Sex differences in a chronometric mental rotation test with cube figures: a behavioral, electroencephalography, and eye-tracking pilot study

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In chronometric mental rotation tasks, sex differences are widely discussed. Most studies find men to be more skilled in mental rotation than women, which can be explained by the holistic strategy that they use to rotate stimuli. Women are believed to apply a piecemeal strategy. So far, there have been no studies investigating this phenomenon using eye-tacking methods in combination with electroencephalography (EEG) analysis: the present study compared behavioral responses, EEG activity, and eye movements of 15 men and 15 women while solving a three-dimensional chronometric mental rotation test. The behavioral analysis showed neither differences in reaction time nor in the accuracy rate between men and women. The EEG data showed a higher right activation on parietal electrodes for women and the eye-tracking results indicated a longer fixation in a higher number of areas of interest at 0° for women. Men and women are likely to possess different perceptual (visual search) and decision-making mechanisms, but similar mental rotation processes. Furthermore, men presented a longer visual search processing, characterized by the greater saccade latency of 0°–135°. Generally, this study could be considered a pilot study to investigate sex differences in mental rotation tasks while combining eye-tracking and EEG methods. ***NeuroReport*** **29:870–875 Copyright © 2018 Wolters Kluwer Health, Inc. All rights reserved.**

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The ability to identify objects that have the same shape despite different two-dimensional or three-dimensional orientations is a classical problem described by mental rotation [1]. In a chronometrical mental rotation test (cMRT), two pictures are presented on the screen, where the participant must decide as fast and as accurately as possible whether the right object is the same or a mirrored image of the left object.

Many studies have shown that sex is one individual factor that influences mental rotation ability favoring men [2]. These results are brought into question by a study of Jansen-Osmann and Heil [3]. With a sufficient number of participants (36 participants per sex, resulting for each kind of stimulus in an assumed effect size of $d=0.50$, $\alpha=0.05$ and a probability of $1-\beta=80\%$), they investigated possible sex differences in mental rotation with five different stimuli and showed that only one stimulus type (i.e. polygons) out of five produced reliable sex differences. For polygons, the effect size in speed of mental rotation was $d=0.73$, which is a large effect size according to the definition of Cohen [4]. This advantage of men compared with women is often expressed in a faster reaction time (RT) and higher accuracy. However, there were no sex differences when using cube figures as stimuli material. This is in contrast to many psychometric studies in mental rotation research that use cube figures as stimuli material in a paper–pencil test [2]. Seven of 15 chronometric studies that were included in a meta-analysis [2] showed no sex differences at all. However, five of those seven studies included children, which makes it difficult to generalize effect-sizes to adults.

According to Corballis [5], mental rotation is processed differently in both hemispheres: if the stimulus is rotated as a whole, that means holistically, the right hemisphere is most involved. In contrast, the analytic process of mentally rotating the stimulus (piecemeal strategy) activates primarily the left hemisphere. Men are known to rather utilize a holistic strategy, whereas women seem to use a piecemeal strategy when rotating polygons as stimuli [6]. These different strategies could easily be investigated using eye-tracking methods, but has only rarely been done so far.

Eye movement analyses provide valuable qualitative and quantitative measurements in visual research [7]. Carpenter [8] proposed that the ability to mentally rotate objects relates to differences in eye movements (e.g. fixations and saccades). Fitzhugh *et al.* [9] indicated that participants with low mental rotation ability present a higher number of fixations than those with high mental rotation ability. They suggested that the latter tend to use a holistic strategy (i.e. rotating the whole object), whereas

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the former rather use a piecemeal strategy (i.e. focusing on details, therefore requiring more fixations). Along the same line, Alexander and Son [10] found that eye movements of men and women are somewhat similar when solving a mental rotation test. However, the number of fixations in correct alternatives was smaller in men. Such findings suggest that men use a holistic strategy, which requires less fixation shifts than women. The cMRT in this study presented five stimuli on the screen, which might limit the interpretation of the eye-tracking results as chronometrical tests use traditionally two stimuli.

Not only the investigation of eye movements but also the analysis of brain processes can provide insight into possible sex differences. Men might show a higher right hemisphere lateralization in the parietal cortex compared with women [6]. In electroencephalography (EEG) studies, this result was obtained with polygons as stimuli type [11], but could not be confirmed with cube figures [12].

