# Mental Rotation Process for Mirrored and Identical Stimuli: A Beta-band ERD Study

Hongzhou Chen, Xiaoli Guo, Yuanyuan Lv, Junfeng Sun, *IEEE Member*, and Shanbao Tong, *IEEE Senior Member*

***Abstract*— This study investigated mental rotation for identical stimuli and mirrored stimuli by both behavior response and event-related desynchronization (ERD) of EEG signals. Results showed that subjects had longer response time for mirrored stimuli than identical stimuli. Beta-band desynchronization appeared in whole brain with the parietal-occipital dominance. The ERD in beta band recovered slowly in an angular order after 450-600 ms of stimulus onset except the sharp rebound in the case of identical stimuli with rotation at 0°. This temporal difference of beta ERD between the identical and the mirrored stimuli at 0° rotation and the ERD topographic difference in left fronto-parietal regions, together with the behavior difference, may imply an extra flip process in mirrored condition.**

## I. Introduction

Mental rotation is a psychological process which people perform to compare two similar objects at different orientations. Such a mental rotation process was firstly revealed in a behavior experiment by Shepard & Metzler [1] with the finding of "angle effect", i.e., linear relationship between response time and orientation difference. With the quantifiable load relative to orientation difference, mental rotation task was widely used in studies of motor imagery and motor disability [2]. Though the judge of the stimulus parity (i.e. identical and mirrored stimulus) has been popularly used in mental rotation task, the cognitive process of different parities has not yet well investigated [3-8]. It was reported in behavior studies that response to mirrored stimuli needed longer response time (RT) [9-11]. Cooper and Shepard attributed this longer response time to a "response-preparation theory" [9]. They suggested that subjects tend to prepare a motor response for identical stimuli. Thus, for mirrored stimuli, inhibiting and refreshing the preparation would inhibit the subject's response. Paschke et al. suggested that a poorer performance in judging the mirrored stimuli would be expected when applying this theory [11]. On the other hand, Hamm and colleagues reported enhanced ERP amplitudes and longer latencies for mirrored stimuli irrespective of the orientation [10]. They assumed an additional visuospatial "flip" process for mirrored stimuli, that is, subject may imagine the axial transformations of mirrored object to match the reference object. "Flip theory" suggested that the mirrored objects may induce stronger activations in areas related with mental rotation.

Hamm et al. provided ERP evident of parity difference in early 600 ms [10]. Nevertheless, some late oscillations are not ideally phase-locked, and thus be eliminated in ERP averages. Event-related (de)synchronization (ERD/ERS) analysis which keeps the phase-unlocked information can preserve the dynamic and multi-band information in the frequency domain [12]. As generally recognized, beta activity is closely linked to motor preparation and execution, and mental rotation task has been thought a kind of motor imagery [6, 13]. During motor imagery, desynchronization of beta oscillations appeared in the early stages followed by a recovery called "beta rebound" [12]. To compare the cognitive difference between identical stimuli and mirrored stimuli during mental rotation, we propose to study the behavior response and beta band ERD in a mental rotation task, i.e., comparing one object to its identical or mirror-rotated counterpart, so as to reveal the possible influence of rotating strategy and the effect of stimulus parity in the time course of mental rotation.

## II. Materials and Method

### A. Participants

Twenty-nine healthy young adults were randomly divided into two groups performing the task by the strategies of exogenous force (n=16, denoted as EX hereafter) and endogenous force (n=13, denoted as EN hereafter) respectively [3]. Subjects in two groups are homogenous in age (EX: 21.8 ± 1.7 yrs; EN: 22.1 ± 2.1 yrs), education (yrs of schooling: EX: 15.6 ± 2.7 yrs, EN: 15.4 ± 6.4 yrs) and gender (male/ female: EX: 9/ 7, EN: 7/ 6). The key inclusion criterion was that the subject should be able to complete the motor imagery according to the movement imagery questionnaire [14]. All subjects gave their written informed consents and received remuneration after the experiments regardless of their performance.

