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EEG coherence during mental rotation of letters, hands and scenes

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ABSTRACT

The purpose of the present study was to investigate differences in the electrocortical synchronization pattern during mental rotation of three different object categories as well as six different rotation angles. Therefore, event-related coherence of the electroencephalographic (EEG) activity between selective frontal and parietal electrode pairs of ten subjects was measured during the performance of a mental rotation task consisting of rotation of letters, hands and scenes. Statistical analysis showed an increased coherence of frontal and parietal electrode pairs for the condition LETTER in comparison to the other conditions in the alpha$_1$- (8.5–10 Hz) and alpha$_2$-band (10, 5–12 Hz) supporting the notion of different mental rotation mechanisms for externally and internally represented objects. Additionally decreased coherence of the frontal and parietal electrode pairs was found for the rotation angles 30° to 150° in comparison to the 0° and 180° rotations for the alpha$_1$- and alpha$_2$-band as well as the gamma frequency band (30–45 Hz). It is assumed that this decrease of synchronization reflects the mental rotation process implying that the mental rotation process of 180° differs from the rotation process of all other rotation angles.

1. Introduction

Mental rotation implies the judgment of objects, which are presented in different orientations. Behavioral studies revealed that with growing disparity between the normal upright and the presented position of object reaction time increases (Ionta et al., 2007; Kessler and Thomson, 2010; Shepard and Metzler, 1971). This phenomenon was shown for different kinds of objects such as letters, human shapes (hands, body parts) and complex scenes (landscapes, table scenes). However, the interpretation of this phenomenon differs depending on object style. It has been suggested that external objects, such as letters, were mentally rotated in an allocentric reference frame before judging them (object-based transformation). On the contrary, for scenes and human shapes, instead of rotating the object a mental self-rotation is performed before defining it in an egocentric reference frame (egocentric perspective-taking) (Kessler and Thomson, 2010; Kozhevnikov and Hegarty, 2001; Zacks and Michelon, 2005). Behavioral experiments show that scene rotation is executed faster and more accurately than object rotation (Amorim and Stucchi, 1997; Keehner et al., 2006; Wraga et al., 1999; Zacks and Michelon, 2005); Furthermore hand rotation is faster and more accurately than object rotation (Kosslyn et al., 1998). However, only two of three stimulus categories have been considered in these studies. In order to close this research gap Dalecki et al. (2012) have been the first to compare all three stimulus categories within one experiment. The results confirmed the existence of distinct mechanisms for external stimuli based on object transformation and stimuli, such as scenes and body parts, based on an egocentric perspective-taking.

In addition to the behavioral evidence, neuroimaging studies investigating mental rotation have provided different electrocortical activation patterns for different object categories. However, differences could not clearly be reduced to the distinct object categories but rather differed within the object categories when investigated by different studies. Regarding mental rotation of external objects, one study reported activation of the left parietal cortex and the right caudate head (Alivisatos and Petrides, 1997). Another study found activation of the left and right parietal cortices and the associative visual cortex (Brodmann area (BA) 19) (Kosslyn et al., 1998), and again others determined activation of the right parietal cortex only (Harris et al., 2000; Núñez-Peña and Aznar-Casanova, 2009; Zacks et al., 2003). In a few studies mental rotation of hands was associated with activation of the left primary motor and insular cortices and BA 6, 7, and 9, (Kosslyn et al., 1998; Parsons et al., 1995) and in another study with activation of both parietal, extrastriate and premotor cortices (Vingerhoets et al., 2002). For mental rotation of scenes, Creem et al. (2001) found activation of the left posterior parietal, secondary visual, premotor and frontal areas, whereas Zacks et al. (2003) reported activation of the left temporal areas.

These various results indicate that mental rotation is a complex cognitive function involving numerous sub-processes located in different brain areas. But they cannot clearly support the existence of different mechanisms for mental rotation. However, studies using

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an electroencephalograph (EEG) found consistent results investigating event-related potentials (ERPs) during mental rotation for the different object categories (Heil, 2002; Jansen-Osmann and Heil, 2007; Milivojevic et al., 2009; Tao et al., 2009; Wijers et al., 1989). They found that ERPs over the parietal electrodes become more negative with increasing rotation angles, which is termed as rotation related negativity. A further EEG study focused on the synchronization pattern of mental rotation of external objects (Bhattacharya et al., 2001). Results showed increased synchronization between frontal cortex and parietal cortex in the gamma-band compared with resting condition. Indeed, this study provides a first insight in the communication of different brain regions during mental rotation, but it did not consider different object categories.

The purpose of the present study is to investigate the synchronization patterns during mental rotation of different object categories. Therefore, an approach similar to Bhattacharya et al. (2001) is used and combined with the approach of Dalecki et al. (2012), which contains three different object categories (LETTER, HAND and SCENE). In contrast to Bhattacharya et al. (2001), synchronization patterns are compared to 0° rotation rather than to a resting condition allowing to differentiate clearly between mental rotation processes and other task-involved cognitive performances such as the identification of the object alignment. Synchronization patterns are determined in the $alpha_1$- and $alpha_2$-band as well as in the gamma-band. Indeed, changes in synchronization during cognitive performances have been observed in different frequency bands (Gevins et al., 1997; Rodriguez et al., 1999; Sauseng et al., 2005; Varela, 1995; Singer and Gray, 1995; Weiss and Rappelsberger, 2000). Especially gamma-band synchronization is associated with large-scale cognitive integration (Rodriguez et al., 1999; Singer and Gray, 1995; Varela, 1995) But also changes of synchronization in the alpha-band have been found during several cognitive demands such as executive processes (Sauseng et al., 2005; Weiss and Rappelsberger, 2000). Therefore, both, low frequencies (alpha-bands) and high frequencies (gamma-band) are taken into consideration for the present study. Based on the hypothesis that different mechanisms for external and internal object categories exist (Kessler and Thomson, 2010; Kozhevnikov and Hegarty, 2001; Zacks and Michelon, 2005), different synchronization patterns for the condition letter in comparison to hand and scene are expected. Additionally differences in synchronization pattern for the 0° rotation compared with rotated objects are assumed.

