Fast and Careless or Careful and Slow? Apparent Holistic Processing in Mental Rotation Is Explained by Speed-Accuracy Trade-Offs
Heinrich René Liesefeld, Xiaolan Fu, and Hubert D. Zimmer

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Fast and Careless or Careful and Slow? Apparent Holistic Processing in Mental Rotation Is Explained by Speed-Accuracy Trade-Offs

Heinrich René Liesefeld
Ludwig-Maximilians-Universität and Saarland University

Xiaolan Fu
Chinese Academy of Sciences

Hubert D. Zimmer
Saarland University

A major debate in the mental-rotation literature concerns the question of whether objects are represented holistically during rotation. Effects of object complexity on rotational speed are considered strong evidence against such holistic representations. In Experiment 1, such an effect of object complexity was markedly present. A closer look on individual performance patterns, however, revealed that only some participants showed this effect. For others, rotational speed was independent of object complexity. The assumption that these fast-rotating participants use a holistic representation that equally well holds simple and complex objects would explain these results. Taking error rates into account disproved this explanation: Fast participants simply committed more errors in those conditions for which careful participants invested more rotation time. Whether this speed-accuracy trade-off is a stable personality trait or a somewhat flexible strategic choice was examined in Experiments 2 and 3. In Experiment 2, participants received monetary incentives that encouraged them to minimize errors. In line with a certain degree of flexible strategic control over speed-accuracy trade-offs, a large majority of participants showed effects of object complexity on rotational speed. When, in contrast, time pressure was induced in Experiment 3, error rates increased considerably and most participants’ rotational speed became independent of object complexity. Our results indicate that all our participants performed mental rotation on a nonholistic representation and that apparent holistic processing strategies in mental rotation (and potentially also in other spatial tasks) might actually be speed-accuracy trade-offs in disguise.

Keywords: spatial abilities, working memory, imagery, object complexity, cognitive strategies

Mental rotation is a working memory function that involves not only the passive storage of feature information but also its active manipulation (Albers, Kok, Toni, Dijkerman, & de Lange, 2013; Kaufman, 2007; Tong, 2013; Zimmer, 2008). An object is first encoded into a mental representation and this representation is then manipulated in a rotation-like manner. A similar passive working memory task without an active manipulation component is the heavily examined change-detection task (e.g., Liesefeld, Liesefeld, & Zimmer, 2014; Luck & Vogel, 1997). Alvarez and Cavanagh (2004) showed that change-detection performance decreases with the complexity of the to-be-remembered objects. This finding that more complex objects apparently need more working memory resources is of importance in the debate on whether objects are represented holistically. A holistic representation contains the object as an integrated whole instead of, for example, a collection of its constituent parts. Although earlier studies pointed toward holistic working memory representations (e.g., Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997; Rouder et al., 2008), more recent research speaks in favor of nonholistic alternatives (e.g., Alvarez & Cavanagh, 2004; Bays, Wu, & Husain, 2011; Fougnie, Cormiea, & Alvarez, 2013).1

A similar topic is independently discussed in the mental-rotation literature. Here too, effects of object complexity are examined to

1 Also in the working memory literature this debate is not yet settled and several additional characteristics of working memory representations are intensely discussed, including limits on the number of objects or features and the precision with which this information is stored (e.g., Oberauer & Eichenberger, 2013; Zhang & Luck, 2008, 2011).
differentiate between holistic and nonholistic object representations. An established and straightforward method to examine the influence of object complexity on the working memory representation used for mental rotation is to test whether an increase in object complexity influences \textit{rotational speed} (Cooper, 1975; Cooper & Podgorny, 1976). The classical finding in mental-rotation tasks is that the time participants take to perform a rotation (\textit{absolute rotation time}) increases as a function of rotational angle. Rotation speed is defined as the size of this mental-rotation effect, that is, as the slope of the function relating absolute rotation time to rotational angle. The major advantage of examining rotational speed instead of absolute rotation time is that this isolates effects on mental rotation proper from effects on the encoding or comparison stages of the task. An effect that emerges at the actual rotation stage of mental rotation must influence rotational speed, whereas main effects on absolute rotation times can also be driven by encoding or comparison processes. If objects were represented holistically, rotational speed should be independent of an object’s complexity. In contrast, several studies showed that rotational speed is higher for simple objects than for complex objects (Bauer & Jolicoeur, 1996; Folk & Luce, 1987; Heil & Jansen-Osmann, 2008; Jolicoeur, Regehr, Smith, & Smith, 1985; Liesefeld & Zimmer, 2013; Yuille & Steiger, 1982). This indicates that the working memory representation of a complex object is more difficult to manipulate compared with the representation of a simple object. The typical account for complexity effects on rotational speed assumes a piecemeal (nonholistic) rotation. That is, a complex object is dismantled and represented as several simpler pieces. If each such piece has to be rotated separately, actually several rotations must be performed and this leads to a decrease in measured average rotational speed (Just & Carpenter, 1976; Just & Varma, 2007; Pylyshyn, 1979; Yuille & Steiger, 1982).

The holistic/nonholistic distinction also plays a prominent role in the literature on individual differences in spatial abilities. Individuals apparently use different strategies to solve spatial tasks in general and mental-rotation tasks in particular. This strategy use is a moderately stable personality trait (e.g., Contreras, Rubio, Peña, & Santacreu, 2010, observed that after 1 year 60% of their participants had maintained a stable strategy). Strategies are related to an individual’s gender but they also depend on task affordances and experience with the task (Cochran & Wheatley, 1989; Geiser, Lehmann, & Eid, 2006; Heil & Jansen-Osmann, 2008; for a review, see Gluck & Fitting, 2003). This opens the possibility that complexity effects on mental rotation actually are driven by only part of the subject sample. Potentially, some participants rotate objects holistically whereas those that actually cause complexity effects in the averaged data use a piece-meal strategy (see Heil & Jansen-Osmann, 2008; Khooshabeh, Hegarty, & Shipley, 2013). For example, Heil and Jansen-Osmann (2008) found that women, but not men, show effects of object complexity on rotational speed. They concluded that women prefer a piecemeal strategy whereas men prefer holistic rotations. Alternatively, these interindividual and intraindividual differences in mental-rotation performance might not reflect qualitatively different processing styles but instead go back to variability in speed–accuracy trade-off. Interindividual differences in speed–accuracy trade-offs are known to occur in mental rotation (see, e.g., Goldstein, Haldane, & Mitchell, 1990; Hertzog, Vernon, & Rypma, 1993; Lohman, 1986), but their influence on effects of object complexity was not yet examined. It is, therefore, unknown whether the interindividual differences in complexity effects that are typically interpreted in terms of the holistic/piecemeal distinction can be explained by interindividual differences in speed–accuracy trade-off. This new hypothesis appears most probable in the face of recent findings that the mental representation in mental rotation is not a holistic visual image, but contains only certain types of spatial-relational information (Liesefeld & Zimmer, 2013). Potentially, some participants decide to emphasize speed and rotate simple and complex objects at the same (high) speed. If rotations are not holistic, such a strategy must necessarily lead to a higher error rate for complex objects. To maintain a high speed even for complex objects, these participants must either rotate each object piece less carefully or perform a full rotation on only a subsample of the pieces. In both cases, some information on complex objects is lost and these participants must, therefore, often resort to guessing. Other participants may decide to rotate each piece with the same care and, therefore, have to adjust their average rotational speed to the complexity of the rotated object to avoid errors.