### B. Stimuli Creation

We created a 3D-shaped object as those proposed by Shepard and Metzler [1] using Autodesk 3ds Max 2013 (Autodesk, Inc.) and Matlab 2013 (MathWorks, Inc.) for stimulation. The standard 3D object was in an arm-like shape, consisting of eleven cubes (1×1cm) glued together (see Fig. 1). All cubes of the reference object are in the same color except that one end cube was red tagged so as to provide an

This work was supported by National Basic Research Program of China (973 Program) (No. 2011CB013304), and SJTU Med-X Research Fund (YG2012MS09).

H. Chen (email: chen_hongzhou@sjtu.edu.cn), X. Guo (email: meagle@sjtu.edu.cn), Y. Lv (email: lvyuanyuanoo@gmail.com), J. Sun (corresponding author; phone: +86-21- 62933291; e-mail: jfsun@sjtu.edu.cn), and S. Tong (e-mail: stong@sjtu.edu.cn) are with the School of Biomedical Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China.

explicit cue to the axial orientation. During the experiment, the subjects were asked to judge whether the simultaneously presented target (blue) and the reference (grey) objects are identical or mirrored. To minimize the EEG noises caused by saccadic eye movements, we made the target translucent and then superimposed it on the reference. The reference objects in all trials are the same. While the target objects were created by mirroring and rotating processing of the reference object. Mirror processing was performed in x-z plane before the rotation. After that, the object was rotated to a certain orientation (angle= 0°, ±30°, ±60°, ±90°, ±120°, ±150°, 180°) along only one axis (either x-, or y-, or z-axis), referring to the reference object respectively. Targets of the same parity with the same absolute rotation angle were considered as the same stimulus type regardless of the rotation axis. So in total, we have fourteen, i.e. 7 (absolute rotation angle= 0°, 30°, 60°, 90°, 120°, 150°, 180°) ×2 (identical, mirrored) , different types of stimulation. We manually discarded those rotated objects that all cubes were not implicitly recognized in current view. For each stimulus type, though we could have different versions of rotation, e.g. 1 for 0°, 3 for 180° and 6 for any other angle, to avoid the fatigue of the subjects, we randomly selected two objects from each stimulus type as the target, i.e. 14×2=28 in total. In each trial, one of the 28 targets will be presented together with the reference.

## *C. Experimental Procedure*

An event-related self-paced paradigm was used (Fig. 1). For each trail, a stimulus picture was presented in a pseudo-random sequence at equal probability. The picture was presented until the subject responded. A red fixation cross was displayed during the 800 ms inter-stimulus interval (ISI). Subjects were asked to judge whether the two geometries were the same or mirrored pair by mentally rotating the blue one, and then press the "F" key for the case of "same pair" and press the "J" key for the case of "mirrored pair". Subjects were required to keep their hands on the keyboard to minimize body movements during the experiment.

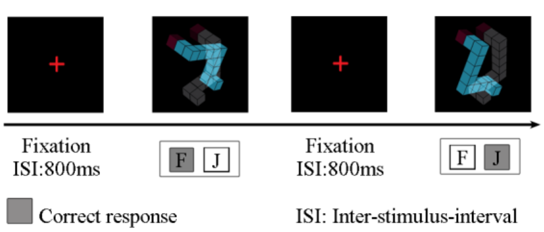


Figure 1. Experiment paradigm. A crosshair was presented for 800ms before the objects was presented. The target (blue) was presented together with the reference object (grey) until the subject reponded by pressing the key "F" or "J" before the next trial starts.

Before the formal experiment, subjects received a training to understand their rotation strategy. EX group watched a video showing the geometry rotating by itself, while EN group hold a wooden geometry and rotated it with their own hands. Then both the EX and the EN groups had a test block until they got a response accuracy above 80%. EX group should imagine the geometry's self-rotation, while EN group was required to imagine to manually rotate the geometry with their own hands.

The whole test consisted of 8 blocks, with each block containing 84 (28 stimulus pictures × 3 times) trails. There was 1~2 min break between two successive blocks. The timing of the presentation was controlled and synchronized to the EEG data by E-Studio (E-Prime v2.0, Psychology Software Tools, Inc.). All experiments were conducted in an acoustic and electric shielding room (3×3.5m, Union Brother, China).

