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Research Article

Individual Differences in Mental Rotation

Piecemeal Versus Holistic Processing

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Abstract. Two experiments tested the hypothesis that imagery ability and figural complexity interact to affect the choice of mental rotation strategies. Participants performed the Shepard and Metzler (1971) mental rotation task. On half of the trials, the 3-D figures were manipulated to create "fragmented" figures, with some cubes missing. Good imagers were less accurate and had longer response times on fragmented figures than on complete figures. Poor imagers performed similarly on fragmented and complete figures. These results suggest that good imagers use holistic mental rotation strategies by default, but switch to alternative strategies depending on task demands, whereas poor imagers are less flexible and use piecemeal strategies regardless of the task demands.

Keywords: mental rotation, strategies, individual differences

In a classic mental rotation study (Shepard & Metzler, 1971) participants were asked to determine whether two three-dimensional (3-D) figures, which differed in orientation, had the same shape. Response time increased linearly with the angular difference in orientation between the two figures. Shepard and Metzler proposed that people use a holistic, analog mental rotation process akin to physical rotations. This finding is perhaps the strongest evidence for the existence of mental images as a form of knowledge representation (Kosslyn, 1994; Pylyshyn, 2003). Mental rotation tasks (e.g., Vandenberg & Kuse, 1978) have also been central to the study of individual differences in spatial ability, which is important for success in a variety of scientific and technical professions (Hegarty & Waller, 2005). With current interest in the training of spatial skills (e.g., National Research Council, 2006), initial training studies have focused on mental rotation as a fundamental spatial thinking process (e.g., Terlecki, Newcombe, & Little, 2008). It is timely to examine whether people with good and poor imagery abilities differ in how they perform the classic Shepard and Metzler mental rotation task.

Whereas Shepard and Metzler (1971) initially proposed that mental rotation is a holistic analog process, later research indicated a variety of strategies, including holistic rotation, piecemeal rotation, and viewpoint independent strategies, depending on such factors as complexity, familiarity, and meaningfulness of the stimuli (Folk & Luce, 1987; Just & Carpenter, 1976, 1985; Kail, 1985, 1986; Kail, Pellegrino, & Carter, 1980; Mumaw, Pellegrino, Kail, & Carter, 1984; Shepard & Metzler, 1988; Yuille & Steiger, 1982). A holistic strategy involves rotating the mental image as a whole. A piecemeal strategy involves decomposing the mental image into pieces (e.g., "arms" of the figures shown in Figure 1), mentally rotating one piece into congruence with the comparison figure, and then applying the same rotation to the other parts of the figure to see if they match. A viewpoint independent strategy involves examining internal relations between the parts of the objects to be compared, independently of their orientation (e.g., noticing that the two end arms of the objects in Figure 1 are parallel to each other).

One debate about mental rotation strategies has centered on whether objects and shapes are rotated holistically or piecemeal. In the literature on mental rotation, inferences about the strategy used for mental rotation are typically made from examining response times as a function of angular disparity of the two shapes to be compared. It is assumed that the slope of the response function reflects the mental rotation process whereas the intercept reflects such processes as encoding the stimuli and deciding on the response.

A standard assumption in this literature is that a piecemeal strategy will be accompanied by steeper slopes of the response time function. Cooper (1975) argued that if mental rotation is piecemeal, rotation time should be a function of not just the angle of rotation but also the complexity of the object or shape (i.e., number of pieces to be rotated). Using 2-D polygons in which complexity was defined as the

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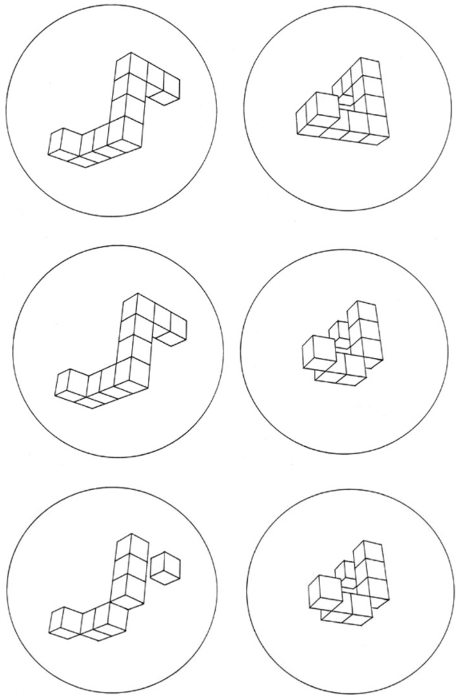

Figure 1. Top: Example of a control task (both figures complete). Middle: Example of a fragmented trial from Experiment 1. Bottom: Example of a fragmented trial from Experiment 2. The figures were adapted from the original images used by Shepard and Metzler (1971).

number of vertices, Cooper (1975; Cooper & Podgorny, 1976) found no effects of complexity and concluded that rotation was holistic. However, other studies found effects of stimulus complexity with more difficult rotation tasks with both 2-D (Folk & Luce, 1987) and 3-D stimuli (Yuille & Steiger, 1982). Furthermore, Bethell-Fox and Shepard (1988) found that complexity affected the rate of mental rotation before but not after practice, suggesting that unfamiliar objects are rotated piecemeal, but, with practice, people develop more integrated representations of objects that can be rotated holistically.