The aim of the present study was to investigate whether biopsychological measurements are a more sensitive tool to investigate possible sex differences in chronometric mental rotations tasks than the behavioral measurements of RT and accuracy. We therefore chose a stimuli material for which no sex differences in a chronometric test were found before [3]. We aimed to investigate whether there are sex differences in eye movements and EEG when solving a chronometrical mental rotation test with two simultaneously presented three-dimensional cube figures. We hypothesized that: (a) men would present longer fixations durations and higher saccade latencies compared with women in all angular disparities and (b) men would show a right hemispheric lateralization and women a left one.

Patients and methods

Participants

Thirty healthy young adults with normal or normally corrected vision (15 men and 15 women; mean ± SD: men 23 ± 4 year; women 23 ± 3 year volunteered) were included in this study. They provided written informed consent to participate in the study and received course credit for their participation. The experiment was conducted according to the ethical guidelines of the Helsinki Declaration.

Materials and procedure

Mental rotation test

The cMRT was performed on a laptop using Presentation software (version 20.0; Neurobehavioral Systems Inc., Berkeley, California, USA) with a 15.6’ monitor located ~ 60 cm in front of the participant while binocular gaze and EEG was monitored continuously. Participants viewed two three-dimensional block figures (a block pair) and indicated whether the pair was the same or different.

The cMRT consisted of 192 unique block pairs, each presented twice, throughout the course of the test (total of 384 randomized trials), showing 50% ‘same’ and 50% ‘different’ pairs. The stimuli were presented pair-wise in eight different angular disparities of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. Each figure had a dimension of 400 × 400 pixels. A practice block of 32 trials with feedback preceded the main experiment. During the main experiment, a self-controlled pause screen showed up at every 28 trials. Each trial was preceded by a fixation cross (*) in the middle of the screen for 1000 ms.

Eye-tracking measurement

Eye movement metrics (i.e. fixations, saccades, average dwell time, fixation duration, saccade duration, saccade direction, and saccade latency) were recorded continuously using SMI REDn scientific 60 Hz eye-tracking equipment (iViewX; SMI GmbH, Teltow, Germany). The ambient light in the testing room was held constant throughout the entire protocol. After the training trials, a five-point calibration was performed in the eye-tracker before the start of the test.

Electroencephalography measurement

The EEG data were collected using 32 Ag/AgCl active electrodes (Brain Products, Gilching, Germany), which were placed in a recording cap (ActiCap) according to the 10–20 system. In addition, four bipolar passive eye electrodes sampled the vertical and the horizontal eye movements. Data were recorded using the BrainVision Recorder 1.21 software (Gilching, Germany) at a continuous sampling rate of 500 Hz. The signal was amplified using the BrainVision QuickAmp USB 40-channels (32 EEG channels) and referenced to an average reference. No offline filters were applied and electrical impedance was always maintained under 20 kΩ. Electrical noise was avoided by running all technical advices on battery.

Data and statistical analyses

RT more than three SDs above or below the mean of each respective angular disparity was excluded. This resulted in an exclusion rate of 10.8% for women and 9.74% for men. The results obtained (see the Results section) did not differ from the ones that would follow without trimming. For RT, only the responses for the nonmirrored trials were analyzed because angular disparity is not defined clearly for mirror-reversed responses [13].

Behavioral data

Two repeated analyses of variance were carried out, with RT and accuracy rate as dependent variables, and angular disparity and sex as between-subject factors.

Eye-tracking data

The use of eye tracking enabled the quantification of the participants’ gaze locations during each one of the 384 trials. A previous study using eye tracking during a

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mental rotation task only measured accuracy and analyzed the number and duration of fixations [10].

1. We propose that a smaller number of fixation shifts indicate a longer fixation duration for the use of a more holistic strategy. Fixation detections were performed using BeGaze 3.7 (SMI GmbH), at which only fixations longer than 80 ms were considered [14]. For the number of fixations and fixation duration, an analysis of variance (ANOVA) was carried out with angular disparity as the within-participant factor and sex as the between-participant factor.
2. Because participants were required to inspect objects in detail [14], we additionally measured the saccadic eye latency, which indicates whether the holistic or the piecemeal strategy was used. An ANOVA was run with angular disparity as the within-participant factor and sex as the between-participant factor that showed a main effect on angular disparity.
3. Furthermore, fixation maps were created for each participant using a Gaussian distribution to represent visual acuity [15]. Thus, fixation maps for each trial represented both the special distribution of fixations and the relative duration. Thereafter, each map was normalized to the magnitude of the 'Region of Highest Salience' for that trial. Normalized maps (i.e. heat maps) of each participant were combined to produce overall visual acuity maps for men and women. Gridded areas of interest (AOI) were created with 3 × 3 equally divided squares (Fig. 1) for each angular disparity [16] to characterize each group (men and women) into either a holistic or an analytic visual search strategy. Each square contains the average dwell time (ms) of overall angular disparities and was color-coded similar to the aforementioned heat maps. For the AOI, a multivariate analysis was carried out across the nine AOI of the right object and of the comparison object; sex was set as an independent variable. If the visual search strategy is concentrated on a few squares, a more holistic strategy is assumed, whereas a focus on a wider distribution of squares refers to a more analytic strategy.