## *D. EEG Data Acquisition and Processing*

The EEG signals were recorded with BrainAmp (Brain Products GmbH, Germany) from an 32 channel Ag-AgCl cap (Easycap, Brain Products GmbH) at a sampling rate of 1000 Hz. Vertical and horizontal electro-oculograms were recorded for detecting the eye-movements and blinks. FCz served as the reference. Electrode impedance at each channel was kept below 15 kΩ during recording.

EEG preprocessing was performed offline using BrainVision Analyzer (v2.0, Brain Products GmbH). First, the EEG data were band-pass filtered (0.016~40 Hz). Then ocular artifacts were removed by semi-automatical ICA method. EEG episodes with gradient more than 50 μV/ms and absolute value of amplitude more than 200 μV were strictly rejected by semi-automatically detecting. EEG epochs of trials with correct response and response time less than 6000 ms were segmented from -200 ms to 1500 ms referring to the stimulus onset.

All the selected artifact-free EEG epochs were band-pass filtered into the beta band (14~30 Hz) for ERD/ERS analysis. The ERD/ERS, which refers as the reducing/enhancing of EEG power in specified frequency band relative to the baseline [12], were calculated using a toolbox (Component Version 2.0.5857) of BrainVision Analyzer. Briefly, let $P$ denote the power within the frequency band of interest in the period after the event and $R$ denote the power of the preceding baseline or reference period within the same frequency band, then ERD (or ERS) is defined as the percentage of power decrease (or increase) after the event, respectively, relative to the baseline by the expression $ERD\% = (P-R)/R \times 100\%$. To investigate the process of mental rotation, the ERD/ERS result was assessed for 9 phases, i.e., I (0~150 ms), II (150~300 ms), III (300~450 ms), IV (450~600 ms), V (600~750 ms), VI (750~900 ms), VII (900~1050 ms), VIII (1050~1200 ms), IX (1200~1350 ms), respectively.

## *E. Statistical Analysis*

Both behavioral data and ERD/ERS results were statistically analyzed by repeated-measures analysis of variance (ANOVA) with the Strategy (EX vs. EN) as the between-subjects factor. Statistical significance was accepted for values of $p<0.05$. The data of two mirrored pictures at 90° and 150° were excluded in further analysis because of the poor performance in almost all participants. Except these two particular cases, each datasets of two pictures belong to the same stimulus type were merged together for further statistical analysis. The statistical analysis for ERD data were taken separately for each phase.

## III. Results

### A. Behavioral Results

All subjects had an accuracy rate (ACC) more than 85% in any orientation of either parity, indicating that subjects well understood the experimental procedures and the mental rotation were successfully implemented. Two-way repeated measures ANOVA was performed on both ACC and response time (RT). The within-subjects factors were stimulus Parity (identical vs. mirrored) and Rotation (0° vs. 30° vs. 60° vs. 90° vs. 120° vs. 150° vs. 180°). The between-subject factor Strategy didn't show any main effect on either RT or ACC.

The main effects of Rotation were significant for both ACC and RT, i.e., the RT increased with the angle from the upright position (0°) and the ACC concordantly decreased with the angle ($p<0.001$), which was well known as "angle effect" in mental rotation.

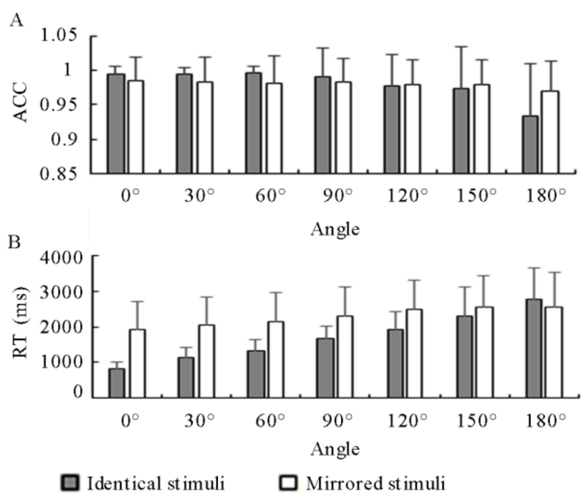


Figure 2. Grand averaged accuracy rates (ACCs) and response times (RTs) showed a strong "angle effect".