The aim of Experiment 1 was to determine whether individual differences in mental-rotation strategy are better explained in terms of the holistic/nonholistic dichotomy or in terms of speed–accuracy trade-offs. Speed–accuracy trade-offs would predict that participants who do not show an effect of object complexity on rotational speed show such an effect in their error rates and this effect should be more pronounced compared with participants who show the effect on rotational speed. If, in contrast, some participants perform holistic rotations, complexity effects should be absent from both their rotation times and their error rates. To test these predictions, we administered a computerized mental-rotation task with objects of different complexity and divided the subject sample into those who show an effect of object complexity on rotational speed and those who do not. Our results show that when effects of object complexity do not emerge in measured rotation times, error rates increase, respectively, as predicted by the speed–accuracy-trade-off hypothesis.

\section*{Experiment 1}

\subsection*{Method}

\textbf{Participants.} Our sample consisted of 27 university students (15 female; age range: 17–36 years, \textit{Mdn} age: 22 years) recruited at the campus of Saarland University, Germany. All participants reported normal or corrected-to-normal vision and gave informed consent. Data from one further participant were not included for failure to follow the instructions as evidenced by an overall error rate of .47, which is just below chance level (.50). An outlier analysis on absolute rotation times, rotational speed, and error rates did not indicate any further outliers. Throughout this article,

\footnote{Different analyses on part of the data from Experiment 1 are reported in HRL’s doctoral thesis (Liesefeld, 2012, Experiment 1a). In contrast to this previous work, we here analyze the full subject sample, without excluding participants who ignored object features. Note that Liesefeld (2012) examined whether the mental representation in mental rotation has visual properties, whereas the present work examines differences in task performance between groups.}
outliers are defined as values larger than 1.5 interquartile differences above the third or below the first quartile of the respective empirical distribution (Tukey, 1977).

**Material.** To examine complexity effects, it is of major importance to manipulate not just the complexity of any stimulus feature, but the complexity of a stimulus feature that is actually represented during task performance (e.g., Zimmer & Liesefeld, 2011). For example, when examining complexity effects on verbal working memory, it is not sufficient to only manipulate the complexity of the font type in which the to-be-remembered words are printed. The same is true for mental rotation: Liesefeld and Zimmer (2013) showed that the cognitive process of mental rotation works on orientation-dependent information only and is not influenced by the visual complexity of the stimuli. Orientation-dependent information refers to stimulus features that change whenever the stimulus changes its orientation (e.g., when it is rotated). All orientation-dependent information can be reduced to left/right, above/below, in front of/behind. Because only orientation-dependent information plays a role in mental rotation, a reliable manipulation of complexity can only be achieved by manipulating the amount of represented orientation-dependent information (Liesefeld & Zimmer, 2013). Based on this general criterion, Liesefeld and Zimmer (2013) developed their stimulus set, which consists of the three types of objects displayed in Figure 1a. Complex objects contain two pieces of orientation-dependent information whereas simple objects contain only one piece of orientation-dependent information. As a consequence, the average rotational speed is lower for complex objects than for objects of the two simple types. The two simple object types both contain only one piece of orientation-dependent information and, therefore, rotational speed of these two object types is equal (Liesefeld & Zimmer, 2013). A further advantage of these stimuli is that they are as simple as possible while still reliably inducing complexity effects in mental-rotation tasks. This simplicity should homogenize the way participants represent these stimuli and thereby reduce the influence of extraneous variables on task performance (see Liesefeld & Zimmer, 2013, as well as Liesefeld, 2012 for a detailed discussion of these stimulus characteristics).

**Procedure.** Each trial (see Figure 1b) started with a fixation cross shown for 500 ms, followed by a 1,000-ms presentation of one object (Simple 1, Simple 2, or Complex). Objects were 3° of visual angle in size and presented in black against a gray background at the center of the screen. Two arcs whose one end touched the original stimulus’ main axis appeared 200 ms before onset of the to-be-rotated object and indicated the direction (clockwise or counterclockwise) and amount (45°, 90°, or 135°) of to-be-performed rotation. Participants had to encode the object into working memory and to mentally rotate this representation according to the rotation cues. As soon as they had finished the rotation, they proceeded to a comparison object by pressing the space bar on a standard computer keyboard with the thumb of either hand. The time from onset of the rotation cue (when rotation can possibly start) until this space-bar press is the measure of absolute rotation time from which we derived the measure of rotational speed analyzed below. The comparison object was shown for 500 ms and always appeared in the orientation that was indicated by the rotation cue. This object was either a rotated version of the original object or differed additionally in one feature: As displayed in Figure 1a, the shorter stroke (and the flag for objects of type Simple 2 and Complex) could be on the wrong side of the longer stroke (Change 1; this change was possible for all objects), the square could be on the wrong position on the shorter stroke (it was either at the end of the shorter stroke as in Figure 1 or in the middle of that stroke; Change 2; this change was possible for objects of type Simple 2 and Complex), and the square could be on the wrong side of the shorter stroke (Change 3; this change was possible for complex objects only). For simple objects, all changes were equiprobable; for complex objects, the probability of Change 3 was as high as the combined probability of Change 1 and 2. Because Change 3 could only occur for complex objects, its overall probability would otherwise have been rather low and we were afraid that participants would then not pay attention to this change. However, it turned out that Change 3 was detected even more reliably than the more probable Change 2 and we, therefore, made all types of changes equiprobable in Experiments 2 and 3 (where it was still more reliably detected). Participants’ task was to decide whether the comparison object matched their rotated memory representation or not. They had to answer this question by pressing the “F” or “J” key within a time limit of 800 ms after onset of the comparison object. Assignment of response keys to response categories was counterbalanced across participants. When participants did not answer within the time limit, they received immediate feedback (German words for “too slow” were displayed for 500 ms).