Electroencephalography data

The analysis of the EEG data was carried out using the Brain Vision Analyzer 2.1.1 (Brain Products). All channels were referenced to the averaged TP9 and TP10 electrodes; the sampling rate was reduced to 250 Hz. A band pass from 0.071 to 12 Hz and a notch filter were set offline. The data were divided into segments around stimulus presentation (− 200 to 1300 ms), creating segments of 1500 ms length. A semiautomatic artifact rejection marked segments as poor according to set criteria: maximal allowed voltage step of 30 mV/ms; maximal allowed difference between values of 150 mV; minimal/maximal allowed amplitude of ± 150 mV; and activity lower than 0.5 mV for 100 ms or more. Ocular artifacts were corrected according to Gratton *et al.* [17]. Event-related potentials were evaluated by averaging segments of corrected response to nonmirrored stimuli for each participant.

According to the study of Hahn *et al.* [18], the mean voltages of the F (F3, F4), C (C3, C4), and P (P3, P4) electrodes were analyzed in the time interval between 500 and 800 ms after stimulus onset to a prestimulus baseline of 200 ms. One participant had to be excluded because of a failure in recording the data.

Results

Behavioral data

Reaction time

The ANOVA on RT with angular disparity as the within-participant factor and sex as the between-participant factor showed a main effect on angular disparity: $F(7, 196) = 73.66$, $P < 0.001$, $\eta_p^2 = 0.725$. A *t*-test for paired samples showed that the RTs were higher on each consecutive angular disparity up to 180° ($P \leq 0.001$) and lower on each consecutive angular disparity from 180° up to 315° ($P < 0.001$). Because of multiple testing, Bonferroni correction was chosen and the significance standard was set to $\alpha = 0.007$. For the factor sex, there was no main effect of sex on RT: $F(1, 28) = 0.287$, $P = 0.596$, $\eta_p^2 = 0.01$ and no significant interaction between both factors: $F(7, 196) = 0.487$, $P = 0.591$, $\eta_p^2 = 0.02$.

Accuracy rate

The ANOVA on the accuracy rate with angular disparity as the within-participant factor and sex as the between-participant factor showed a main effect on angular disparity: $F(7, 196) = 24.59$, $P < 0.001$, $\eta_p^2 = 0.468$. A *t*-test for paired samples showed the accuracy rate to be higher for the angular disparity of 45° compared with 90°, 135° compared with 180°, 225° compared with 270°, and for the angular disparity of 270° compared with 315° (all $P < 0.001$). All other consecutive comparisons did not show any significance. Because of multiple testing, Bonferroni correction was chosen and the significance standard was set to $\alpha = 0.007$. There was no main effect of sex on the accuracy rate: $F(1, 28) = 0.114$, $P = 0.738$, $\eta_p^2 = 0.004$, and no significant interaction between both factors: $F(7, 196) = 1.130$, $P = 0.346$, $\eta_p^2 = 0.039$.

Eye-tracking data

Fixation numbers

The ANOVA for the number of fixations with angular disparity as the within-participant factor and sex as the between-participant factor showed a main effect on angular disparity: $F(7, 196) = 80.71$, $P < 0.001$, $\eta_p^2 = 0.742$. A *t*-test for paired samples showed the number of fixations to be higher on each consecutive angular disparity up to 180° ($P < 0.001$) and lower on each consecutive angular disparity from 180° up to 315° ($P < 0.001$). Because of multiple testing, Bonferroni correction was chosen and the significance standard was set to $\alpha = 0.007$. There was no main effect of

