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Short article

Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones?

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Sex differences in mental rotation were investigated as a function of stimulus complexity with a sample size of $N = 72$. Replicating earlier findings with polygons, mental rotation was faster for males than for females, and reaction time increased with more complex polygons. Additionally, sex differences increased for complex polygons. Most importantly, however, mental rotation speed decreased with increasing complexity for women but did not change for men. Thus, the sex effects reflect a difference in strategy, with women mentally rotating the polygons in an analytic, piecemeal fashion and men using a holistic mode of mental rotation.

Keywords: Mental rotation; Spatial cognition; Sex differences; Analytic versus holistic processing.

The cognitive process of imagining an object turning around is called mental rotation (Shepard & Metzler, 1971). It constitutes one important operation in the general class of mental transformations as well as a critical component in spatial intelligence. Many authors claim that whereas females outperform males on measures of verbal fluency, males outperform females on certain tests of spatial ability (e.g., Halpern, 1992). Empirical reality, as usual, is more complex than these claims suggest. The male advantage is observed with accuracy-based paper-and-pencil tests of spatial abilities where it is largest on mental rotation (Voyer, Voyer, & Bryden, 1995). For example, with the Vandenberg–Kuse Mental Rotation Test (MRT, Vandenberg & Kuse, 1978) that uses Shepard–Metzler 3D cube figures, the sex differences amount to one standard deviation (see, e.g., Voyer et al., 1995).

Information processing approaches based upon response time (RT) data, however, yielded more heterogeneous results. In RT studies of mental rotation and also in most neuroscientific approaches, two stimuli are presented with varying angular

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disparity, and the RT is measured when participants decide whether these two do or do not match. These studies often completely ignored the sex of the subjects as a potential factor. In cases where sex was included as a factor, the power to pick up any sex effects had often been limited by small sample sizes. Such studies have failed to converge on an unambiguous result (see, e.g., Kail, Carter, & Pellegrino, 1979; Wiedenbauer, Schmid, & Jansen-Osmann, 2007). Most notably, with Shepard–Metzler 3D-cube figures, recent studies did not find reliable sex differences in mental rotation speed (e.g., Peters, 2005; Voyer et al., 2006). Additionally, recent data suggest that mental rotation RT on the one hand and error rates in paper-and-pencil tests of mental rotation on the other hand are independent (Voyer et al., 2006). Even in a selected sample where men outperformed women in the MRT by as much as 1.5 standard deviations, no sex differences in mental rotation RT with the cube figures of the MRT were found (Peters, 2005). Jansen-Osmann and Heil (2007b) investigated sex differences in mental rotation RT with various materials in a design where age and speed-based IQ were comparable across male and female groups and with sufficient sample sizes to allow sex effects a fair chance to be manifest. Polygons were the only material that revealed substantial and reliable sex differences in mental rotation speed. To sum up, empirical evidence suggest (a) that paper-and-pencil-based psychometric and RT-based sex effects are independent, and (b) that the RT effects are limited to polygons as stimuli.

The underlying causes (see, e.g., Voyer et al., 1995) of sex effects are still far from being understood. This might partly reflect the heterogeneity of the effect itself. Two broad classes of explanations are the "psycho-social" variety and the "biological-neuronal" variety. Examples of "psycho-social" accounts include stereotype threat, sex role identification, or differential experience and socialization. Examples of "biological-neuronal" accounts include rate of maturation, genetic complement, sex hormone level, and cerebral lateralization (for details and references of both accounts, see e.g., Voyer et al., 1995; Jansen-Osmann & Heil, 2007b). Although each of these explanations can quote some empirical support, none is currently able to explain the heterogeneity of sex differences in mental rotation comprehensively.

Sex differences in mental rotation RT, in fact, might be traced back to (a modification of) the hemispheric lateralization account. Mental rotation is understood as a cognitive process implemented in the parietal cortex (e.g., Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001). According to Corballis (1997), the relative contribution of the two hemispheres differs as a function of the processing mode that is used for mental rotation: A holistic process capable of mentally rotating the stimulus representation as a whole might preferentially engage the right hemisphere whereas an analytic process of mentally rotating the stimulus in a piecemeal fashion is more likely to involve the left hemisphere (see, e.g., Heil & Jansen-Osmann, 2007). Since men compared to women are assumed to prefer a holistic mental rotation mode (e.g., Cochran & Wheatley, 1989), their parietal brain activity should be more lateralized to the right. Not only can these assumptions be tested in a neuroscientific approach (see, e.g., Hugdahl, Thomsen, & Ersland, 2006), but RT data can also be used when the complexity of the polygons is manipulated according to the following logic.