Eye fixations during mental rotation suggested a piecemeal strategy (Just & Carpenter, 1976, 1985). When rotating 3-D objects, people first looked back and forth between corresponding segments of the two objects, with the number of transitions between objects related to the angle of rotation, suggesting an analog rotation process. Participants then looked at the other corresponding segments of the two objects. On the basis of these data, Just and Carpenter argued that participants first rotated one segment of the object, and later checked whether the other segments were rotated into congruence.

Several researchers have suggested that choice of a holistic or piecemeal strategy might differentiate individuals with good and poor spatial imagery. Mumaw et al. (1984) found that individuals with high-spatial ability had faster rates of rotation than low-spatial individuals and speculated that high spatials formed robust representations of objects that were rotated holistically whereas low spatials had more fragile object representations that seemed to "fall apart" during rotation, in the sense that low-spatial individuals were not able to keep the complete image intact in working memory as they rotated it, and had to rotate the parts individually. Bethell-Fox and Shepard (1988) suggested that high-spatial individuals may develop integrated representations more rapidly (i.e., with less rotation practice) than those with lower spatial ability.

Furthermore, gender differences are sometimes used as a proxy for individual differences in mental rotation (because men outperform women on mental rotation tests on average), and Heil and Jansen-Osmann (2008) found that speed of mental rotation of 2-D polygons is affected by stimulus complexity for women but not for men, suggesting a piecemeal strategy for women and a holistic strategy for men. However an alternative account of individual differences (Just & Carpenter, 1985) is that individuals of all ability levels rotate 3-D objects piecemeal, but low spatials are unable to keep track of the partial products of their rotations, due to working memory limits, so that they have to repeat partial rotations.

Previous studies of 3-D object rotation eliminated participants with large error rates (e.g., Just & Carpenter, 1976; Yuille & Steiger, 1982), or, if they examined individual differences, focused on small samples with three to four participants in each ability group (e.g., Bethell-Fox & Shepard, 1988; Just & Carpenter, 1985). Consequently, there has been no direct test of the hypothesis that poor spatial imagers generally use piecemeal strategies whereas good imagers use holistic strategies. This hypothesis is tested here.

We examined mental rotation of complete objects and fragmented objects that should be very difficult to rotate holistically (see Figure 1). If individuals use a holistic strategy for complete figures, they should have faster and more accurate performance with these figures than with fragmented figures, assuming that fragmented figures cannot be rotated holistically. If individuals use a piecemeal strategy with complete 3-D figures, their accuracy and response times should be the same for whole and fragmented figures. We hypothesized that good imagers would have faster and more accurate performance for complete figures than for fragmented figures, reflecting a switch from holistic to piecemeal processing. This should be reflected in the slope of the response time function, with steeper slopes in the piecemeal condition. In contrast, we predicted that poor rotators would not differ in performance for fragmented and complete figures because they use piecemeal strategies for both.

We contrasted these predictions with two alternative accounts. First, good spatial imagers may fill in the missing cubes in the fragmented figures and perform a holistic rotation. This interpolation hypothesis (Kellman, Garrigan, & Shipley, 2005) predicts that the intercept of the response time function should be greater for fragmented figures than complete figures (reflecting the one-time filling in process), but the slopes should not differ. Second, good rotators may switch from a mental rotation strategy to a viewpoint independent strategy with fragmented objects, in which they examine the internal relations between the parts of the objects to be compared, and do not perform a mental rotation (cf. Just & Carpenter, 1985; Yuille & Steiger, 1982).

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This strategy predicts no effect of angular disparity on rotation time for fragmented figures.

Experiment 1 compared performance on control trials (complete objects) with trials in which one object was complete and one was fragmented (Figure 1-middle). Experiment 2 compared control trials with trials on which both of the objects were fragmented (Figure 1-bottom).