![Figure 1](image-url)

**Figure 1.** Stimulus set and task design. (a) Examples for each object type used and the possible comparison stimuli. (b) An example trial where an object of type Simple 1 is rotated 135°, counterclockwise. Stimuli displayed in white (objects and arrows) were not actually shown but serve to illustrate the mental-rotation process necessary to solve this example trial. As the comparison stimulus (Change 1) differs from the correct rotation result (the to-be-imagined stimulus), the correct response in this example is “mismatch.”
Instructions encouraged participants to perform as fast as possible without sacrificing accuracy. The experiment started with a short practice phase followed by 432 regular trials (48 trials per Object type \(3 \times \) Rotational angle \(3\) cell). Because we analyzed rotation times only for correct trials, trials with incorrect answers or time-outs were rescheduled after the regular trials, so that the same number of observations (48) was available for each experimental cell. Feedback on accuracies and rotation times was provided every 20th trial. Whenever accuracy fell below 90%, participants were reminded of this target value. See Liesefeld (2012, Experiment 1a) for further methodological details.

Results

Trials with outlying log-transformed absolute rotation times per Subject \(\times\) Object type \(\times\) Rotational angle cell were excluded from the analyses. Analyses of rotation times included only trials with correct responses that were given within the time limit. Rescheduled trials were excluded from the analyses of error rates. Analyses of variances (ANOVAs) that include a between-subjects variable are based on Type-II sums of squares. Greenhouse-Geisser corrected \(p\) values \((p_{G})\) and the respective \(\varepsilon\)s are reported where appropriate. Two-tailed \(t\) tests are reported unless otherwise noted. When interpreting the respective \(p\) values, there is no need for multiple-comparison corrections of the \(\alpha\)-error level, as all expected effects were significant (see Hochberg, 1988). For all correlations, bivariate outliers were excluded (results did not change with bivariate outliers included). All reported correlations tested directed hypotheses (a negative relation between speed and error rates) and were, therefore, tested one-tailed. Error bars in figures display 95% confidence intervals (Jarmasz & Hollands, 2009) using the error term from the main effect of object type or from the Object type \(\times\) Rotational angle interaction (as indicated) with degrees of freedoms corrected by \(\varepsilon\) (Greenhouse-Geisser).

Rotation times. A 3 (object type) \(\times\) 3 (rotational angle) within-subjects ANOVA on absolute rotation times (Figure 2a) indicated an interaction, \(F(4, 104) = 7.31, p = .002, \eta_{p}^{2} = .22, \varepsilon = .42\), as well as two main effects, \(F(2, 52) = 16.46, p < .001, \eta_{p}^{2} = .30, \varepsilon = .66\) (object type), and \(F(2, 52) = 60.49, p < .001, \eta_{p}^{2} = .70, \varepsilon = .65\) (rotational angle). Separate analyses for each object type indicated strong linear trends of rotational angle, separately for each object type. The slope for this regression is a robust individual estimate of rotational speed that takes data from all three rotational angles into account. As expected, rotational speed (Figure 2b) was slower for complex objects compared with both types of simple objects, \(t(26) = 3.02, p = .006, dz = .58\) (Simple 1), and \(t(26) = 2.65, p = .013, dz = .51\) (Simple 2), but did not differ between the two simple object types, \(t(26) = 1.72, p = .098, dz = .33\).

Identification of strategy groups. Visual inspection of individual data sets revealed that the effect of object complexity on rotational speed was only present in about half the subject sample (for data from two representative participants, see Figure 2c and 2d). To objectively determine for each individual participant whether this effect was present, we took the following approach: For each Subject \(\times\) Object type \(\times\) Rotational angle cell, we extracted raw rotation times from all trials with correct responses within the time limit (48 per cell) and sorted the individual rotation times in ascending order separately for each cell. Sorting allowed comparing the fastest to the fastest trial, the second fastest to the second fastest trial and so on for each pair of cells and thereby considerably reduced error variance because of intertrial variability in rotation times that is unrelated to the experimental manipulations. For each object type, these vertical vectors were horizontally concatenated to form a 48 (trials) \(\times 3\) (rotational angle) matrix. We then performed row-wise linear regressions of rotation

![Figure 2. Effects of object complexity on mental-rotation times in Experiment 1. (a) Absolute rotation times as a function of object type and rotational angle. Error bars display 95% confidence intervals based on the Object type \(\times\) Rotational angle interaction. (b) The same data as in (a), but displayed as rotational speed. Error bars display 95% confidence intervals based on the main effect of object type. The height of the bars in (b) corresponds to the slope of the lines in (a). Examples of individual data sets are shown in (c) and (d). The participant in (c) shows an effect of object complexity on rotational speed, whereas the participant in (d) does not.](image-url)
times on rotational angle, thereby obtaining 48 measures of rotational speed for each participant and object type (b weights for rotational angle). The mean of these b weights is mathematically identical to the above introduced b weight from the regression of individual mean rotation times on rotational angle (when done without outlier rejection). Next, rotational speeds for complex objects were compared with rotational speeds for the two types of simple objects separately by subtracting speed for simple objects from speed for complex objects. Outlying values from each of the two resulting difference vectors were excluded and each difference vector was tested against zero with a single-sample one-sided t test. If the mean of such a vector differs from zero, this indicates an effect of complexity on rotational speed for the given participant. Only when this t test was significant (p < .01, one-tailed) for both comparisons (complex against both types of simple objects) the respective participant was classified as showing the effect of object complexity on rotational speed. In summary, we classified participants according to whether they showed a significant Rotational angle × Object type interaction in their individual rotation-time patterns, whereby significance was tested based on the individual-between-trials variance.