In mental rotation tasks, functionally independent processes can be differentiated. These are at least (a) perceptual encoding and identification of the stimuli, (b) mental rotation itself, (c) comparison, (d) response selection, and (e) execution. Empirical evidence suggests either that these processes are organized in a strictly sequential manner (e.g., Stoffels, 1996), or that consecutive processes do overlap but only to a very small extent (for a review see, e.g., Heil, 2002). Given that this is not critical for the present experiment, we assume that mental rotation does not begin before perception finishes. Manipulating the complexity of the polygons to be mentally rotated should prolong perceptual encoding and identification irrespective of subject's gender or strategy used for mental rotation itself.

If mental rotation is performed holistically—that is, if the stimulus representation as a whole is rotated—then the duration of the mental rotation process should not depend upon the complexity of the stimulus (i.e., angular disparity and complexity should have additive effects). Estimating the mental rotation speed from the RT function should reveal no differences for simple versus complex polygons. If mental rotation, however, is performed analytically—that is, if individual pieces of the stimulus representation are rotated separately—then the duration of the mental rotation process should increase as a function of the complexity of the stimulus (i.e., angular disparity and complexity should result in an overadditive interaction) given that more complex stimuli require more pieces. Estimating the mental rotation speed from the RT function should thus reveal a slower speed for the more complex polygons.

Thus, if men indeed prefer a holistic mental rotation mode (see, e.g., Hugdahl et al., 2006), then the predictions are straightforward: Men's mental rotation speed should (a) be faster than women's and (b) be independent of stimulus complexity, whereas (c) women's speed should be slower for more complex than for simple polygons.

Method

Participants

A total of 72 adults participated, 36 males and 36 females (median age 24.6 years; age range 19–39 years). All participants were right-handed and had normal or corrected-to-normal vision. Participants were paid €6 per hour. Given this sample size and a desired level of $\alpha = .05$ (one-tailed), an effect size of $d = 0.50$ could be detected with a probability of $1 - \beta = .80$.[1]

Stimuli and procedure

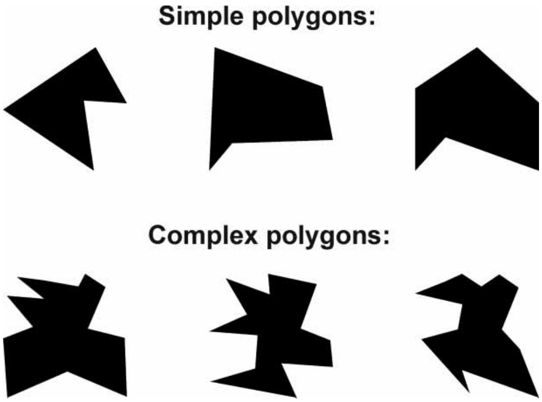

Figure 1. *The three simple (top row) and the three complex (bottom row) polygons used.*

The stimuli consisted of pairs of polygons, similar to those used in Jansen-Osmann and Heil (2007b). Each one had a size of 8 by 8 cm on the screen with a space of 4 cm in between. Participants were free to choose the most comfortable viewing distance. The complexity of the polygons was manipulated. The three simple polygons had 5 or 6 vertices; the three complex polygons had 13 or 14 vertices (see Figure 1). The right stimulus was either identical to the left or mirror reversed. The angular disparity between the two polygons was 30°, 90°, or 150° in a clockwise or anticlockwise direction. Participants responded "same" by pressing the left mouse button with their index finger and "different" by pressing the right mouse button with their middle finger. The experiments were run on a PC with a 17″ monitor (refresh rate: 75 Hz).

Individual test sessions lasted about 90 minutes and took place in a laboratory at the Heinrich-Heine-University of Düsseldorf. Participants were told to respond as quickly and as accurately as possible. Each session was preceded by 48 unrecorded practice trials. Trials were presented in blocks of 48 trials each. Participants initiated each block by pressing a key. Each trial began with a 500-ms background grey screen. Thereafter, the pair of polygons appeared and remained on until the participant responded. Feedback was given in the form of a " + " for

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[1] All power calculations reported in this article were conducted using the G•Power program (Erdfelder, Faul, & Buchner, 1996).

correct responses or a "−" for an incorrect response presented for 500 ms in the centre of the screen. After 1,500 ms the next trial began. Each combination of type of response (same/mirror reversed), polygon stimulus (3), polygon complexity (2), angular disparity (30°, 90°, 150°), and direction of rotation (clockwise/anticlockwise) occurred 6 times resulting in 432 experimental trials.