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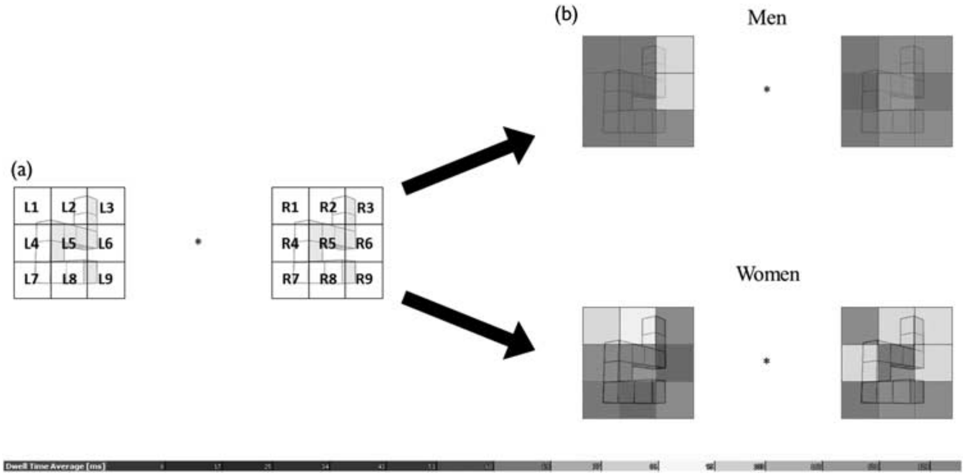
Fig. 1



(a) shows how the stimuli were divided into nine equal blocks. Each block in the left stimulus was named L (left) and numbered from 1 to 9. On the right-hand side, each block was named R (right) and numbered from 1 to 9. (b) shows the difference between men and women in search strategy, with the blocks color coded based on the average dwell time (ms) on each block. Men presented a holistic strategy at 0°, whereas women presented an analytic visual search ($P < 0.05$).

sex on fixation numbers: $F(1, 28) = 0.048$, $P = 0.829$, $\eta_p^2 = 0.002$, and no significant interaction between both factors: $F(7, 196) = 0.34$, $P = 0.754$, $\eta_p^2 = 0.012$.

Fixation duration

The ANOVA for the number of fixation with angular disparity as the within-participant factor and sex as the between-participant factor showed a main effect on angular disparity: $F(7, 196) = 59.49$, $P < 0.001$, $\eta_p^2 = 0.68$. A *t*-test for paired samples showed the duration of fixations to be higher on each consecutive angular disparity up to 180° ($P < 0.001$) and lower on each consecutive angular disparity from 225° up to 315° ($P < 0.001$). There was no significant difference between 180° and 225°. Because of multiple testing, Bonferroni correction was chosen; the significance standard was set to $\alpha = 0.007$. There was a main effect of sex in fixation duration, indicating a longer fixation duration for men (297.01 ± 35.62 ms) compared with women (267.61 ± 41.57 ms): $F(1, 28) = 4.324$, $P = 0.047$, $\eta_p^2 = 0.134$, and no significant interaction between both factors: $F(7, 196) = 1.93$, $P = 0.137$, $\eta_p^2 = 0.065$.

Saccade latency

The ANOVA for the saccade latency with angular disparity as the within-participant factor and sex as the between-participant factor showed a main effect on angular disparity: $F(7, 196) = 21.831$, $P < 0.001$, $\eta_p^2 = 0.438$. There was no main effect of sex on saccade latency: $F(1, 28) = 3.711$, $P = 0.064$, $\eta_p^2 = 0.117$, but a significant interaction between both factors: $F(7, 196) = 2.42$, $P = 0.021$, $\eta_p^2 = 0.080$. Because of multiple testing, Bonferroni correction was applied and the significance level was set to $\alpha = 0.007$. With this level, the latency of men seems to appear, but was not significantly higher than that of women at an angular disparity of 45° $t(28) = 2.46$, $P = 0.020$ and 135°, $t(28) = 2.31$, $P = 0.028$.

Gridded area of interest analysis

A multivariate analysis across the nine AOI with the right object and the comparison object as the dependent variable and sex as the independent variable showed for the right picture at the gridded AOIs of R1 and R5 an effect of sex on the angular disparity of 0°: R1 : $F(1, 28) = 4.61$, $P = 0.041$, $\eta_p^2 = 0.14$ (men = 3.34 ± 12.94 ms; women = 76.62 ± 131.55 ms) R5: $F(1, 28) = 10.64$, $P = 0.003$, $\eta_p^2 = 0.28$ (men = 224.96 ± 164.35 ms; women = 68.26 ± 87.21 ms). This result confirmed the assumption that men rather look at the center of the stimulus. The factor sex did not reach any significance for all other angles (all $P > 0.1$).