Comparison of rotational speed between groups. In line with our visual inspection of individual data patterns (Figure 2c and 2d), an effect of object complexity on rotational speed was present in only 14 out of the 27 participants (51.9%). Based on this effect, we separated our subject sample into two groups—careful rotators that showed the effect of object complexity on rotational speed and fast rotators that did not show this effect. Strong linear trends of rotational angle on rotation times (Figure 3a and 3b) were present for each object type for careful rotators, Fs(1, 13) > 27.95, ps < .001, and for fast rotators, Fs(1, 12) > 15.79, ps < .002; thus, providing evidence that both groups performed mental rotation on each object type. A Group (2) × Object type (3) mixed ANOVA on rotational speed (Figure 3c and 3d) indicated a main effect of object type, F(2, 50) = 9.65, p = .002, η² = .28, ε = .67. Although this effect was predicted, it does not constitute any additional independent evidence for slowed rotation of complex objects, because it reflects the very same data pattern that gave rise to the Object type × Rotational angle interaction on absolute rotation times reported above. The main effect of group was not significant, F(1, 25) = 1.09, p = .308, η² = .04. More important, confirming the validity of our grouping criterion, a Group × Object type interaction was clearly present, F(2, 50) = 7.34, p = .006, η² = .23, ε = .67. In fact, careful rotators (Figure 3a and 3c) reduced rotational speed for complex objects compared with simple objects, t(13) = 3.79, p = .002, dz = 1.01, and t(13) = 3.17, p = .007, dz = 0.85, whereas fast rotators (Figure 3b and 3d) rotated both simple and complex objects at the same speed, t(12) = 0.40, p = .697, dz = 0.11, and t(12) = 0.03, p = .975, dz = 0.01. These analyses demonstrate that our classification criterion effectively divided the subject sample into those who show an effect of object complexity on rotational speed and those that do not show this effect.

Error rates. One plausible explanation for this pattern of results would be that the fast rotators’ performance does not depend on object complexity, because they perform rotation on a holistic representation of the object. Alternatively, these participants were faster for complex stimuli, because they did simply not

Figure 3. Effect of object complexity, separately for careful rotators (n = 14) and fast rotators (n = 13) in Experiment 1. The effect is present in the rotational speed of careful rotators (shown as an interaction in a and as a main effect in c), but not in the rotational speed of fast rotators (b and d). In error rates, in contrast, the effect is weaker for careful rotators (e) compared with fast rotators (f). When a combined speed-accuracy measure of task performance is considered, performance patterns do not differ between groups (g and h). Error bars display 95% confidence intervals based on the Object type × Rotational angle interaction in a and b and e and f and based on the main effect of object type in c and d and g and h.
adequately adjust rotational speed to the task affordances and thereby risked an increased error rate for complex objects. To differentiate between these two hypotheses, we analyzed error rates (Figure 3e and 3f). Note that whereas the group differences in rotation-time patterns are (partly) determined by our grouping criterion, error rates are mathematically independent from that criterion. The analysis of error rates, therefore, is the critical test to determine whether group differences are because of qualitative differences in mental-rotation style (holistic vs. piecemeal) or because of quantitative differences in speed–accuracy trade-offs. A Group (2) × Object type (3) × Rotational angle (3) mixed ANOVA on error rates showed main effects of angle, $F(2, 50) = 44.81$, $p_{c} < .001$, $\eta_{p}^{2} = .64$, $\epsilon = .75$, and of object type, $F(2, 50) = 67.51$, $p_{c} < .001$, $\eta_{p}^{2} = .73$, $\epsilon = .88$, as well as an Angle × Object type interaction, $F(4, 100) = 12.73$, $p_{c} < .001$, $\eta_{p}^{2} = .34$, $\epsilon = .62$, which are of only minor importance for the present analyses as they are unrelated to group. In line with the speed-accuracy-trade-off explanation, there were a main effect of group, $F(1, 25) = 7.41$, $p = .012$, $\eta_{p}^{2} = .23$, a Group × Object type interaction, $F(2, 50) = 4.56$, $p_{c} = .017$, $\eta_{p}^{2} = .15$, $\epsilon = .88$, and a Group × Rotational angle interaction, $F(2, 50) = 6.05$, $p_{c} = .009$, $\eta_{p}^{2} = .20$, $\epsilon = .75$, reflecting that fast rotators showed worse overall performance and stronger effects of object type and rotational angle on their error rates. The three-way interaction, however, missed significance, $F(4, 100) = 2.03$, $p_{c} = .129$, $\eta_{p}^{2} = .08$, $\epsilon = .62$. Apparently, the difference in interactions between groups was not strong enough to yield a significant three-way interaction. The power of this test might be too low because of the rather small sample size ($n = 14$ and $n = 13$ for careful rotators and fast rotators, respectively). Alternatively, this test might be overly conservative, because a categorical differentiation into fast and careful rotators is too coarse and does not accurately capture the underlying distribution (see Figure 4). In particular, if the distribution of this performance attribute is actually continuous, splitting a sample into two groups artificially decreases the amount of information on each participant’s performance and thereby reduces the power of statistical tests. To gain a continuous individual measure of the Object type × Rotational angle interaction (i.e., speed–accuracy trade-offs), we calculated for each participant the difference in the effect of rotational angle (the mental-rotation effect) between complex objects and the second type of simple objects (that are more similar to complex objects in terms of visual complexity, see Liesefeld & Zimmer, 2013) on rotation times and error rates as: $\text{slope}_{\text{complex}} - \text{slope}_{\text{simple2}}$. If a smaller Object type × Rotational angle interaction on rotation times leads to a stronger respective impact on error rates, the difference in slopes for rotation times and error rates should be anticorrelated, which clearly was the case, $r = -.46$, $p = .009$.

This correlation of complexity effects in slopes of rotation times and error rates is evidence for the expected speed–accuracy trade-off. The less a participant adapts rotational speed to object complexity, the stronger the effect of object complexity on his or her error rate becomes. Rotating careless might impact error rates for each object type or, alternatively, the negative consequences of fast rotations might be restricted to complex objects. To differentiate between these hypotheses, we followed up on this correlation by checking for negative correlations between the slopes of error rates and rotation times for each object type independently. As evident in Figure 4, the slopes correlated for complex objects, $r = -.66$, $p < .001$, but not for simple objects, $r = .16$, $p = .778$ (Simple 1), and $r = -.17$, $p = .203$ (Simple 2).