2. Methods

Ten right-handed subjects (6 males), aged 26.7 ± 4.9 years, participated in this study. All were free of sensorimotor dysfunctions except corrected vision, and none of them reported prior experience in sensorimotor research. Prior, all subjects signed an informed consent form approved by the institutional ethics committee. This study has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.1. Mental rotation

Subjects participated in three different mental rotation conditions (LETTER, HAND, SCENE), which have already been used in a previous study (Dalecki et al., 2012). Participants were sitting at a distance of 50 cm in front of a flat-screen monitor, on which objects in different orientations were sequentially presented. The only difference to the previous study was the presentation of objects: in the present study 3D shapes instead of 2D shapes were used, which were presented in an oblique plane (65° above the horizontal) (see Fig. 1). In the condition LETTER a “G” or “R” was displayed (see Fig. 1A left). The subjects were asked to judge whether the letter was non-reversed or mirror-reversed. For the condition HAND subjects were instructed to decide if a right or a left hand is presented (see Fig. 1A middle). In the condition SCENE images of a person sitting on a round table with a flower and a weapon (gun or knife) lying in front of the person were displayed (see Fig. 1A right). The task was to judge whether the weapon was to the person's left or right side. The pictures were displayed on a white background within a black circular mask. The order of versions was balanced between subjects. In each condition objects were presented in the orientations 0°, ±30°, ±60°, ±90°, ±120°, ±150° and 180°, in which 0° denotes fingers pointing upward, letters normally oriented, and persons turning their back to the observer, respectively. In each condition 48 different stimuli were presented: twelve orientations of two different shapes (letters “G” and “R”, two different hands, gun or knife) in two versions (letters were normal and mirror-reversed, left or right hand, weapon to the left or to the right). The 48 stimuli of the three conditions were each presented twice in a randomized order with a short rest break of 10 to 20 s in between; Thus, the total number of presented stimuli was 96 for each condition.

The subjects were instructed to respond to each stimulus quickly and accurately by pressing a key with their right or left index finger. The right key represented a non-reversed letter, a right hand and a weapon on the right side, respectively, and the left key represented the reversed alternative. Each stimulus was displayed until subjects responded, and was followed by a randomly varying inter-trial interval of 0.5 to 1.0 s. The subjects were immediately informed about incorrect responses by a short acoustic signal.

For statistical analysis the reaction time (RT) between stimulus onset and key press was averaged across clockwise and counterclockwise orientation angles, across the two respective stimulus shapes of each condition (“G” and “R”, two different hands, gun or knife), and across repetitions. Similar to the former study (Dalecki et al., 2012) no statistical differences were found between counter- and clockwise stimulus orientations for each angle. Therefore, seven rotation angles for each condition representing the orientations 0°, 30°, 60° 90°, 120°, 150° and 180° were differentiated. Wrong submissions and responses with RT > 3 s (2%) were excluded from the RT analysis. ANOVA observing the factor sex yielded no differences such that this factor was not taken into consideration for further analyses ($p = 0.19$). RT data was submitted to an analysis of variance (ANOVA) with repeated measures on the within-factors Condition (LETTER, HAND, SCENE) and Rotation (0°, 30°, 60°, 90°, 120°, 150°, 180°). Significant effects were scrutinized by Fisher's LSD post-hoc tests.

2.2. EEG

During the whole experiment spontaneous EEG signals were recorded using 64 electrodes arranged according to the extended 10–20-system (Jasper, 1958) located in an elastic cap (ANT, WaveGuard Cap). Impedance was kept below 5 kΩ. Additionally, vertical eye blinks and horizontal eye movements were recorded by two EOG channels placed below and on the outer edge of the left (right) eye. Signals were digitalized by the Asa-Lab TM high density Cap-Amplifier (ANT, Enschede, Netherlands) with a sampling frequency of 1024 Hz and A/D precision of 22 bit. EEG signals were filtered offline (Brain Vision Analyzer software, Brain Products, Munich, Germany) with Butterworth zero phase filters including a notch-filter at 50 Hz, a low cutoff at 3 Hz and a high cutoff at 50 Hz with a time constant of 0.0531 s and 24 dB/oct. For further analysis 800 ms segments relative to the stimulus onset (0 to 800 ms) of the mental rotation task were used, while error segments were rejected. An ocular correction with an independent component analysis algorithm (Infomax Restricted) was implemented and a semiautomatic artifact correction algorithm allowing a maximum voltage step of 50 μV/ms and an amplitude range of −100 to 100 μV were executed. Identified artifacts were marked from 200 ms before and after the event and were manually removed. Afterwards data was visually inspected to eliminate further artifacts if needed. Following the baseline correction all segments were subdivided according to the 7 different rotation angles from 0° to 180°.