Sex differences of event-related potential effects during three-dimensional mental rotation

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Sex differences in performance and in cortical activation patterns during mental rotation have rather consistently been reported. Data regarding sex differences of event-related potentials during the classic three-dimensional mental rotation task developed by Shepard and Metzler, however, are absent, and were therefore being addressed by this study. Mental rotation-related event-related potential effects were observed 900–1000 ms poststimulus at parietal electrodes and 600–700 as well as 800–900 ms poststimulus at right frontal leads, respectively. Sex differences, however, were observed already 400–700 ms poststimulus at right frontal electrodes. These findings suggest that sex differences during three-dimensional mental rotation occurred in relatively early cognitive processing stages presumably including perception and identification of stimuli instead of mental rotation itself.

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Introduction

In the classical three-dimensional (3D) mental rotation task developed by Shepard and Metzler [1], participants are shown pairs of perspective drawings of 3D block figures rotated in depth. The task is to determine whether the two figures are identical or mirror images. Studies following Shepard and Metzler often found men outperforming women in mental rotation [2]. Biological factors [3,4], environmental factors [5], and hemispheric specialization or lateralization [6] have been discussed as possible causes for these sex differences. Moreover, a number of functional magnetic resonance imaging (fMRI) studies successfully addressed the question of sex-dependent neural activities [7–10]. For example, Butler *et al.* [8] accounted a bottom-up neural strategy for men's better visuospatial performance, and Jordan *et al.* [7] observed sex differences in cerebral activation patterns during mental rotation even when performances were similar. A few studies even reported sex differences of event-related potentials (ERPs) during two-dimensional (2D) mental rotation tasks [11–13], but evidence is contradictory [14]. Whether sex affects ERP effects during 3D mental rotation, however, was not yet reported.

On the basis of previous accounts, it is reasonable to divide mental rotation into several processing stages, although the question whether these processes are organized in a strictly sequential manner is debatable [15,16]. These stages consist of (i) perceptual encoding, (ii) identification and discrimination of the objects and identification of their orientation, (iii) mental rotation itself, (iv) judgment of the parity, (v) response selection, and (vi) response execution [17,18]. The functional significance of ERP effects during 2D mental rotation tasks has been studied extensively. The typical finding is that ERP amplitude over parietal electrode leads becomes more negative with increasing rotation angle at a latency of 400–800 ms [17]. The onset of this parietal ERP mental rotation effect has been hypothesized to be a neurophysiological marker for the process of mental rotation itself, because it was delayed when reaction times (RT) increased as a function of a greater difficulty of perceptual encoding or stimulus discrimination [13,17,18]. Surprisingly, no published study exists regarding the ERP modulation as a function of rotation angle in 3D mental rotation.

The purpose of this study, therefore, was to explore 3D mental rotation by investigating (i) whether and how sex differences are reflected in the ERP effects, and (ii) whether and how ERP modulations as a function of mental rotation are present in this 3D task.

Methods

Participants

Twenty-four right-handed volunteers (12 women, mean age 24.1 years, range 20–28; 12 men, mean age 24.0 years, range 22–26), who were undergraduate or graduate students from Dalian University of Technology, participated in this study for pay. All participants had no history

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of neurological or psychiatric illness and had normal or corrected-to-normal vision.

Stimuli

3D objects that were similar to those used by Shepard and Metzler [1] were adopted in this study (Fig. 1). The objects were always presented pair wise, with one object rotated 50° or 100° along its vertical axis relative to the other object. The cubes were white with black background. Light and shadows were used to enhance the feeling of solid. Ninety-six pairs were used for each of the two angular disparities. In half of the pairs for each orientation, the two objects were identical images. In the other half, the objects were mirror images. Experimental program ran on e-Prime (*http://www.pstnet.com/products/e%2Dprime/*) installed in a Dell system. The pictures of stimuli were shown on a 19-inch light emitting diode display.