**Combined speed-accuracy measure.** Obviously, an effect of object complexity emerged in both groups: Those individuals who did not slow down their rotational speed according to object complexity paid for the gain in speed with a respective increase in error rate. One implication of this finding is that to fully appreciate the effect of object complexity on mental-rotation performance, both rotation times and error rates must be taken into account concurrently. Therefore, we constructed a combined measure of overall task performance by subtracting standardized accuracies (1-error rates) from standardized rotation times. In particular, we obtained standardized scores by subtracting from each individual mean rotation time per Subject × Object type × Rotational angle cell the overall mean rotation time (mean over subjects, object types, and rotational angles) and divided the result by the $SD$ of all cells concatenated. The same was done for accuracies. By subtracting standardized accuracies from standardized reaction times (RTs) individually for each experimental cell, we obtained an accumulated measure of task performance. For comparison purposes we then applied a linear transformation to this measure to bring it to the scale of rotation times. A 2 (group) × 3 (object type) × 3 (rotational angle) mixed ANOVA showed main effects of angle, $F(2, 50) = 168.26$, $p_{c} < .001$, $\eta_{p}^{2} = .87$, $\epsilon = .78$, and of object type, $F(2, 50) = 104.06$, $p_{c} < .001$, $\eta_{p}^{2} = .81$, $\epsilon = .83$, as well as an Angle × Object type interaction, $F(4, 100) = 21.59$, $p_{c} < .001$, $\eta_{p}^{2} = .46$, $\epsilon = .65$, which are of only minor importance for the present analyses as they are unrelated to group. More important, this ANOVA also revealed that the two groups did not differ in this measure of overall task performance: main effect of group, $F(1, 25) = .73$, $p = .402$, $\eta_{p}^{2} = .03$, Group × Object type interaction, $F(2, 50) = 0.86$, $p_{c} = .414$, $\eta_{p}^{2} = .03$, $\epsilon = .83$, Group × Rotational angle interaction, $F(2, 50) = 1.83$, $p_{c} = .181$.

**Figure 4.** Scatterplots displaying correlations between rotational speed and the slope of the error rate (as a function of rotational angle). Speed-accuracy trade-offs occur only for complex objects and are distributed continuously. Plus signs indicate bivariate outliers, which were excluded from the correlational analyses.
The existence of differences in speed–accuracy trade-off observed in Experiment 1 raises questions about the nature of these differences. Potentially, being a fast rotator or a careful rotator is a stable personality trait that cannot be changed at will. Alternatively, participants only have a tendency to rotate either fast or careful. The latter would be a kind of strategic choice rather than a personality trait. It then might be possible to experimentally influence speed–accuracy trade-offs by task demands so that even those with a tendency to rotate fast will change their behavior to be more careful. In particular, rewarding participants for very accurate performance should—to a certain extent—override a tendency to rotate fast and carelessly and make most participants rotate slowly and carefully. We verified this hypothesis in Experiment 2. Inducing a shift of rotation behavior toward the opposite pole should also be possible. To do this, we introduced a time-limit to the rotation phase in Experiment 3. Under time pressure, most participants indeed used a fast and careless strategy.

Method

Participants. Our final sample comprised of 22 participants (11 female; age range: 17–25 years, Mdn age: 21 years) for Experiment 2 and 24 participants (16 female; age range: 20–25 years, Mdn age: 23 years, 1 male participant did not report his age) for Experiment 3. Participants were recruited at universities in Beijing, China. All participants reported normal or corrected-to-normal vision and gave informed consent. Data from one further participant of Experiment 2 were collected but not included into the final analyses because of an outlying average rotational speed. No outliers were detected in Experiment 3.

Design. The general task design was the same as in Experiment 1. Rotation time was unlimited in Experiment 2 and limited to 5,000 ms in Experiment 3. This limit in rotation times was the only difference between the designs of Experiments 2 and 3.

To motivate a careful strategy in Experiment 2, participants of both experiments were informed that, in addition to a 30 RMB (Chinese Yuan) basic pay, they would receive a bonus of 10 RMB for an overall accuracy rate of 90% or above and would be penalized 0.1 RMB for each miss. A trial counted as a miss whenever the response was not given within the time limits. That

Discussion

Experiment 1 replicated an effect of object complexity on rotational speed (e.g., Bauer & Jolicoeur, 1996; Folk & Luce, 1987; Heil & Jansen-Osmann, 2008; Jolicoeur et al., 1985; Liesefeld & Zimmer, 2013; Yuille & Steiger, 1982). In an important extension of these earlier findings, a closer look on individual performance patterns indicated that the effect of object complexity was driven by only a subset of participants. Obviously, our subject sample comprised of participants who focused on speed (fast rotators) and of participants who focused on accuracy (careful rotators). A differentiation between holistic and nonholistic processing strategies does not account for these differences, because effects of object complexity should be absent from all measures of rotation performance of a holistic rotator. In particular, a holistic rotator should be able to rotate complex objects at the same speed as simple objects without sacrificing accuracy. Although fast rotators did not show an effect of object complexity in their rotation time data, they showed the respective effect in their error rates and this effect on error rates was amplified compared with careful rotators. As a consequence, the two groups did not differ in a combined performance measure that controls for speed–accuracy trade-offs. That is, group differences in rotational speed and group differences in error rates fully cancelled each other out. This shows that the manipulation of object complexity used here increases the difficulty of rotation in both groups to the same degree.

Additional analyses on speed–accuracy trade-offs separately for each object type indicated that a fast and careless rotation comes with a cost only for objects of a certain complexity. A negative correlation between the speed of rotation and the slope of the error rate emerged for complex objects but not for simple objects. This means that a fast strategy is more efficient whenever only simple stimuli are rotated. Investing additional effort into a careful rotation only pays off when stimuli are sufficiently complex.

Although we categorized our subject sample into fast and careful rotators to simplify data analysis and interpretation, we do not purport that these two categories accurately capture the characteristics of the underlying distribution. In fact, as evident in Figure 4, the distribution of carefulness in mental rotation is continual rather than categorical (otherwise two clearly separable clusters would have been discernible). Such a continuous distribution is also more compatible with a speed-accuracy explanation than with the holistic/nonholistic dichotomy.
is, participants lost money when they were too slow with the rotation (Experiment 3) or with the comparison (Experiment 2 and 3). In case of a miss, participants received immediate feedback (Chinese words for “too slow” were displayed for 500 ms). Additionally, feedback on accuracies, misses, and RTs was provided in a self-terminated break after every 20th trial. Whenever participants’ mean accuracy between two breaks fell below 90% they were reminded of this target value. The same general monetary incentive scheme was used in both experiments. However, by the same scheme, participants of Experiment 3 could additionally lose money by missing the rotation-time deadline. This increased risk of performing badly and of losing money should induce a fast strategy in Experiment 3.

To restrict the time pressure in Experiment 3 to the rotation phase, the encoding time-window in both experiments was self-paced (space-bar press) and the response deadline for the comparison between the imagined and the comparison object was extended to 1,000 ms. Furthermore, the to-be-encoded object was masked and the object’s main axis remained on the screen throughout the rotation period (all object types and versions share the same main axis, so this axis does not contain any information about the to-be-rotated object). In pretests, this proved necessary for the correct interpretation of the rotation cues. Participants were instructed how exactly the comparison object might differ from the to-be-imagined object to make sure that they would process all relevant object features. All this was done to maximize the influence of mental rotation proper on measured task performance and to minimize the influence of extraneous variables. In contrast to Experiment 1, rescheduled trials were inserted randomly into the sequence of trials instead of being presented after all regular trials were finished. This served to mitigate the increased probability of difficult trials toward the end of a block. For a detailed discussion of these methodological improvements, see Liesefeld (2012). See Liesefeld and Zimmer (2013) for further methodological details.

