



Sex differences in mental rotation and cortical activation patterns: Can training change them?

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ABSTRACT

In two experiments the neuronal mechanisms of sex differences in mental rotation were investigated. In Experiment 1 cortical activation was studied in women and men with similar levels of mental rotation ability (high, and average to low), who were equalized with respect to general intelligence. Sex difference in neuroelectric patterns of brain activity were observed only in participants with high mental rotation ability. Females displayed more theta synchronization, especially in frontal brain areas. In the second experiment we examined whether training can increase mental rotation performance in females and change their brain activity patterns measured with neuroelectric and hemodynamic imaging techniques. In a parallel group experimental design, respondents from the origami group (rotation training), after 18 h of training, significantly increased their performance on a test of mental rotation. Females' brain activation patterns on a posttest, as compared with a pretest, showed decreased frontal brain activity. Parallel to this, increased activity in parietal brain areas was observed. By contrast, respondents from the active control group (participating in 18-hour communication training) showed no improvements in performance and no pre-/posttest differences in cortical activity.

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1. Introduction

Men typically demonstrate distinct advantages on a broad range of visual tasks. The most pronounced sex differences of nearly one standard deviation have been reported mainly for mental rotation, the ability to imagine visual shapes rotated to an orientation other than the one in which they are presented (Mackintosh & Bennett, 2005; Masters & Sanders, 1993; Voyer, Voyer, & Bryden, 1995). Mental rotation tasks can therefore serve as a useful probe for investigating the neural underpinnings of sex differences in cognition. Studies investigating this phenomenon have produced rather diverse results.

Several functional magnetic resonance imaging (fMRI) studies have reported significant differences in brain activity between males and females who were involved in solving

mental rotation tasks, even though no differences in performance were observed (Butler et al., 2006; Hugdahl, Thomsen, & Ersland, 2006; Jordan, Wüstenberg, Heinze, Peters, & Jäncke, 2002). On the other hand, some studies have reported no significant between-sex differences in brain activity, although men outperformed women on the spatial rotational tasks used during brain imaging (Bell Willson, Wilman, Dave, & Silverstone, 2006; Halari et al., 2006). Furthermore, there are still other studies – employing neuroelectric or hemodynamic brain imaging techniques – showing sex differences in performance as well as brain activation patterns (Gootjes, Bruggeling, Magnee, & Van Strien, 2008a, 2008b; Gur et al., 2000; Hahn, Jansen, & Heil, 2009).

It has been observed that, while solving mental rotation tasks, males showed predominantly parietal activation, whereas females also showed frontal brain activity (Butler et al., 2006; Hugdahl et al., 2006). A meta-analysis of some early studies on sex differences in brain lateralization in relation to mental rotation have indicated a strong preference for the right hemisphere in males, while females showed no

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hemispheric advantage (Vogel, Bowers, & Vogel, 2003). On the other hand, some recent studies have revealed that, during spatial processing, men showed greater and more bilateral activation than women (Gur et al., 2000), and that such differences can even be observed in preschool children (Hahn et al., 2009).

Despite some specific inconsistencies in the findings, it has most often been suggested that men and women apply different strategies while solving mental rotation tasks (Butler et al., 2006; Gootjes et al., 2008a, 2008b; Hugdahl et al., 2006; Jordan et al., 2002). It was hypothesized that women performed mental rotation tasks in an effortful, “top-down” way, whereas men’s performances used an automatic, “bottom-up” strategy. The top-down processing was linked to the activation of the prefrontal cortex, associated with decision making and spatial working memory. In contrast, the bottom-up approach was associated with less prefrontal involvement, less frontal control of task performance and a greater involvement of primary sensory brain regions (Butler et al., 2006). A similar distinction was proposed by Hugdahl et al. (2006), who associated the frontal lobe activity of females with a serial reasoning strategy and activity in the parietal lobe with a “gestalt” perceptual strategy displayed by men. On the other hand, Gootjes et al. (2008a, 2008b) related male right hemispheric activity with a holistic strategy, and a more intense left hemispheric activity observed in females with an analytic strategy.