Stimulus parity showed a main effect on RT ($p<0.001$). RTs in mirrored condition (1922.46 ± 791.65 ms) were longer than those in identical condition (1707.41 ± 213.37 ms). However, stimulus Parity had no significant main effect on ACC ($p=0.148$). Significant Parity × Rotation interaction effect was observed on both ACC ($p=0.002$) and RT ($p<0.001$), which was mainly due to the significantly slower change in mirrored conditions.

### B. ERD Results

Obvious beta-ERD was observed after 150 ms post the stimulus onset (Fig.3A). With respect to time, the desynchronization strengthened and reached its maximum around phases IV and V, then weakened slowly after 750 ms post the stimulus onset. In spatial distribution, the desynchronization widely appeared in the whole brain with the parietal-occipital dominance. In this paper, we treat the EN and EX group as a whole since between–group factor Strategy didn't show any main effect in any phase or any electrode.

Significant "angle effect" was found in ERD result. ANOVAs with Electrode (28 electrodes showed in Fig. 3), stimulus Parity and Rotation angle considered as within-subjects factors revealed significant main effect of Rotation in phases VI ($P=0.008$), VII ($p<0.001$), VIII ($p<0.001$), and IX ($p<0.001$). Beta-ERDs increased with rotation angle in most electrodes in phase IX [see inset panel (i) in Fig. 4A for an example], but decreased in phases IV, V, and VI in T8, CP2, O2 , Pz and Cz [see inset panel (ii) in Fig.4B for an example](all $p<0.05$).

ERD also showed different spatiotemporal patterns in identical and mirrored condition. Stimulus Parity showed significant main effect in phases VII ($p=0.001$), VIII ($p=0.029$), and IX ($p=0.022$) when considering electrode as a within-subjects factor. The beta-ERD difference between identical and mirrored stimuli appeared at late stages and indicated a greater desynchronization in mirrored conditions, especially in the left parietal and the right prefrontal cortices (channels with significant main effect of Parity marked with white circles in Fig. 3B). There are significant interactions between Parity × Rotation in phases VI, VII, VIII, and IX, which is mostly due to the beta-ERD at angular 0°: ERD of identical 0° showed a sharp rebound after phase V (this

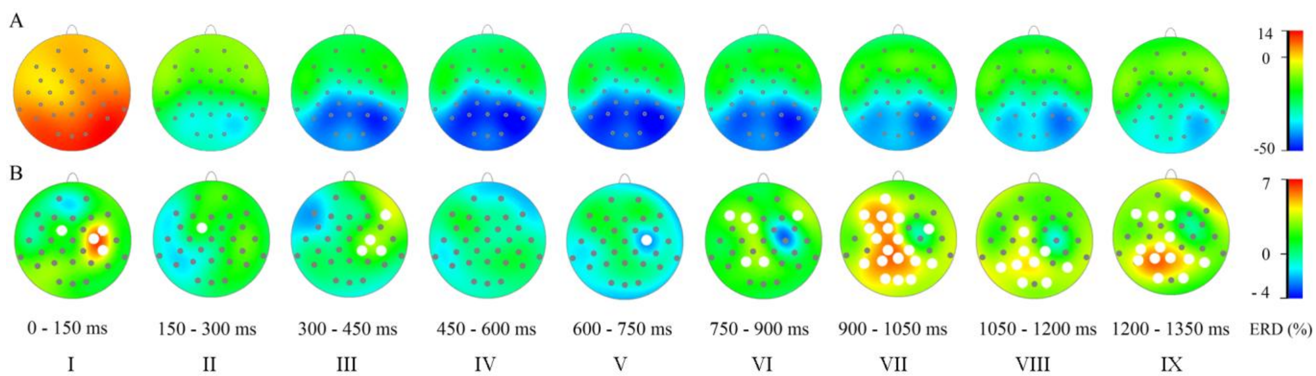


Figure 3. The topography of ERDs in beta band. A: Mapping view of grand averaged beta-ERD. B: The difference between the ERD of identical stimuli and the ERD of mirrored stimuli. Channels with significant main effect on parity are marked with white circles in panel B.

distinguished it from other rotation angle, see Fig. 4B for an example), while beta-ERD of mirrored stimuli showed a similar pattern as other angles (see Fig. 4A for an example).