Experiment 1

Method

Materials

Five different objects and their mirror images (adapted from Shepard & Metzler, 1971) were used to create the experimental trials. Figures were paired such that they differed in angular disparity between 0° and 180° in 20° increments. All rotations were along the elongated axis of the objects, in depth. There were 100 control trials in which both figures were complete (Figure 1: top) and 100 trials with one complete figure and one fragmented figure (Figure 1: middle), that is, 5 "same" pairs and 5 "different" pairs for 10 different levels of angular disparity. Only the "same" figures were used in the analyses.

Participants

Thirty-eight undergraduate students (24 female, 14 male) at the University of California, Santa Barbara participated. Participants were classified as good or poor imagers on the basis of accuracy on the 50 "same" complete figure trials. Good imagers (six males, eight females) consisted of approximately the top third of the distribution[1] (mean number correct = 47.43, SD = 1.74) and poor imagers (2 males, 11 females) were in the bottom third (M = 33.92, SD = 5.36).[2]

Procedure

First, participants were shown complete figures, followed by fragmented figures and were instructed that their judgment of whether the shapes were the same or different should be based on the overall shape of the two figures, ignoring the missing cubes. They were explicitly told not to simply respond that the figures were different just because one had missing cubes. Then participants were given 8 practice trials with feedback, followed by the 200 experimental trials, which were presented in random order. Participants pressed the "S" on the keyboard for same shapes and "D" for different shapes (mirror images) and their response times were recorded.

Results and Discussion

Response Times

Analyses are based on "same" trials only, as is typical in studies of mental rotation.[3] Figure 2 presents the response times for good and poor imagers as a function of angle of rotation and figure type (complete, fragmented). As predicted, imagery ability interacted with figure type, $F(1, 25) = 7.14$, $p = .01$, $\eta_p^2 = .22$. Consistent with a switch from a holistic strategy to a piecemeal strategy, the good imagers were significantly slower in rotating fragmented figures (M = 4601.04 ms, SD = 1944.14) than complete figures (M = 3260.75 ms, SD = 1516.09), $F(1, 25) = 25.89$, $p < .001$, $\eta_p^2 = .51$. In contrast, response times for poor imagers did not significantly differ for fragmented (M = 4440.99 ms, SD = 2017.29) and complete figures (M = 4115.49 ms, SD = 1574.15), $F(1, 25) = 1.42$, $p = .25$, as is predicted if they use a piecemeal strategy for both types of figures. Also consistent with this account, good imagers were faster (M = 3260.75 ms, SD = 1516.09) than poor imagers (M = 4115.49 ms, SD = 1574.15) at rotating complete figures, $F(1, 25) = 4.13$, $p = .05$, $\eta_p^2 = .14$, but the two groups did not differ for fragmented figures, $F = .09$.

Consistent with a mental rotation strategy, there was a significant main effect of angular disparity on response time, $F(9, 225) = 26.68$, $p < .001$, $\eta_p^2 = .52$, which conformed to a linear trend, $F(1, 25) = 72.75$, $p < .001$, $\eta_p^2 = .74$.

Slope and Intercept Analysis

We fit a regression line to each participant's response times and calculated the slope and intercept of this line. Switching from a holistic strategy on complete figures to a piecemeal strategy on fragmented figures should be reflected in a steeper slope of the response time function for fragmented figures (cf. Cooper, 1975). As predicted, there was an interaction of figure type and imagery ability for the slope measure, $F(1, 25) = 7.77$, $p = .01$, $\eta_p^2 = .24$. Good imagers had steeper slopes on fragmented (M = 28.29 ms/degree, SD = 17.03) than complete figures (M = 20.43 ms/degree, SD = 5.99), $F(1, 25) = 6.65$, $p = .02$, $\eta_p^2 = .21$, but the slopes of poor imagers on the fragmented (M = 19.77 ms/degree, SD = 17.37) and complete figures

1 The numbers of participants in the two groups differ by one because of ties and natural breaks in the distribution of scores.

2 The classification of participants was based on the distribution across all participants, both male and female. Although there were more females than males in the low scoring group, overall, there were no significant sex differences in performance in either of the experiments reported here.

3 The response times for "different" pairs are not typically analyzed in mental rotation experiments as the angle through which these can be rotated into congruence with the standard figure is not defined (Metzler & Shepard, 1974).