Some authors have further suggested that these differences in brain activation patterns are the result of sex-specific organization of the neural networks involved in spatial processing (Jordan et al., 2002) and are present in children as young as 5 (Hahn et al., 2009). In contrast, other authors have suggested that the differences are the result of experience and the differential participation of male and female children in activities, combined with hormonal changes during puberty (Jordan & Wüstenberg, 2010; Roberts & Bell, 2002). Support for the latter hypothesis is provided by recent studies showing that mental rotation performance can be enhanced with practice, and that these enhancements are sex-specific (Feng, Spence, & Pratt, 2007; Neidhardt & Popp, 2010; Quaiser-Pohl & Lehmann, 2002).

There are three main shortcomings that might have biased the differences in brain activity between males and females as reported in the studies reviewed:

First, the participants were not matched for their level of general cognitive ability or intelligence although there exist numerous findings establishing the intelligence–brain relationship. Even though there is no firm consensus about any particular brain–intelligence relation, most of the studies demonstrated a negative correlation between brain activity under cognitive load and intelligence (for review, Neubauer & Fink, 2009). The explanation for these findings was an efficiency theory: the non-use of many brain areas irrelevant to the task performance, as well as the more focused use of specific task-relevant areas in individuals with high IQ (Haier, 1993). This inverse intelligence–activation relationship appears to be moderated by task content, the individual’s sex, and motivation — when individuals estimate that they cannot solve a problem, they stop trying. (Doppelmayr, Klimesch, Hödlmoser, Sauseng, & Gruber, 2005; Jaušovec & Jaušovec, 2008; Neubauer & Fink, 2003; Neubauer, Fink, & Schrausser, 2002; Neubauer, Grabner, Fink, & Neuper, 2005).

Second, respondents were not matched with respect to spatial ability, which is an important component of general intelligence (Kaufman, 2007). The importance of spatial ability and especially of mental rotation has been argued quite recently by Johnson and Bouchard (2005). They posit that the fluid and crystallized intelligence stratum should be replaced with a stratum consisting of verbal, perceptual, and image rotation ability. Johnson and Bouchard (2007) further found that sex differences on these dimensions were strong. Both men and women were located throughout the ranges of dimensions, but women were concentrated towards the verbal poles, and men were concentrated towards the rotation poles. That the rotation–verbal dimension was related to brain structure was demonstrated in a recent study by Johnson, Jung, Colom, & Haier (2008), who correlated the rotation–verbal dimension with brain volumes of gray and white matter. The correlations involving the rotation–verbal dimension were relatively localized to areas of the brain that have been implicated in tasks involving the relevant content areas in prior studies. As argued by Johnson and Bouchard (2007) the relation between general cognitive ability and specific abilities, like mental rotation, contribute to the difficulties we experience in trying to identify the brain functions underpinning sex differences in mental abilities. For example, a female of high intelligence but little mental rotation ability who is solving a mental rotation task may do as well as a male of lower intelligence who has greater mental rotation ability. This could be so because the two people would use different strategies and brain areas.

The third factor that could have biased the reported differences in brain activity between males and females is the relationship between hormonal changes during the female’s menstrual cycle, performance on spatial rotation tasks and brain activity. It has been shown that the relative release of sexual hormones in different phases of the menstrual cycle affects cognitive and affective responses of females. High levels of estrogen and progesterone have been associated with positive affect and higher activity in the prefrontal cortex (Amin, Epperson, Constable, & Canli, 2006; Berman et al., 1997). Some studies have reported that women perform better on mental rotation tasks during cycle phases characterized by low, rather than high estrogen levels (Hampson, 1990; Phillips & Silverman, 1997). Moreover, it has been shown that blood estrogen level had a profound effect on the size but not on the lateralization or the localization of cortical activation patterns (Dietrich et al., 2001).

The objective of the present study was to further investigate the neuronal mechanisms of sex differences in mental rotation. For that purpose two experiments were conducted.

2. Experiment 1

Cortical activation was studied in women and men with similar levels of mental rotation ability (high, and average to low), who were equalized with respect to general intelligence. Additionally, all women were tested during the low-estrogen phase of the menstrual cycle. Such an experimental design allowed us to evaluate the factor of sex, independent of differences in ability levels and hormonal changes.

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