Results

According to the analysis of individual rotational-speed patterns developed for the analysis of Experiment 1, 17 out of the 22 participants in Experiment 2 (77.3%) rotated carefully, whereas only 5 out of 23 participants rotated carefully in Experiment 3 (21.7%). This difference in the proportion of careful rotators was significant, \( \chi^2(1) = 13.88, p < .001 \). That is, significantly fewer individuals showed an effect of object complexity on rotational speed when a response deadline was introduced to the rotation phase of the task. In line with these results, an Experiment \( \times \) Object type \( \times \) Rotational angle mixed ANOVA on rotation times (Figure 5a and 5b) showed a main effect of experiment, \( F(1, 44) = 14.53, p < .001, \eta_p^2 = .25 \), an Experiment \( \times \) Object type interaction, \( F(2, 88) = 15.20, p < .001, \eta_p^2 = .26, \epsilon = .59 \), an Experiment \( \times \) Rotational angle interaction, \( F(2, 88) = 19.37, p < .001, \eta_p^2 = .31, \epsilon = .60 \), and a three-way interaction, \( F(4, 176) = 9.56, p < .001, \eta_p^2 = .18, \epsilon = .46 \). Linear effects of rotational angle on rotation times were present for each object type in Experiment 2, all \( F(1, 21) > 32.38, \) all \( p < .001 \), and in Experiment 3, all \( F(1, 23) > 20.71, \) all \( p < .001 \); thus, providing evidence that mental rotation was performed on each object type by both groups of participants. There were also main effects of angle, \( F(2, 88) = 61.02, p < .001, \eta_p^2 = .58, \epsilon = .60 \), and of object type, \( F(2, 88) = 37.33, p < .001, \eta_p^2 = .46, \epsilon = .59 \), as well as an Angle \( \times \) Object type interaction, \( F(4, 176) = 8.63, p < .001, \eta_p^2 = .16, \epsilon = .46 \), which are of only minor importance for the present analyses as they are unrelated to group differences. Of major interest for the current purposes is the Experiment \( \times \) Object type \( \times \) Rotational angle three-way interaction, because such an interaction must occur if participants’ strategies differ between experiments. It indicates an influence of the response deadline on whether participants rotate fast or carefully. Separately conducted follow-up two-way within ANOVAs for each experiment showed main effects of rotational angle, \( F(2, 42) = 40.98, p < .001, \eta_p^2 = .66, \epsilon = .61 \) (Experiment 2); \( F(2, 46) = 25.06, p < .001, \eta_p^2 = .52, \epsilon = .56 \) (Experiment 3) and object type, \( F(2, 42) = 24.86, \).
FAST OR CAREFUL MENTAL ROTATION

$p_c < .001, \eta_p^2 = .54, \epsilon = .59$ (Experiment 2); $F(2, 46) = 31.86, p_c < .001, \eta_p^2 = .58, \epsilon = .62$ (Experiment 3). Importantly, these ANOVAs confirmed a significant interaction in Experiment 2, $F(4, 84) = 9.45, p_c < .001, \eta_p^2 = .31, \epsilon = .43$, but not in Experiment 3, $F(4, 92) = 0.56, p_c = .622, \eta_p^2 = .02, \epsilon = .66$. In fact, rotational speed (Figure 5c and 5d) differed between simple and complex objects in Experiment 2, $t(21) = 3.72, p = .001, dz = 0.79$, and $t(21) = 3.47, p = .002, dz = 0.74$, but not in Experiment 3, $t(23) = 0.29, p = .774, dz = 0.06$, and $t(23) = 0.15, p = .885, dz = 0.03$. This pattern of results unequivocally shows that object complexity influenced rotational speed in Experiment 2, but not in Experiment 3. Obviously, the introduction of a response deadline strongly influenced the way, participants performed the task.

To see how this changed behavior influenced performance accuracy, we also conducted an Experiment × Object type × Rotational angle mixed ANOVA on error rates (Figure 5e and 5f). There were the usual main effects of angle, $F(2, 88) = 40.30, p_c < .001, \eta_p^2 = .48, \epsilon = .93$, and of object type, $F(2, 88) = 62.00, p_c < .001, \eta_p^2 = .59, \epsilon = .77$, as well as an Angle × Object type interaction, $F(4, 176) = 5.61, p_c = .001, \eta_p^2 = .11, \epsilon = .78$. Of interest was a strong main effect of experiment on error rates, $F(1, 44) = 11.13, p = .002, \eta_p^2 = .20$ (higher error rates for Experiment 3), without any interaction involving experiment, $F(2, 88) = 1.40, p_c = .253, \eta_p^2 = .03, \epsilon = .77$ (object type), $F(2, 88) = 0.72, p_c = .491, \eta_p^2 = .02, \epsilon = .93$ (angle), $F(4, 176) = 1.17, p_c = .324, \eta_p^2 = .026, \epsilon = .75$ (three-way interaction). Follow-up two-way within ANOVAs on error rates showed that the Object type × Rotational angle interaction was present for both experiments, $F(4, 84) = 9.27, p_c < .001, \eta_p^2 = .31, \epsilon = .77$ (Experiment 2), and $F(4, 92) = 6.57, p_c < .001, \eta_p^2 = .22, \epsilon = .68$ (Experiment 3). The less interesting main effects of rotational angle, $F(2, 42) = 40.98, p_c < .001, \eta_p^2 = .66, \epsilon = .61$ (Experiment 2), $F(2, 46) = 25.06, p_c < .001, \eta_p^2 = .52, \epsilon = .56$ (Experiment 3); and object type, $F(2, 42) = 24.86, p_c < .001, \eta_p^2 = .54, \epsilon = .59$ (Experiment 2), $F(2, 46) = 31.86, p_c < .001, \eta_p^2 = .58, \epsilon = .62$ (Experiment 3) were also present. As a consequence of the rotation-times and error-rates patterns, a strong Object type × Rotational angle interaction on the combined measure was present for both experiments, $F(4, 84) = 17.50, p_c < .001, \eta_p^2 = .46, \epsilon = .74$ (Experiment 2), and $F(4, 92) = 6.02, p_c < .001, \eta_p^2 = .21, \epsilon = .76$ (Experiment 3). Again, we also found main effects of rotational angle, $F(2, 42) = 58.11, p_c < .001, \eta_p^2 = .74, \epsilon = .75$ (Experiment 2), $F(2, 46) = 30.95, p_c < .001, \eta_p^2 = .57, \epsilon = .71$ (Experiment 3); and object type, $F(2, 42) = 84.29, p_c < .001, \eta_p^2 = .80, \epsilon = .70$ (Experiment 2), $F(2, 46) = 39.09, p_c < .001, \eta_p^2 = .63, \epsilon = .66$ (Experiment 3).