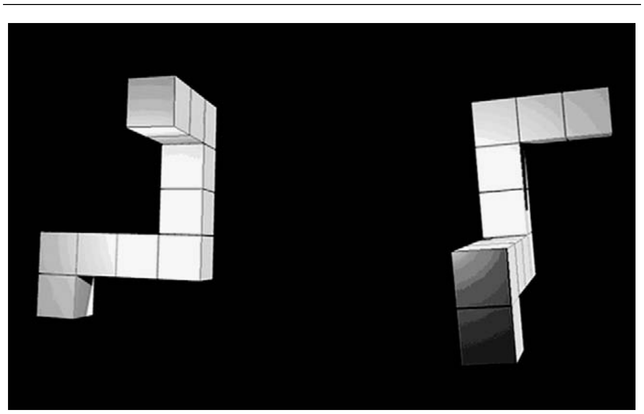
Procedure

Participants were asked to look at each pair of 3D objects. The task was to identify whether the two objects were identical or mirror images and to indicate their choice by pressing one of the two buttons on a response box placed under their right hands as quickly and accurately as possible. They should press a blue button of the response box if the two objects were identical images and press a red button for the other case. The stimuli remained on the screen for a maximum of 4000 ms or until the subject pressed any button, whichever was the sooner. A blank screen would replace the stimulus after its disappearance. Inter stimulus interval was pseudorandom between 500 and 1500 ms. Each participant practiced 18 trials to familiarize with the task. The experiment lasted about 20 min. Both behavioral and electroencephalogram (EEG) data were recorded.

Event-related potentials

EEG was recorded from 61 Ag/AgCl scalp electrodes recording System (Brain Products GmbH, Munich, Germany). Standard electrode sites followed the International 10–20 System nomenclature. A reference electrode was placed at the center between Cz and Fz. Both horizontal and vertical eye movements were recorded by electrooculogram electrodes. All interelectrode impedance was kept below 10 kΩ. Signals were amplified with bandpass (0.05–100 Hz) and notch (50 Hz) filter and were digitized at 500 Hz.

Fig. 1



An example of stimuli used in the present study.

Off-line EEG data analysis was performed with Brain Vision Analyzer software (Brain Products GmbH). EEG data were re-referenced to both ear lobes and digitally filtered with 35 Hz lowpass. EEG files were segmented in epochs of 1400 ms (including 100 ms before stimulus onset) after ocular and nonspecific artifact removal. Baseline correction was performed relative to the 100 ms before stimulus onset. ERPs were calculated by averaging trials with correct responses separately for each participant, electrode, and angular disparity. In line with earlier studies [19], only stimuli with identical objects were included in the analysis. To capture possible rotation-related and sex-related modulations, mean ERP amplitudes were determined in seven time intervals: 300–400, 400–500, 500–600, 600–700, 700–800, 800–900, 900–1000 ms after stimulus onset. According to previous 2D mental rotation experiments [17], rotation-related effects are usually found at parietal leads. Therefore, parietal electrodes (P1, P2, P3, P4, Pz) were selected for statistical analysis. In addition, visual inspection of grand-averaged ERPs revealed that mental rotation effects were at right frontal electrode sites (Fp2, AF8, F8). Therefore, these electrodes were also selected for statistical analysis. To examine whether the corresponding left frontal leads also have mental rotation effects, Fp1, AF7, and F7 were statistically analyzed.

Statistical analysis

RT and accuracy (ACC) of trials with identical objects were analyzed separately using repeated measures analysis of variance with angular disparity (50° and 100°) as within-subjects variable and sex as between-subjects variable. Trials involving incorrect or missing responses were excluded from the analysis of RT.

ERPs were analyzed separately for the parietal (P1, P2, P3, P4, Pz), right frontal (Fp2, AF8, F8), and left frontal (Fp1, AF7, F7) electrodes using repeated measures analysis of variance with angular disparity and electrode as within-subjects variable and sex as between-subjects variable. F ratios were tested with Greenhouse–Geisser corrected degrees of freedom.

Results

Behavioral measures

Sex clearly affected ACC, showing men performed better ($M = 93.0\%$) than women ($M = 87.5\%$) [$F(1,22) = 5.923$, $P = 0.024$] (Fig. 2). In addition to a main effect of angular disparity [F(1,22) = 34.619, $P < 0.001$], there was also an interaction between these two factors [F(1,22) = 5.485, $P = 0.029$]. Post-hoc analysis revealed that men were significantly better than women for stimuli rotated 100° [F(1,22) = 9.365, $P = 0.006$], whereas the sex difference showed no significance for stimuli rotated 50° [F(1,22) = 0.606, $P = 0.444$].

For RT, participants were slower for the larger angular disparity compared with the smaller angular disparity ($M = 2094$ vs. 1661 ms) [F(1,22) = 128.992, $P < 0.001$]. Neither the main effect of sex [F(1,22) = 1.357, $P = 0.257$] nor the interaction between sex and angular disparity turned out to be significant [F(1,22) = 3.267, $P = 0.084$].