Results

Because angular disparity is not unambiguously defined for "different" responses (see, e.g., Jolicœur, Regehr, Smith, & Smith, 1985), all statistical analyses were restricted to "same" responses only. Analyses of variance (ANOVAs) were calculated with the between-subject factor "sex" and the within-subject factors "complexity" and "angular disparity".

Error rates were affected significantly only by angular disparity, $F(2, 140) = 53.92$, $p < .01$. Error rates increased with increasing angular disparity (3.0% vs. 7.9% vs. 11.3%). Most importantly, however, sex had no effect on error rates, neither as a main effect, $F(1, 70) = 1.62$, *ns*, nor in any interaction term (all p-values $> .15$). Individual error rates ranged between 1.8% and 16.9% for women and between 0.9% and 18.4% for men.

Only trials with correct responses were used for RT analyses. Prior to the analysis, RT data were trimmed for outliers. RTs more than 2 standard deviations above or below the mean per condition and per subject were excluded (4.2% of the data on average). Main effects of sex, $F(1, 70) = 12.38$, $p < .01$, complexity, $F(1, 70) = 119.11$, $p < .01$, and angular disparity, $F(2, 140) = 202.81$, $p < .01$, were obtained. RT increased with increasing angular disparity (30°, 1,172 ms vs. 90°, 1,484 ms vs. 150°, 1,694 ms), RT was longer for complex (1,642 ms) than for simple polygons (1,259 ms), and RT was longer for women (1,627 ms) than for men (1,274 ms; sex effect size $d = 0.83$). Moreover, all three of the two-way interactions—complexity by sex, $F(1, 70) = 20.39$, $p < .01$; angular disparity by sex, $F(2, 140) = 11.05$, $p < .01$; complexity by angular disparity, $F(2, 140) = 8.68$, $p < .01$—as well as the three-way interaction, $F(2, 140) = 3.50$, $p < .05$, turned out to be significant. The effect of polygons' complexity was larger for women than for men and larger for greater angular disparities for women only, see Figure 2.

Tested separately for the two types of polygons, the main effect of sex and the interaction of sex and angular disparity were significant for the simple polygons—sex, $F(1, 70) = 4.93$, $p < .05$; sex by angular disparity, $F(2, 140) = 4.21$; $p < .05$—and increased for the complex polygons—sex, $F(1, 70) = 17.53$, $p < .01$; sex by angular disparity, $F(2, 140) = 12.32$; $p < .01$. Tested separately for women and men, the results differed qualitatively: For women, we obtained main effects of complexity, $F(1, 35) = 83.75$, $p < .01$, and angular disparity, $F(2, 70) = 139.09$, $p < .01$, as well as an interaction, $F(2, 70) = 10.37$; $p < .01$. RT increased with increasing complexity and with increasing angular disparity. These two effects when combined resulted in an overadditive interaction. For men, however, we only obtained main effects of complexity, $F(1, 35) = 35.37$, $p < .01$, and angular disparity, $F(2, 70) = 66.95$; $p < .01$, but no significant interaction, $F(2, 70) = 0.84$. Thus, these two effects turned out to be additive for men.

The most direct test of the predictions outlined above, however, is based on estimates of mental rotation speed. Therefore, the comparison of main interest was based on the inverse of the slope of the regression line, calculated separately for each participant, relating RT to angular disparity, expressed as degrees per second. The results validate the aforementioned conclusions. For men, the mental rotation rate did not differ as a function of complexity (268°/s vs. 251°/s) whereas women's rotation rate decreased when stimulus complexity was increased (186°/s vs. 133°/s). As a consequence, the effect size of the sex difference in mental rotation speed increased from $d = 0.59$, $F(1, 70 = 6.23$, $p < .05$, for simple polygons to $d = 0.80$, $F(1, 70) = 11.47$, $p < .01$, for complex polygons.