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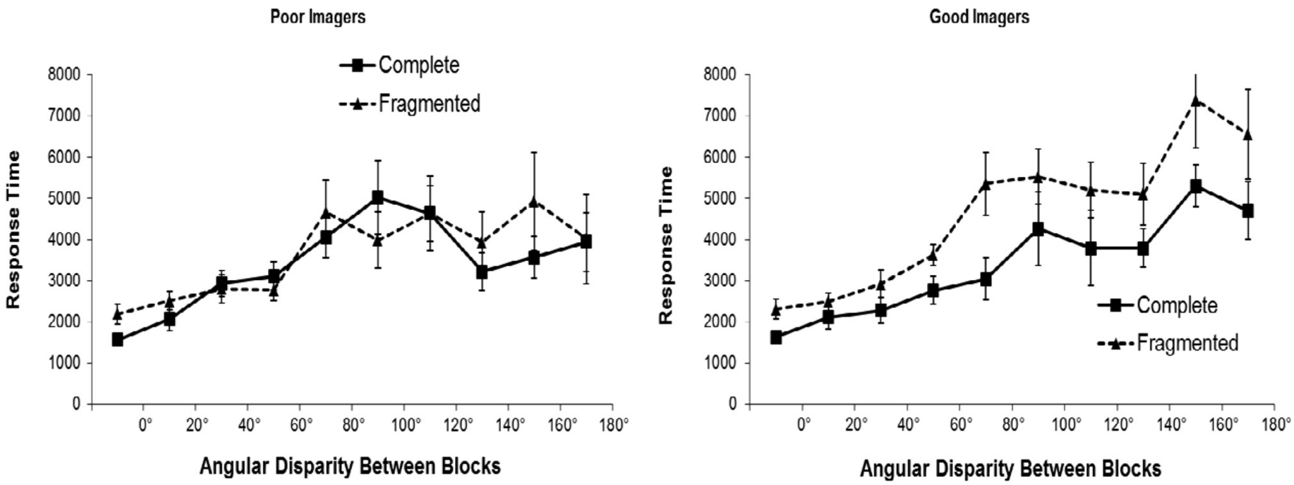

Figure 2. Response time as a function of angular disparity for the two different types of figures in Experiment 1. The left graph shows data for poor spatial imagers and the right shows the data for good spatial imagers.

(M = 24.15 ms/degree, SD = 13.84) did not significantly differ. There was no main effect of figure type or imagery ability on the slope measure (Fs = .63, .23, respectively).

The intercepts of the response time functions were larger for fragmented figures (M = 2722.59 ms, SD = 949.28) than complete figures (M = 1966.26 ms, SD = 604.59), $F(1, 25) = 22.95$, $p < .001$, $\eta_p^2 = .48$, suggesting that fragmented figures took longer to encode. Imagery ability did not affect the intercept, $F(1, 25) = 1.58$, $p = .22$.

Accuracy

Figure 3 presents the accuracy data. Consistent with a mental rotation strategy, there was a linear decrease in accuracy as a function of angular disparity, $F(1, 25) = 61.77$, $p < .001$, $\eta_p^2 = .71$. As expected, accuracy was greater for complete (M = 3.98, SD = .39) than for fragmented figures (M = 3.63, SD = .54), $F(1, 25) = 18.74$, $p < .001$, $\eta_p^2 = .43$. Good imagers were more accurate in rotating complete figures, $F(1, 25) = 73.07$, $p < .001$, $\eta_p^2 = .75$, confirming our selection criteria. They were also more accurate in rotating fragmented figures, $F(1, 25) = 28.82$, $p < .001$, $\eta_p^2 = .54$. The interaction of imagery ability and figure type did not reach significance, $F(1, 25) = 1.65$, $p = .21$. Imagery ability interacted with angular disparity $F(8, 220) = 5.06$, $p < .001$, $\eta_p^2 = .17$, such that accuracy decreased more with angular disparity for poor imagers, $F(8, 18) = 21.18$, $p < .001$, $\eta_p^2 = .90$, than for good imagers, $F(8, 18) = 2.75$, $p = .04$, $\eta_p^2 = .55$.

The results of Experiment 1 are consistent with our hypotheses and with previous speculations (Bethell-Fox &