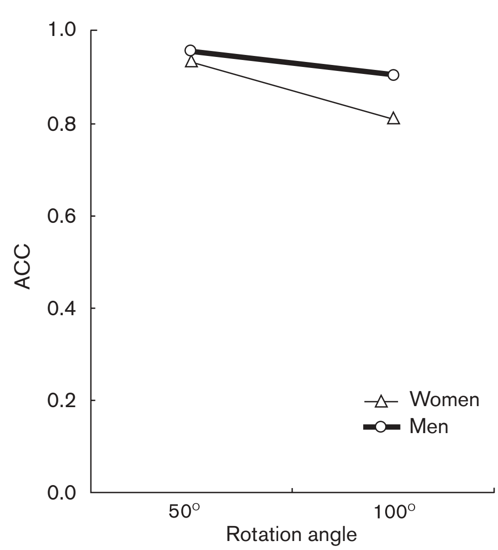
Parietal event-related potentials

At time interval 900–1000 ms, amplitude became relatively more negative with increasing angular disparity [F(1,22) = 5.140, $P = 0.034$] (event-related potentials at Pz as a function of angular disparity are shown in Fig. 3). At parietal electrodes, sex effects were absent both as main effects [F(1,22) < 0.516, $P > 0.480$] and as interactions [F(1,22) < 1.444, $P > 0.242$].

Frontal event-related potentials

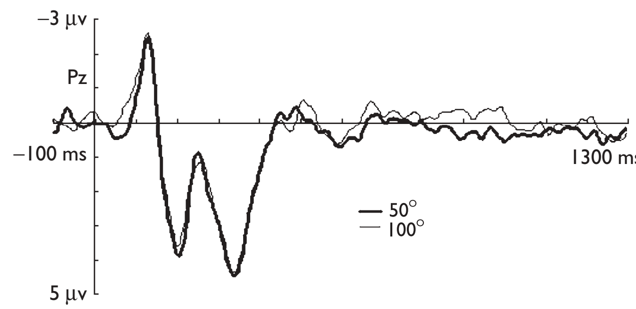
For right frontal sites, at time intervals 400–500, 500–600, and 600–700 ms, women consistently showed more negative amplitudes at right frontal electrodes (Fp2, AF8, F8) [for all time intervals: F(1,22) > 4.4 $P < 0.05$] (event-related potentials at AF8 are shown in Fig. 4). At other time intervals, no significant main effect of sex was found. At time intervals 600–700 and 800–900 ms, amplitudes became relatively more negative with increasing angular disparity [for 600–700 ms: F(1,22) = 4.806, $P = 0.039$; for 800–900 ms: F(1,22) = 4.292, $P = 0.05$] (event-related potentials at AF8 as a function of angular disparity are shown in Fig. 5). No significant interaction effect was found at any time interval.

Fig. 2



Accuracy for women and men as a function of angular disparity.

Fig. 3



Grand average (all participants, including both women and men) event-related potentials at Pz as a function of angular disparity (50° and 100°).

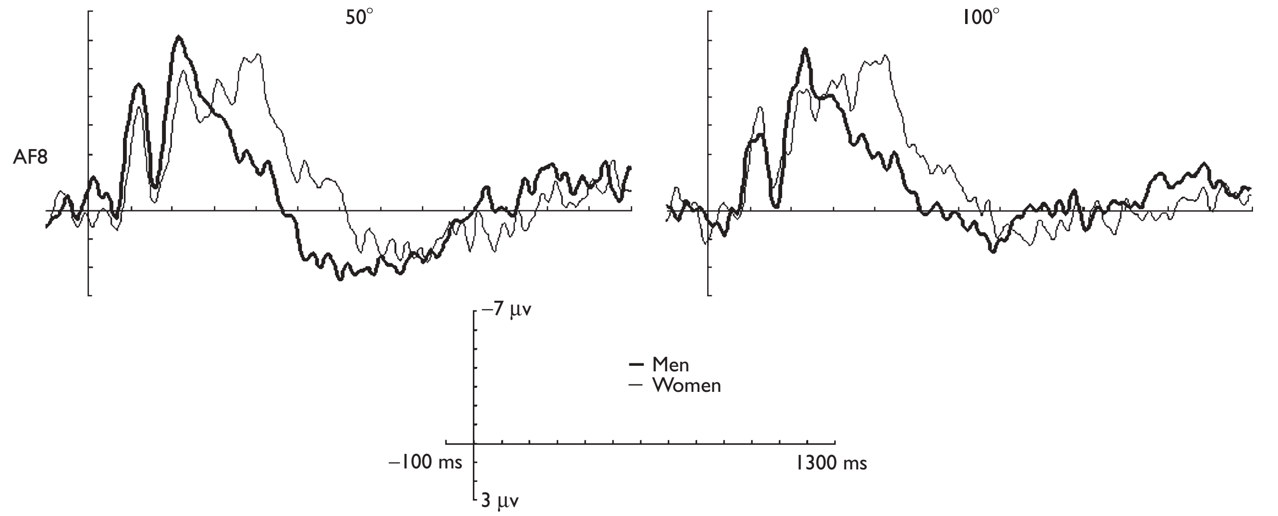
For left frontal sites, neither significant main effects of angular disparity [for all time intervals: F(1,22) < 4.108, $P > 0.055$] and sex [for all time intervals: F(1,22) < 0.438, $P > 0.515$] nor significant interaction effect between angular disparity and sex [for all time intervals: F(1,22) < 0.888, $P > 0.356$] were found.