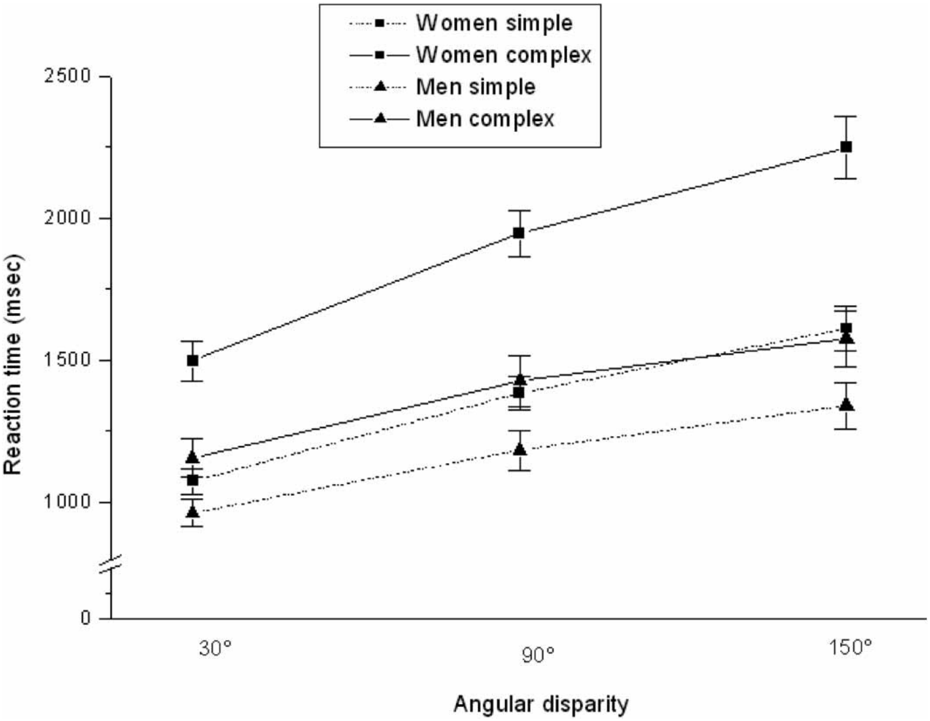

Figure 2. *Mean reaction time (in ms) as a function of angular disparity, separately for women and men as a function of the polygon's complexity. Error bars indicate standard errors.*

Discussion

According to the modified hemispheric lateralization account, holistic mental rotation processes preferentially engage the right hemisphere while analytic processes of piecemeal mental rotation preferentially engage the left hemisphere (Corballis, 1997). Men compared to women are assumed to prefer a holistic mode (e.g., Cochran & Wheatley, 1989) resulting in a right lateralized brain activity for men (e.g., Hugdahl et al., 2006). In the present work, we manipulated the complexity of polygons in order to test this account on the basis of behavioural data. If men prefer a holistic mental rotation mode, then their mental rotation speed should be faster than women's and should be independent of the polygons' complexity. If women prefer an analytic mental rotation mode, however, then their mental rotation speed should be slower for more complex than for simple polygons. RT data as well as mental rotation speed estimates validated these predictions.

We obtained sex differences in mental rotation speed with polygons, thus replicating our earlier results (Jansen-Osmann & Heil, 2007b). Men's mental rotation speed turned out to be faster and was independent of stimulus complexity whereas women's speed decreased with increasing stimulus complexity. Thus, depending upon polygons' complexity, we observed medium to large sex effect sizes.

The decrease in mental rotation speed with increasing complexity observed for women suggests an analytic, "piecemeal" process where the image is parsed into units, which are then rotated individually, whereas the data for men suggest a "holistic" process—that is, the entire image is mentally rotated in a unitary process (Folk & Luce, 1987). Thus, we suggest that women (more often) use a piecemeal strategy for mental rotation preferentially engaging the left hemisphere whereas men prefer a holistic process preferentially engaging the right parietal hemisphere (see, e.g., Corballis, 1997; Jansen-Osmann & Heil, 2007a). Admittedly, this conclusion remains speculative but empirical tests utilizing brain-imaging data are hopefully conducted in the near future. We predict a greater right than left hemisphere activation for men independent of stimulus complexity but a greater left than right hemisphere activation for women, the more so the more complex polygons are presented.

But even if these experiments would validate the interpretation outlined above, one question would still remain open: Does lateralization lead to processing preferences or do the preferences lead to lateralization effects? The answer to this basic question determines which of the two aspects is an epiphenomenon, the neuroscientific aspect because the cognitive one is essential, or the cognitive aspect because the neuroscientific one is essential. As a consequence, in the former case psycho-social explanations (see above) could still be valid in that they might determine the processing mode. Finally, even if the processing mode/lateralization account might be validated with brain-imaging data using polygons of different complexity, it is still open how this account might explain the absence of sex effects in mental rotation speed with stimuli other than polygons (Jansen-Osmann & Heil, 2007b). Much more data, but also new ideas and creative paradigms are indeed needed to solve these still open questions.

To sum up, our data clearly support a modified hemispheric lateralization account of sex effects in mental rotation speed. Under this account, men and women differ according to which processing mode (analytic vs. holistic) they prefer, reflecting sex-related differences in the relative contribution of the two hemispheres. We provided evidence that men prefer a holistic mode because their mental rotation speed was not affected by stimulus complexity. In contrast, women might prefer an analytic processing mode because their mental rotation speed decreased with increasing stimulus complexity.

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