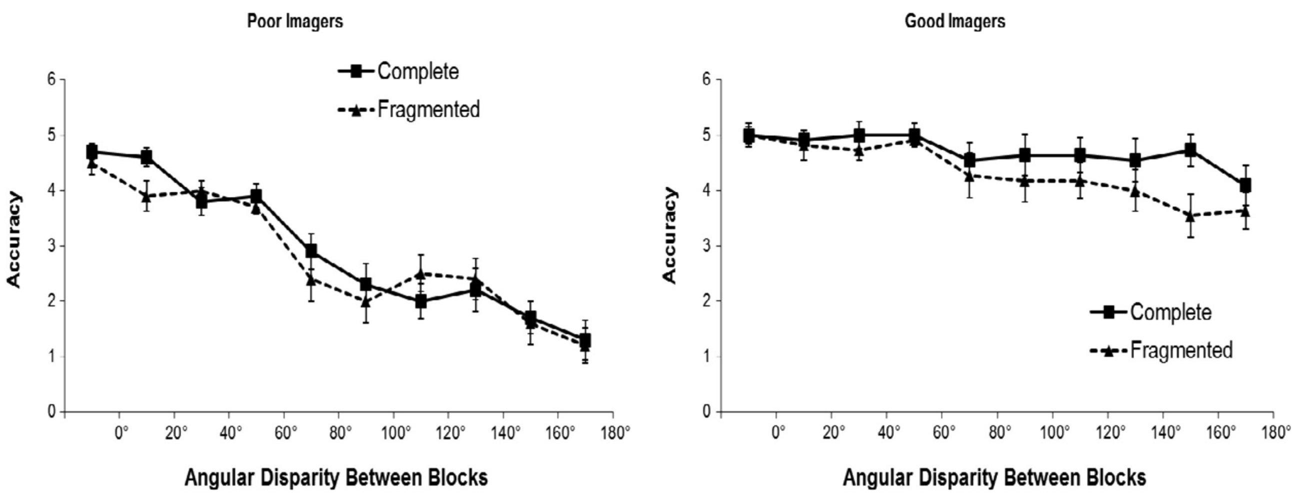

Figure 3. Mean number correct (maximum = 5) as a function of figure type (complete or fragmented) and angular disparity in Experiment 1. The left graph shows data for poor spatial imagers and the right shows the data for good spatial imagers.

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Shepard, 1988; Mumaw et al., 1984) that good imagers rotate complete figures in a holistic manner whereas poor imagers rotate these objects piecemeal. They suggest that when confronted with fragmented objects, good imagers switch to a piecemeal rotation strategy, as indicated by the steeper slope of their response time functions. An alternative interpolation strategy of first filling in the missing pieces (cf. Kellman et al., 2005) and performing a holistic rotation is not consistent with the steeper slopes found for these participants in the fragmented trials, as filling in the missing pieces should increase the intercept but not the slope of the reaction time.

Our results suggest that poor imagers used the same piecemeal strategies for fragmented and complete objects, as indicated by their similar response time functions. It might be argued that poor imagers essentially guessed on large angle fragmented trials, so that their response times were relatively short for these angles and this is the reason why poor imagers did not show steeper slopes for fragmented objects. However, accuracy and response times for poor imagers were almost identical for complete and fragmented objects, even for small angle trials in which their performance was well above chance. Furthermore, correlations between accuracy and response times (computed across angular disparities) for these participants did not indicate a speed-accuracy tradeoff (r = .27, p = .38, for complete figures; r = .31, p = .29, for fragmented figures). The results are most consistent with the use of the same, presumably piecemeal strategy for complete and fragmented objects.

In the fragmented trials of Experiment 1, one of the figures to be compared was complete and the other was fragmented. Rather than switching to a piecemeal strategy, another possible approach in this situation is to rotate the complete object into congruence with the fragmented object in a holistic manner. This strategy is inconsistent with the steeper slopes observed for good imagers on these trials. Nevertheless, we conducted a second experiment with a stronger manipulation of fragmentation, such that both figures were fragmented rather than one. When both figures are fragmented, it is not possible to perform a holistic rotation of one figure into congruence with the other without first mentally filling in the missing cubes. The second experiment also allowed us to replicate the general effects of fragmentation observed in Experiment 1.

Experiment 2

Method

Participants

Fifty-seven undergraduate students (37 female; 20 male) at the University of California, Santa Barbara participated. As in Experiment 1, participants in the top tercile (9 female, 11 male) were classified as good imagers and those in the bottom tercile (12 female, 7 male) were classified as poor imagers.[2]

Materials and Procedure

The materials and procedure were identical to those used in Experiment 1, except that in Experiment 2, both figures shown on fragmented figure trials had missing cubes (see Figure 1: bottom).

Results and Discussion

Response Time

Figure 4 shows response times for good and poor imagers. As in Experiment 1, the predicted interaction of figure type