Discussion

RTs and ACC were clearly affected by mental rotation, showing slower responses and lower ACC with increasing angular disparity. They are in line with the literature [20,21] and indicate the participants actually performed mental rotation. Although women and men, showed equal RTs, women had a lower ACC than men, especially for an angular disparity of 100° which indicated that men performed better. This result is consistent with previous 3D mental rotation studies [22,23].

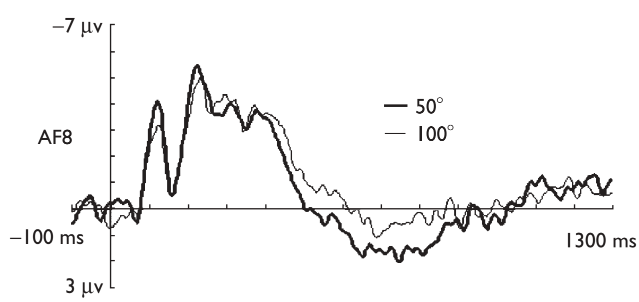
Consistent with earlier 2D mental rotation ERP studies [17,18], we observed a parietal effect of angular disparity with more negative amplitudes as rotation angle increased, although the latency was later (900–1000 ms) and the effect was smaller than in 2D studies. Both, however, are in line with the predictions because stimulus encoding is more difficult with 3D objects and RT variance (and, as a consequence, amplitude jitter) is greater. Moreover, additional mental rotation effects were found at right frontal leads (Fp2, AF8, F8). At 600–700 and 800–900 ms, more negative amplitude was associated with larger angular disparity. These results indicate visual–spatial perceptions during those time intervals involve right frontal areas in this 3D mental rotation. These frontal ERP mental rotation effects were observed somewhat earlier than the effect at parietal electrodes. It

Fig. 4



Grand average event-related potentials at AF8, separately for each angular disparity (50° and 100°) for women and men.

Fig. 5



Grand average (all participants, including both women and men) event-related potentials at AF8 as a function of angular disparity (50° and 100°).

is difficult to say whether they are also neurophysiological markers for the process of mental rotation itself during 3D mental rotation. Owing to its topography, the frontal rotation effect has been thought to be associated with sensory processing and simple stimulus evaluation during 2D mental rotation [24]. Nevertheless, these effects were found only at the right hemisphere, which is consistent with previous results [11]. Functional MRI studies have also found activation of right frontal areas during 3D mental rotation [20].

Most interesting sex differences were only found at right frontal electrodes (Fp2, AF8, F8). Women showed more negative amplitude than men as early as 400–700 ms poststimulus. Different activations at right frontal area between women and men during 3D mental rotation have also been reported by fMRI studies [9,10]. The sex-dependent amplitude modulation, in fact, was observed earlier than the mental rotation effects and additionally, turned out to be independent of angular disparity. These results indicate that sex differences in 3D mental rotation occurred in relatively early cognitive processing stages, which probably include perception and identification of stimuli. This suggestion is supported by earlier studies that have found sex differences in those stages during 2D [13] and even in 3D mental rotation [23]. Our findings suggest that neural mechanisms of 3D mental rotation differ between sexes. The difference of neural mechanisms is presumably induced by different strategies used by women and men. Several studies have shown that men prefer to use a holistic strategy whereas women prefer an analytical strategy during mental rotation [9,25]. Sex differences that were only found in right hemisphere suggested women and men might have different holistic processes, as it had been suggested that holistic strategy engages specifically right hemisphere [9]. That no sex difference was found at parietal electrodes in this study suggested sex differences did not occurr during mental rotation itself.

Conclusion

To our knowledge, this is the first study that examined sex differences of ERP effects during 3D mental rotation. Men outperformed women with respect to ACC. ERP mental rotation effects were found at 900–1000 ms at parietal electrodes and at 600–700, 800–900 ms at right frontal electrodes, respectively. Sex differences of ERP effects were found as early as 400–700 ms at right frontal electrodes. These results suggest sex differences in the 3D mental rotation occurred in relatively early cognitive processing stages, which presumably included perception and identification of stimuli.

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