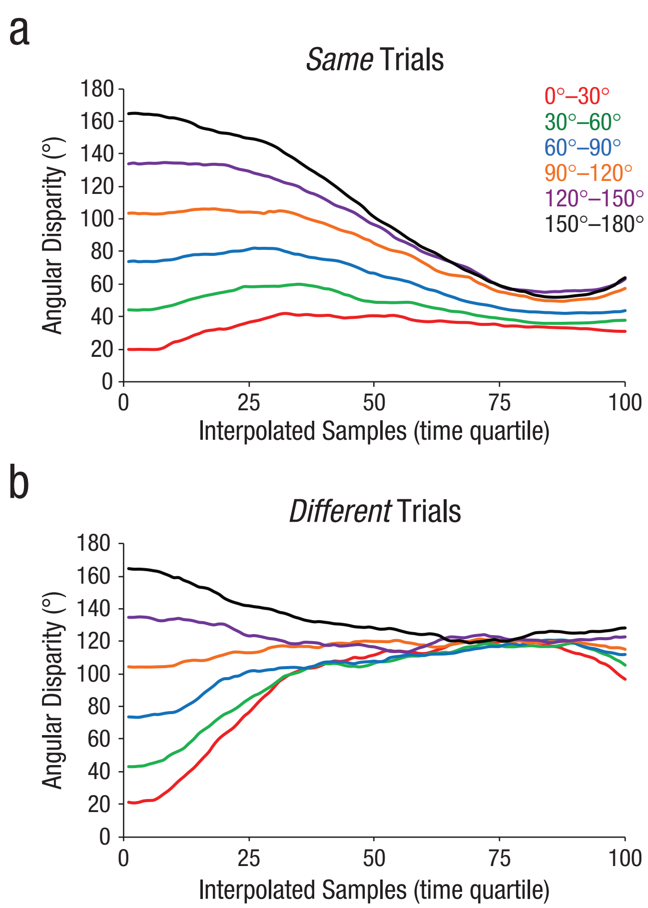

Fig. 3. Fine-grain angular disparity dynamics for correct responses during physical rotation trials as a function of time quartile and initial-angular-disparity bin. Results are shown separately for *same* (a) and *different* (b) trials.

high arm weighting are particularly lengthy. During physical rotation, participants necessarily use a holistic rotation strategy (Robertson & Palmer, 1983; Yuille & Steiger, 1982), because whole-figure movement corresponds with their manual action. Leone, Taine, and Droulez (1993) hypothesized that participants mentally rotate objects about their principal planes. Regarding our block stimuli, this plane intersects each figure's center. Leone et al. (1993) suggested that a figure's principal plane is efficiently rotated holistically, whereas its arms are rotated separately through a slower search and confirmation process. Symmetric figures with high arm weighting are ill-suited for this strategy, precisely because they possess the majority of blocks in their arms. Further, when figure arms have equal numbers of blocks, a contrast heuristic cannot be used. However, mental rotation can employ both piecemeal and holistic strategies and is consequently less sensitive to these stimuli features.

What does physical rotation reveal about mental rotation?

The results for physical rotation have two implications for mental rotation. First, participants did not rotate figures to achieve a match on either *same* or *different* trials. Strikingly, participants rotated figures on *same* trials with near-matching initial angular disparities (~20°) away from 0°, responding when rotation (49°) was further removed from a match. This challenges the assertion that mental rotation involves rotating objects to achieve a match, although it still supports rotation of analog mental images. What cognitive processes may underlie this novel