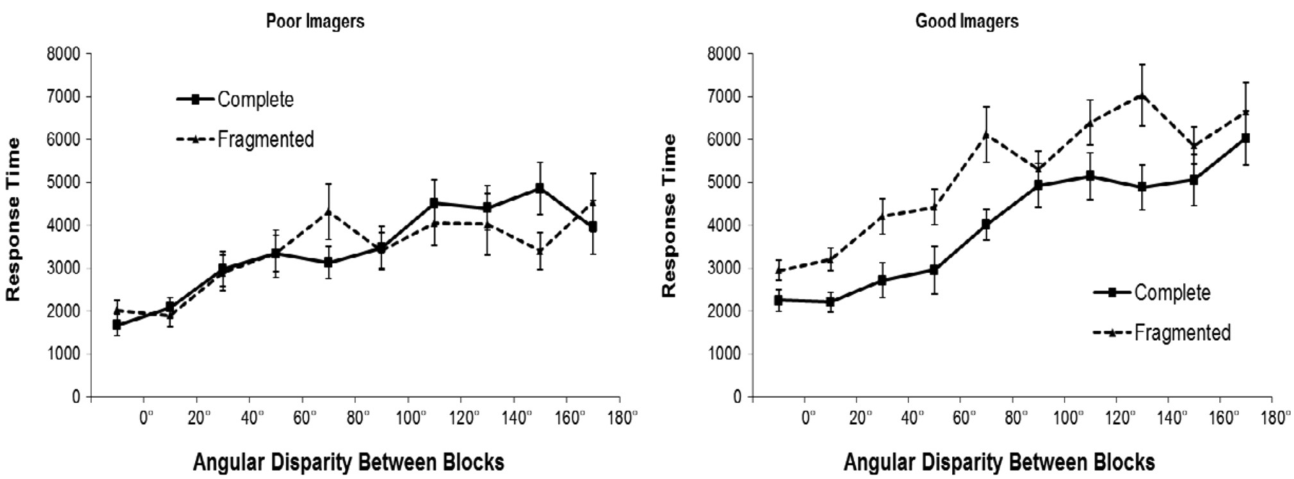

Figure 4. Response time as a function of angular disparity for the two different types of figures in Experiment 2. The left graph shows data for poor spatial imagers and the right shows the data for good spatial imagers.

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and imagery ability, $F(1, 37) = 21.49$, $p < .001$, $\eta_p^2 = .37$, was observed. Participants with good spatial imagery had longer response times on fragmented figures ($M = 5216.12$, $SD = 1983.47$) than on complete figures ($M = 4021.54$, $SD = 2031.19$), $F(1, 37) = 40.56$, $p < .001$, $\eta_p^2 = .52$, consistent with a switch from a holistic to a piecemeal strategy. Poor imagers did not differ on fragmented ($M = 3392.53$, $SD = 2033.72$) and complete figures ($M = 3443.76$, $SD = 2060.64$), $F = .07$, consistent with use of a piecemeal strategy for both figure types. Good and poor imagers did not differ in response times on complete figures, $F(1, 37) = 1.54$, $p = .22$. In this experiment, good imagers were slower on fragmented figures compared to poor imagers, $F(1, 37) = 16.08$, $p < .001$, $\eta_p^2 = .30$. Finally, there was a significant main effect of figure type, $F(1, 37) = 19.14$, $p < .001$, $\eta_p^2 = .34$.

As predicted by a mental rotation strategy, there was a significant main effect of angular disparity, $F(9, 333) = 31.35$, $p < .001$, $\eta_p^2 = .46$, which conformed to a linear trend, $F(1, 37) = 91.23$, $p < .001$, $\eta_p^2 = .71$.

Slope and Intercept Analysis

ANOVA on the slope measure showed a main effect of imagery ability, $F(1, 37) = 6.49$, $p = .02$, $\eta_p^2 = .15$, with steeper slopes for good imagers ($M = 24.83$ ms/degree, $SD = 17.91$) than for poor imagers ($M = 14.22$ ms/degree, $SD = 18.98$). There was also a main effect of figure type, $F(1, 37) = 4.24$, p = .05, $\eta_p^2 = .10$, but contrary to prediction, slopes were shallower for fragmented figures ($M = 17.35$ ms/degree, $SD = 13.17$) than for complete figures ($M = 21.70$ ms/degree, $SD = 16.72$).

A closer examination of Figure 4 suggests that for the good imagers, the slopes from 0° to 80° are steeper for fragmented figures than complete figures (consistent with Experiment 1) whereas for larger angles, the slopes are not systematically related to angle of rotation. A post hoc analysis indicated an interaction of ability and figure type for the angles from 0° to 80° $F(1, 37) = 5.46$, $p = .03$, $\eta_p^2 = .13$. Across these angles, good imagers had steeper slopes for fragmented ($M = 45.21$ ms/degree, $SD = 7.26$) than for complete figures ($M = 25.44$ ms/degree, $SD = 4.64$). For poor imagers, the slopes did not differ for fragmented ($M = 25.40$ ms/degree, $SD = 8$) and complete ($M = 27.22$ ms/degree, $SD = 5.21$) figures. Good imagers' slopes across the larger range of angles (from 100° to 180°) for fragmented figures did not differ from zero, $t(19) = .17$, $p = .88$. This pattern would be expected if good imagers used a piecemeal strategy on fragmented figures for smaller angles, but switched to a viewpoint independent strategy for larger angles, a result that is not without precedent in the literature. For example, Yuille and Steiger (1982) found shallower slopes when they increased the complexity of objects to be rotated, and suggested that for difficult trials, people switch to a viewpoint independent strategy in which they examine relations between diagnostic parts of the two shapes, avoiding the mental rotation process.