In summary, results from both experiments speak against holistic rotations, because strong effects of object complexity on mental-rotation performance emerged. In Experiment 2, the effect was clearly present in both rotational speed and error rates. More important, the response deadline in Experiment 3 suppressed the effect of object complexity on rotational speed whereas this effect showed up in the error rates even though overall error rates were strongly increased.

**Discussion**

Monetary reward and a focus on accuracies in the instructions of Experiment 2 proved successful in biasing participants toward a careful mental-rotation strategy; the effect of object complexity on rotational speed was strong and the error rate was low. The introduction of a liberal rotation deadline in Experiment 3 made participants shift strategies toward the opposite direction; rotational speed became independent of object complexity and the error rate increased considerably. Actually, mean rotation time nearly halved from Experiment 2 (2.41 s) to Experiment 3 (1.34 s). This increase in speed from Experiment 2 to Experiment 3 came with a respective cost in accuracies: Whereas error rate was low in Experiment 2 (9.4%) it was nearly twice as high in Experiment 3 (18.0%). Additionally, an analysis of individual data patterns showed that, compared with the subject sample of Experiment 1 (51.9%), the percentage of careful rotators was high in Experiment 2 (77.3%) and low in Experiment 3 (21.7%). Therefore, we conclude that the differentiation between fast rotators and careful rotators observed in Experiment 1 does not go back to a stable trait, but instead reflects a strategic choice that can (to some degree) be shifted at will in accordance with task demands. In other words, interindividual differences in speed-accuracy trade-off can be driven by differences in motivation and are not determined by differences in abilities.

The 5-s deadline in Experiment 3 should be ample time to finish the rotation even for those who would rotate relatively slowly without a deadline (in Experiment 1, overall mean rotation time was 1.85 s; range over participants: 0.89s-3.37s). Nevertheless, the sheer presence of such a deadline obviously was sufficient to induce a strategy shift toward a fast and more careless rotation strategy. This is in line with Voyer (2011) who showed that only whether a time limit is imposed, and not how strict this time limit is, influences individual differences (between genders) in pencil-and-paper mental-testing tasks.

**General Discussion**

We set out to determine whether the effect of object complexity on mental-rotation performance (Bauer & Jolicoeur, 1996; Folk & Luce, 1987; Heil & Jansen-Osmann, 2008; Jolicoeur et al., 1985; Liesefeld & Zimmer, 2013; Yuille & Steiger, 1982) is present for each individual participant or whether it is driven by only some individuals. In Experiment 1, indeed, only about half our subject sample showed an effect of object complexity on rotational speed (careful rotators). However, an analysis of error rates showed that those participants whose rotational speeds were not influenced by object complexity (fast rotators) do not rotate more efficiently or in a qualitatively different way (holistic vs. piecemeal), but trade off accuracy for a constant rotational speed. Consequently, the cognitive processes involved in mental rotation do not fundamentally differ between these groups of participants, but participants simply differ in their speed-accuracy trade-offs. Depending on whether participants rotate fast or carefully, an effect of object complexity emerges only in their error rates or also in their rotational speeds. Experiment 2 showed that, given proper instructions and motivation, most participants (77%) will adapt their rotational speed to avoid errors and, therefore, show an effect of object complexity on rotational speed. This pattern was turned upside-down by imposing a response deadline in Experiment 3. There, only 22% of the subject sample rotated carefully. Obviously, participants can choose to either perform mental rotation carefully or to do it fast and this strategic choice depends on task affordances.
That a considerable portion of participants uses a nonholistic mental representation in the present task was shown by Liesefeld and Zimmer (2013). Experiment 1 examined the possibility that at least part of the subject sample uses a holistic representation. On first sight, the absence of an effect of object complexity on rotational speed indeed appeared to reflect a holistic processing style in fast rotators. However, when also error rates were taken into account, this difference turned out to merely reflect speed–accuracy trade-offs. The differentiation between holistic and non-holistic spatial processing does, therefore, clearly not apply to the present mental-rotation task (cf. Heil & Jansen-Osmann, 2008; Khooshabeh et al., 2013). Participants do not use qualitatively different processing styles, but rotation is influenced by object complexity in all participants.

As rotational speed arguably is the cleaner measure of task performance in mental-rotation tasks, a preponderance of analyses from experimental studies focuses on this dependent variable. However, the speed–accuracy trade-offs observed here clearly demonstrate the need for careful analyses of error rates in research on mental rotation. Furthermore, such trade-offs might explain apparent holistic/nonholistic dichotomies in other spatial tasks as well (e.g., in mechanical reasoning, see Hegarty, 2004; similar differences in trade-offs appear somewhat more parsimonious than postulating qualitatively different cognitive processes or mental representations (e.g., holistic vs. piecemeal) in different individuals.

A major advantage of the task and stimulus set used here is that they induce complexity effects more reliably than other mental-rotation tasks. Our complex stimuli were particularly designed to force participants to rotate at least two object features. If, for complex objects, participants had chosen to rotate only one feature, they would not have been able to detect all possible changes (see Liesefeld & Zimmer, 2013, or Liesefeld, 2012, for detailed discussions). The most typical stimuli used in studies that examine effects of object complexity on mental-rotation performance are random polygons (e.g., Cooper, 1975; Cooper & Podgorny, 1976; Heil & Jansen-Osmann, 2008). As discussed in length in Liesefeld and Zimmer (2013), to solve a mental-rotation task with random polygons, rotation of only a single object feature is usually sufficient. That is, rotational speed can in principle be independent of a polygons complexity (see Cooper, 1975; Cooper & Podgorny, 1976). Complexity effects on the rotation of random polygons