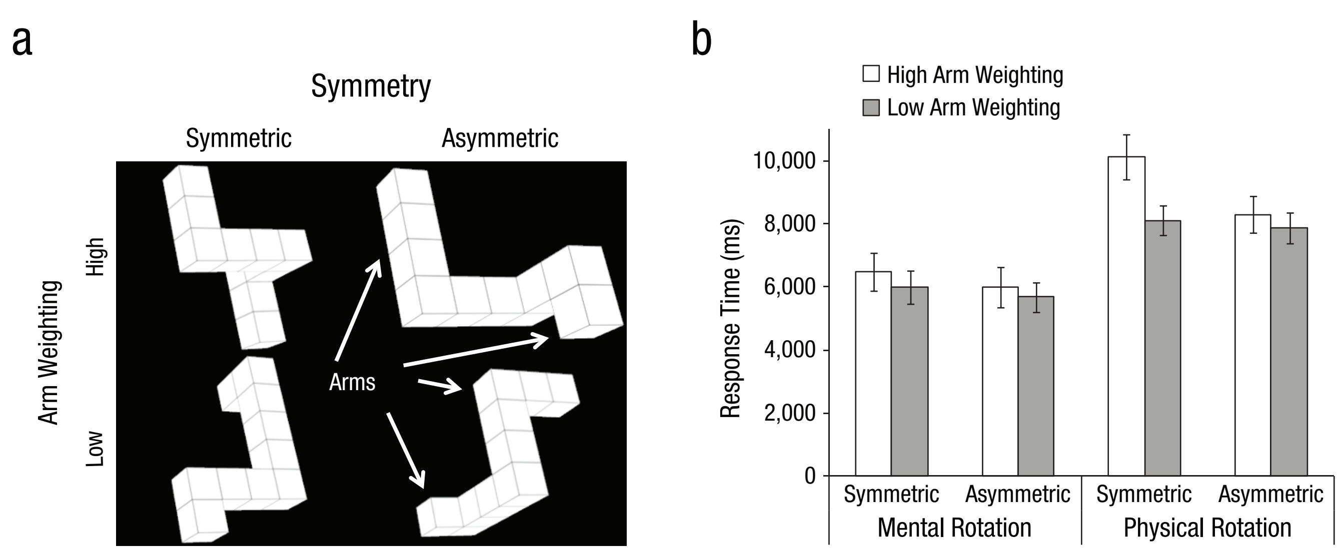

Fig. 4. Examples of figures with differing symmetry and arm weighting (a) and related results (b). Figures were considered symmetric if their exterior arms had an equal number of blocks and asymmetric if they did not. Figures in which the majority of blocks were contained in their arms were coded as having high arm weighting; otherwise, they were coded as having low arm weighting. The graph shows mean response time for correctly answered *same* and *different* trials (collapsed) as a function of whether figures were symmetric or asymmetric and had high or low arm weighting. Results are shown separately for the mental and physical rotation tasks. Error bars show standard errors.

behavioral observation? Seminal perception research demonstrated consistent preference for off-axis (3/4) canonical views of objects, likely because they display the most surfaces (Palmer, Rosch, & Chase, 1981). If mental rotation involves phenomenologically depicting and manipulating an analog mental image, it follows that rotation converges to a similar off-axis canonical difference. Though this assumption is speculative, our results provide some evidence for it.

Second, the data for continuous physical rotation suggest that *same* and *different* judgments employ distinct strategies. Rotation converged to markedly different angular disparities on *same* (49°) and *different* (113°) trials. Participants rotated *same* figures to a canonical difference and *different* figures to a distinct view. Here, we define a canonical difference as an off-axis rotation that affords an optimized view for perception and comparison of stimuli features. The RT data provide further evidence for distinct strategies. RTs and error rates for both mental and physical rotation yielded ADEs for *same* trials, but no consistent relationship with angular disparity for *different* trials. Shepard and Metzler (1971) argued that analyzing *different* trials was impossible because different figures cannot be rotated to achieve a match. However, the continuous physical-rotation data demonstrate consistent convergence suggesting that both *same* and *different* judgments involve rotation to a stable comparative.

Future directions

Our ADE findings and similar response patterns for mental and physical rotation suggest shared processes. However, this remains an assumption, and it is premature to definitively state that rotation of mental images corresponds with the continuous physical-rotation data. Neuroimaging during physical rotation may reveal neural correlates that are coactive during mental rotation, supporting this assumption. For example, neuroimaging research has found neural correlates of angular disparity during mental rotation (Gauthier et al., 2002; Shelton & Pippitt, 2006). However, to date, no researchers have directly compared neural activation between mental rotation and physical rotation. Combining our physical rotation task with neuroimaging would lead to further understanding of the links between mental rotation, physical rotation, and mental representation in general.

Conclusions

In sum, we found that physical rotation of Shepard and Metzler (1971) figures suggests that mental rotation of analog mental images converges to a canonical difference rather than to an exact match and that *same* and *different* judgments require markedly different cognitive strategies.

Appendix A

Angular-disparity calculation

$$\text{Quaternion}_{\text{Target}}\left(\text{Q}_{\text{T}}\right) = \left[x_1\ y_1\ z_1\ w_1\right]$$

$$\text{Quaternion}_{\text{Response}}\left(\text{Q}_{\text{W}}\right) = \left[x_2\ y_2\ z_2\ w_2\right]$$

$$\left[x_3\ y_3\ z_3\ w_3\right] = \text{Q}_{\text{T}} \times \text{Q}_{\text{W}}^{-1}$$

$$\text{Angular Disparity (AD)} = 2 \times \left(\frac{180 \times \cos^{-1} w_3}{\pi}\right)$$

Angular-disparity transformation

If AD > 180 then AD = (360 – AD)

else

AD = AD

Author Contributions

A. L. Gardony and H. A. Taylor developed the study concept and design with input from T. T. Brunyé. A. L. Gardony created the stimuli and programmed the stimuli presentation and task. A. L. Gardony collected and analyzed the data under the supervision of H. A. Taylor. A. L. Gardony drafted the manuscript, and H. A. Taylor and T. T. Brunyé provided critical revisions. All authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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