As in Experiment 1, the intercepts were significantly larger for fragmented ($M = 3193.74$ ms, $SD = 1467.09$) than complete figures ($M = 2218.67$ ms, $SD = 1366.30$), $F(1, 37) = 26.32$, $p < .001$, $\eta_p^2 = .42$. The main effect of imagery ability was not significant, $F(1, 37) = 2.66$, $p = .11$, but ability interacted with figure type, $F(1, 37) = 11.01$, $p = .002$, $\eta_p^2 = .23$. Good imagers had larger intercepts for fragmented ($M = 3808.80$ ms, $SD = 1457.23$) than for complete figures ($M = 2229.30$ ms, $SD = 1000.61$), $F(1, 37) = 36.62$, $p < .001$, $\eta_p^2 = .49$, but the intercepts of poor rotators did not differ for complete ($M = 2207.47$ ms, $SD = 1696.65$) and fragmented figures ($M = 2546.32$ ms, $SD = 1199.01$), $F(1, 37) = 1.60$, $p = .21$. The longer intercepts for good imagers might reflect the time taken to choose a strategy (either piecemeal rotation or the viewpoint independent strategy).

Accuracy

ANOVA with accuracy as the dependent measure showed a significant effect of figure type, $F(1, 37) = 7.18$, $p = .01$, $\eta_p^2 = .16$, and a significant interaction of figure type and imagery ability, $F(1, 37) = 5.22$, $p = .03$, $\eta_p^2 = .12$. As predicted, participants with good imagery ability were less accurate on fragmented ($M = 4.49$, $SD = .59$) than on complete object trials ($M = 4.88$, $SD = .39$), $F(1, 37) = 12.35$, $p = .001$, $\eta_p^2 = .25$, whereas poor imagers' accuracy did not differ for fragmented ($M = 3.40$, $SD = .60$) and complete trials ($M = 3.43$, $SD = .41$), $F = .06$. Good imagers were more accurate than poor imagers on complete figures, $F(1, 37) = 123.74$, $p < .001$, $\eta_p^2 = .77$, confirming our selection criteria. They were also more accurate on fragmented figures, $F(1, 37) = 31.78$, $p < .001$, $\eta_p^2 = .46$. As Figure 5 shows, accuracy decreased with increasing angular disparity, $F(9, 333) = 20.34$, $p < .001$, $\eta_p^2 = .36$, and angular disparity interacted with imagery ability, $F(9, 234) = 10.80$, $p < .001$, $\eta_p^2 = .23$. Accuracy decreased with angular disparities larger than zero for poor imagers, $F(8, 30) = 11.52$, $p < .001$, $\eta_p^2 = .75$, but not good imagers, $F = .99$.

General Discussion

In two experiments, participants with good imagery ability were significantly slower at mental rotation of fragmented figures than complete figures whereas poor imagers showed similar latencies to rotate the two types of figures. In Experiment 1, the fragmented object trials required participants to compare one complete and one fragmented figure. In this experiment, the additional time spent by good imagers was reflected in the slope of the response time function and not in the intercept. Slopes were steeper for fragmented figures, suggesting that good imagers switched from a holistic to a piecemeal process. In Experiment 2, the fragmented trials required participants to compare two fragmented