### Table 1

<table>
<thead>
<tr>
<th>Principle</th>
<th>Explanation</th>
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<tr>
<td>Manipulate the amount of orientation-dependent information</td>
<td>Potential changes must be from “left” to “right,” from “top” to “bottom”, or from “in front of” to “behind” (reflections). This is important, because in mental-rotation tasks only such orientation-dependent information needs to be rotated; all other information can be compared without a rotation. Other manipulations of complexity might trick participants for a while, but sooner or later at least some participants will rotate only relevant (i.e., potentially changing) orientation-dependent information.</td>
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<tr>
<td>Make sure that participants really have to encode orientation-dependent information</td>
<td>It must not be possible to encode the relevant orientation-dependent information in an orientation-independent way or to encode several pieces of orientation-dependent information as one chunk. For example, an arrow attached to another stimulus pointing to the right (orientation-dependent) might also point to the stimulus’ center of gravity (orientation-independent). Chunking is possible whenever several pieces are from the same spatial dimension.</td>
</tr>
<tr>
<td>Complexity can range between 1 and 3 pieces of information</td>
<td>Even the least complex stimulus must reliably induce mental rotation. This is the case whenever at least one piece of orientation-dependent information can potentially change (see Takano, 1989). Together with the previous points, this means that the complexity of mental-rotation stimuli can only vary in between 1 and 3 (1 and 2 for two-dimensional stimuli).</td>
</tr>
<tr>
<td>Be aware of the limitations of certain types of mental-rotation tasks</td>
<td>In many mental-rotation tasks, one spatial dimension is already used for determining the rotational angle and can, therefore, not be used to increase complexity. For example, in character rotation (see, e.g., Liesefeld &amp; Zimmer, 2011), the character must usually be compared with an upright-oriented long-term memory entry and therefore only left/right differences (between the stimulus and the long-term memory entry) but no top/bottom differences are possible (the latter would simply be a different rotational angle). Such tasks do not allow for a proper manipulation of object complexity.</td>
</tr>
<tr>
<td>Make the informational content of your stimuli obvious</td>
<td>If stimuli contain much extraneous detail in addition to the relevant orientation-dependent information, it is difficult for participants to discover which stimulus features must be rotated and which features either never change or can be compared without rotation. This causes intra- and interindividual error variance and spurious effects of complexity, because some participants find out about the informational content later than others. Stimuli must, therefore, be free of extraneous detail, participants must be instructed about the relevant information, or participants must have discovered the relevant information by themselves prior to the actual mental-rotation tasks (e.g., by carefully examining the full stimulus set).</td>
</tr>
<tr>
<td>Reliably measure mental rotation proper</td>
<td>Rotation times are less influenced by extraneous processes than error rates are. Therefore, a careful strategy should be encouraged (see Experiment 2). Using a combined speed-accuracy measure is a valid alternative but is necessarily less clean than pure rotation times from a homogenous group of careful rotators. Furthermore, it is advantageous (but not indispensable) if the rotation phase is isolated from the encoding and comparison phase (as in the present task design).</td>
</tr>
<tr>
<td>Analyze slopes instead of intercepts</td>
<td>Analyses should focus on the slopes of the functions relating dependent measures to rotational angle (or alternatively on interactions with rotational angle). Effects on these slopes very likely reflect effects on mental rotation proper, whereas effects on the intercept might relate to all kinds of additional processes involved in stimulus processing and response generation.</td>
</tr>
</tbody>
</table>
would then only emerge when some participants unnecessarily perform redundant checks that involve additional rotations of further object features. Therefore, the reasons for complexity effects on rotational speed differ between Heil and Jansen-Osmann (2008) and the present study. Whereas rotational speed must be adapted to object complexity to solve the present mental-rotation task, such slowing down for more complex objects is not necessary for tasks involving the rotation of random polygons. We think that this is the reason why Heil and Jansen-Osmann did not observe increased error rates for the group that did not show complexity effects on rotation times (“holistic strategy,” men). In a task where it is sufficient to rotate only one object piece, carefully rotating several pieces (“piecemeal strategy,” women) does not lead to lower error rates. Such double-checking only increases a rotator’s confidence in the result.

No single set of studies can fully exclude the possibility that some task or some set of stimuli exists where people, in contrast to the present study, rotate holistic representations. Special classes of stimuli like faces, for example, might be processed in a qualitatively different way compared with other objects (see, e.g., Cheung & Gauthier, 2010). The task and stimuli used here were designed in a way that reliable induces complexity effects in mental rotation (see Material and Liesefeld & Zimmer, 2013). Unfortunately, earlier studies with other stimulus and task designs do not usually feature such a valid manipulation of object complexity and their data is, therefore, not suitable to answer the questions addressed here. To conceptually replicate our effects with different tasks and different stimuli we consider the general design and analysis choices detailed in Table 1 as indispensable.

Any interpretation of averaged results strongly depends on the assumption of a homogenous subject sample. If participants fundamentally differ in the way they perform mental rotation, this difference must be taken into account in data analysis and in cognitive theories on the processing steps and mental representations involved in mental-rotation tasks. Our results demonstrate that participants do not differ fundamentally in the way they perform mental rotation, indicating that a general theory of mental rotation is possible without postulating different processing styles (e.g., holistic vs. piecemeal). However, because participants differ in speed–accuracy trade-offs, to fully appreciate complexity effects, rotation times and error rates should be taken into account concurrently (as in Experiment 1). An analysis that is purely focused on error rates would strongly underestimate complexity effects for careful rotators; an analysis that is purely focused on rotation times would likely completely miss complexity effects for fast rotators. A further alternative is to experimentally induce a certain extreme speed–accuracy trade-off in all (or most) participants by a careful choice of experimental designs (as in Experiments 2 and 3).

The presence of different speed–accuracy trade-offs in mental rotation is also of relevance for the interpretation of results from paper-and-pencil tests of mental-rotation ability. Notably, such tests are usually speeded, that is, participants are allotted only a certain amount of time (e.g., 10 min) to solve as many test items as possible. This focus on speed might lead to an uneven advantage for fast rotators compared with careful rotators. This is of particular importance in tasks where a careless rotation is a successful strategy (as for random polygons). As a consequence, careful rotators would gain low scores on tests of mental-rotation ability (e.g., Goldstein et al., 1990; Voyer, 2011). If these seemingly bad rotators actually merely rotate more carefully, this would strongly influence the interpretation of individual differences (e.g., sex differences) in mental-rotation ability (see Goldstein et al., 1990).

Within the broader scope of the visual-working memory literature, the present results are further evidence against the assumption that objects are represented in working memory as integrated wholes (cf., e.g., Luck & Vogel, 1997). Earlier studies have already shown that object complexity influences working memory performance (Alvarez & Cavanagh, 2004) and that even features that belong to the very same object are stored separately (Bays et al., 2011; Fougnie et al., 2013). Our results further support and extend these earlier findings by showing that in addition to the passive retention of working memory representations, also an active manipulation of these representations is strongly and consistently influenced by object complexity.

References


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