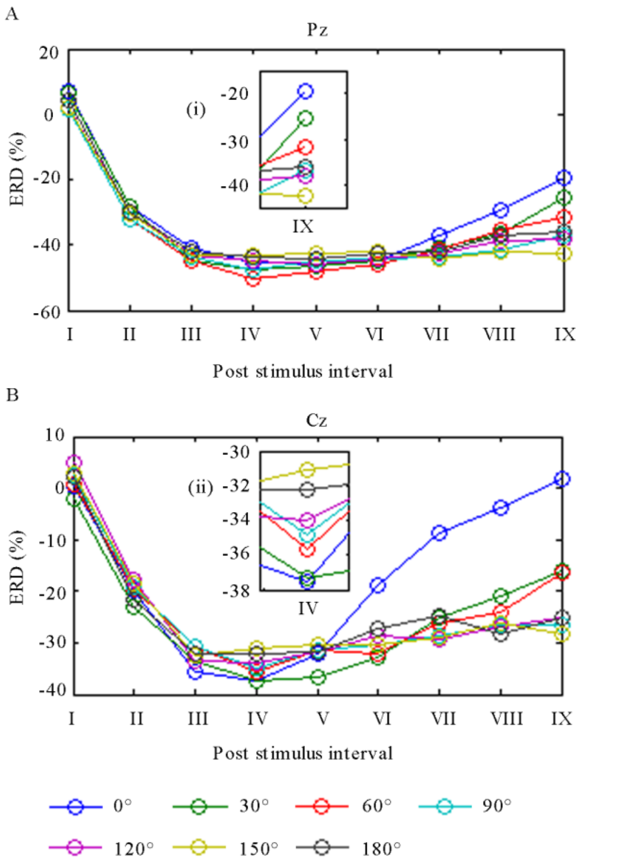


Figure 4. The event-related desynchronization of electrode Pz in the mirrored condition (A) and of electrode Cz in the identical condition (B) in beta band (beta-ERDs). The inset panel (i) demonstrates the angle effect of electrode Pz in mirrored condition in phase IX: the absolute value of beta-ERDs increases along with the increase of rotation. The inset panel (ii) indicates the angle effect of electrode Cz in the identical condition in phases IV: beta-ERDs decreases along with the increase of rotation.

## IV. Discussion and Conclusion

In this study, we found that the RT in mirrored condition was significantly longer and with weaker angle effect than that in identical one, which is consistent with previous studies [9-11]. Such a behavior difference implies the different load for identical and mirrored conditions in mental rotation. For ACC, we found no significant difference for Parities, which doesn't support the "response-preparation theory" [9].

Identical and mirror tasks in un-rotated condition showed different "beta rebound" patterns in late stage (Fig. 4), implying a possible additional cognitive process when judging a mirrored stimulus. The beta ERD/ERS for identical stimuli without rotation showed a sharper rebound than the rotated ones (Fig. 4B). In contrast, the "beta rebound" for mirrored stimuli at angle 0° was similar with the rotated ones in a linear angular order [Fig. 4A, inset (i)]. Such a similarity might indicate the occurrence of "mental rotation" in mirrored "un-rotated" condition. Furthermore, during 900-1350 ms, mirrored conditions induced stronger activations in left fronto-parietal regions (Fig.3B), which was thought highly related with mental rotation processing according to a meta-analysis [5]. These all support the "flip theory" [10], that is, subject tends to flip the mirrored object into identical representation additionally to the rotation process.

The desynchronization of beta-band EEG oscillations after 150 ms with the parietal-occipital dominance demonstrated a similar topological distribution as the work by Chen *et al.* [15]. The decrease of P300's amplitude in ERP studies [8] was explained as a negativity restricted to the ERPs and suggested that this component is the manifestation of a mental rotation process [7, 8]. ERD decreases along with the increase of rotation around phase IV is consist with the trend of this negative component. This angle effect may imply the start of mental rotation at 450 ms post stimulus onset.

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