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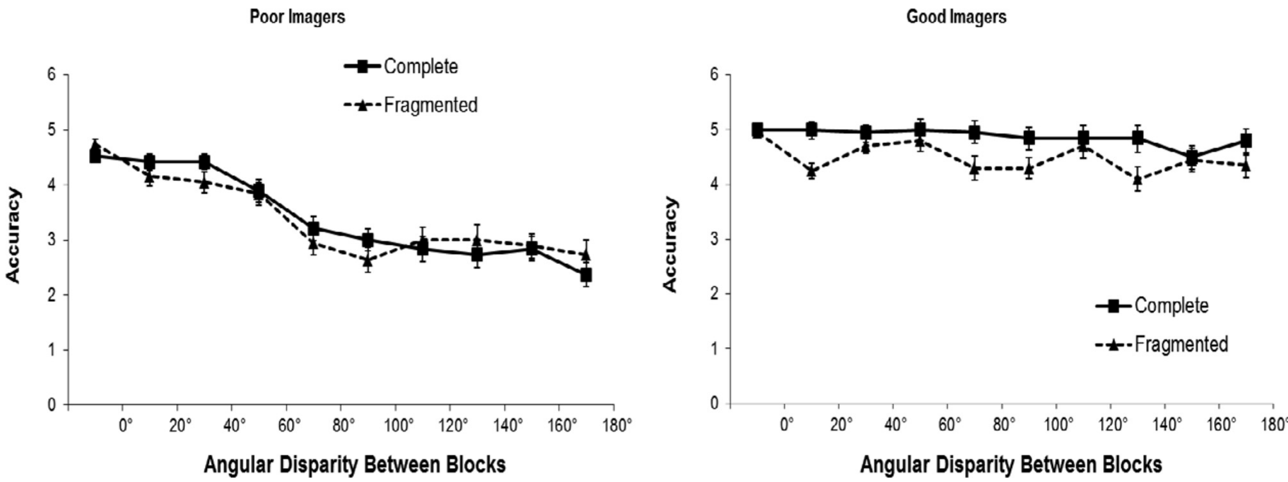

Figure 5. Mean number correct (maximum = 5) as a function of figure type (complete or fragmented) and angular disparity in Experiment 2. The left graph shows data for poor spatial imagers and the right shows the data for good spatial imagers.

figures. In this experiment, the additional time was reflected in larger intercepts and the slope was again steeper for fragmented figures for smaller angular disparities (< 90°) but shallower for larger angular disparities. This pattern of results is consistent with a switch from a piecemeal strategy for small angles to a viewpoint independent strategy for large angles, with the larger intercepts reflecting time to choose a strategy (cf. Yuille & Steiger, 1982). Again, an alternative account, in which high-spatial individuals mentally "fill in" the missing pieces (interpolation hypothesis) is not consistent with the data, as this hypothesis would predict an increase in the intercept but no change in the slope of the response time function. Good imagers were selected based on accuracy for complete figures. They were also very accurate fragmented figures, suggesting that their strategy shifts were adaptive.

In contrast, individuals with poor mental imagery did not differ in response time or accuracy for complete and fragmented figures in either experiment, suggesting that they used the same piecemeal rotation strategy for both types of figures. This strategy became less successful for larger rotations so that accuracy for larger angles fell to chance levels for both complete and fragmented figures.

Consistent with the speculations of other researchers (Bethell-Fox & Shepard, 1988; Mumaw et al., 1984) we have characterized the default strategy of good imagers (with complete objects) as holistic and that of poor imagers as piecemeal. This is somewhat inconsistent with the results of eye fixation experiments, which suggested a piecemeal strategy for both good and poor imagers. However, in those studies, participants completed only 42 mental rotation trials. It is possible that good imagers in our study started by using a piecemeal strategy for the complete objects and developed more integrated representations that allowed holistic rotation as a result of practice (cf. Bethell-Fox and Shepard, 1988). All we can say on the basis of the current experiments is that the strategy of good imagers is more holistic than that of poor imagers.

The performance of poor imagers in our experiments, showing a higher error rate for larger angular disparities, is entirely consistent with Just and Carpenter's (1985) characterization of low-spatial individuals as piecemeal rotators who are unable to keep track of the intermediate products of their partial rotations, so that their accuracy drops for larger angles. In general, our results suggest that poor imagers adhere to a single mental rotation strategy and that they are unable to adapt as the task becomes more difficult, so that their performance suffers, whereas good imagers are flexible spatial thinkers who adjust their strategies depending on task demands.

One limitation in this research is that participants' strategies were inferred from their response time functions and we did not ask them directly about the strategies that they used. Another limitation is that the good and poor imagery groups were defined on the basis of performance of the mental rotation task. In future research it will be important to classify students on the basis of an independent measure of imagery ability and to collect strategy reports from students of different ability levels. Finally, our results may appear somewhat inconsistent with respect to the issue of sex differences. We observed no significant sex difference in performance overall, despite the fact that there were more women in the low-ability groups in both studies. While there are large sex differences in the Vandenberg and Kuse (1978) mental rotation test, sex differences in the Shepard and Metzler (1971) mental rotation paradigm used here are smaller and less robust (Peters & Battista, 2008). The current study was not designed to study sex differences and did not have the power to detect a relatively small sex difference.

This work contributes to the study of individual differences in spatial thinking by showing that individuals with good abilities can adapt their strategies in order to accommodate to novel external representations. Individuals with poor abilities, however, persist with their default strategies for different external representations. Given current interest in the training of spatial thinking skills (National Research

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Council, 2006), our research suggests that teaching a range of spatial thinking strategies, and how to select these strategies adaptively, may be a promising avenue for training.

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