Electroencephalography data

A repeated-measures ANOVA was run on the mean voltage with the within-subject factors caudality (F vs. C vs. P), laterality (left vs. right electrodes), and angular disparity and the between-subject factor sex. There was a main effect of the factor laterality: $F(1, 27) = 4.14$, $P = 0.045$, $\eta_p^2 = 0.141$, and a two-way interaction between laterality and sex: $F(1, 27) = 5.64$, $P = 0.025$, $\eta_p^2 = 0.173$. This two-way interaction was qualified by a three-way interaction between laterality, sex, and caudality, $F(2, 54) = 4.89$, $P = 0.011$, $\eta_p^2 = 0.154$. Only the activity on the P4 electrode showed a significant sex difference, $F(1, 27) = 4.76$, $P = 0.038$, $\eta_p^2 = 0.150$. Men (317.65 ± 412.59 μV) showed lower activity on the right parietal electrode compared with women (665.74 ± 444.01 μV). There were neither relevant main effects for the factors angular disparity, $F(1, 189) = 0.513$, $P = 0.824$, $\eta_p^2 = 0.019$, caudality, $F(2, 54) = 0.93$, $P = 0.399$,

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$\eta_p{}^2 = 0.03$, or sex, $F(1, 27) = 0.629$, $P = 0.435$, $\eta_p{}^2 = 0.02$, nor any other possible two, three, or four-way interaction that showed significance (all $P > 0.1$).

Discussion

The present study investigated eye-tracking and EEG responses in men and women when solving a three-dimensional cMRT. There were no sex differences in RT or accuracy, which is in line with the study of Jansen-Osmann and Heil [19]. Beside the missing sex differences in the behavioral data, the main results of the eye-tracking data showed a sex difference in fixation duration, that is, men showed a longer fixation duration than women. However, no sex difference was found for the number of fixations. The gridded AOIs analysis showed a different visual search strategy at an angular disparity of 0°, indicating that men use a holistic strategy and women a piecemeal strategy. Furthermore, EEG data showed a higher right lateralization for women compared with men.

As mentioned above, for the behavioral data, our results confirmed the absence of sex differences in a chronometric mental rotation task, which is in line with the study of Jansen-Osmann and Heil [3]. It would be interesting to carry out the same study with stimuli material for which sex differences appear more probable, for example polygons. However, the result that sex differences are present in biopsychological measurements, but not at the behavioral level, is quite interesting and confirms previous findings showing a different mental rotation performance dependent on the measurement methods in chronometric tasks [18].

However, using eye-tracking data, we could find sex differences in a chronometric mental rotation task, which includes three distinct processes: (a) a perceptual stage (i.e. visual search, identification of the target/stimuli, identification of orientation); (b) a rotation stage (i.e. mental rotation); and (c) a decision-making stage (i.e. response selection and execution) [20–22]. For the angular disparity of 0°, the perceptual and decision-making stages are separated from the rotation stage as no mental rotation needs to be performed. In this context, the novel gridded AOIs analysis [23], which showed sex differences only at 0°, suggests that men and women are likely to possess different perceptual (visual search) and decision-making mechanisms, but similar mental rotation processes.

In the present study, although not significant, higher saccade latencies might appear for men compared with women at 45° and 135°, a result that has to be confirmed in a larger sample. As women were faster in responding to the first saccade and as there were no differences observed in RT between men and women, it is suggested that women used a visual strategy characterized as a piecemeal (or detailed thinking) strategy, whereas men prefer a holistic (or generally thinking) approach in the aforementioned angular disparities. This assumption is in line with the result that the fixation duration of men is longer than that of women, with longer fixation durations considered to be associated with a holistic viewing strategy.

For the EEG data, the results contradict our hypothesis. Women showed a higher right lateralization on the parietal electrodes compared with men, which is in contrast to other studies [11]. However, as in the study of Pellkofer *et al.* [11] the results confirm that men show a higher bilateral activation than women. Both studies differ in the stimuli used (cube figures vs. polygons). Our results partly agree, however, with those of a study with 32 participants (16 men and 16 women) of Roberts and Bell [12], who showed a higher right activation for both women and men with three-dimensional cube figures. The conflicting findings support the assumption that lateralization effects originate in the type of stimuli and need further investigations. Overall, women showed a much higher EEG magnitude on both sides (P3 and P4), which could be interpreted as greater effort to achieve a similar performance.

Limitations and conclusion

To the best of our knowledge, this is the first (pilot) study investigating sex differences in mental rotation performance with behavioral as well as eye-tracking and EEG data. The study is limited by the low sample rate of the eye tracker (i.e. 60 Hz) as well as the small number of participants, but it points to the importance of combining both methods to investigate sex-dependent strategy differences while solving mental rotation tasks. In conclusion, the present study showed, through a novel AOIs analysis, that visual search strategies are distinguishable between men and women. Men tend to present a slower visual process, characterized by higher but non-significant saccade latencies. This supports the hypothesis that men are likely to use a holistic visual search strategy, whereas women rather use a piecemeal approach, thus requiring faster visual search processes.

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Conflicts of interest

There are no conflicts of interest.

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