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An event-related potential study on the time course of mental rotation in upper-limb amputees

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HIGHLIGHTS

- Amputees and controls showed a comparable P100 during early visual processing phase of a mental hand rotation task.
- Amputees exhibited a reduced N200 in the categorization of hand stimuli, and this abnormality was correlated with the duration since amputation.
- Amputees had a larger P300 for the intact upright hand in the mental rotation phase, indicating that the intact hand gained more significance.

ABSTRACT

Objective: Mental rotation of body parts involves sequential cognitive processes, including visual processing, categorization and the mental rotation process itself. However, how these processes are affected by the amputation of a limb is still unclear.
Methods: Twenty-five right upper-limb amputees and the same number of matched healthy controls participated in a hand mental rotation task. Thirty-two-channel electroencephalography (EEG) was recorded and the event-related potentials (ERPs) were analyzed.
Results: In the early visual processing phase, amputees and controls showed a similar P100. During the categorization phase, the amputees exhibited a decreased N200 compared with controls, and the decline was positively correlated with the time since amputation. In the mental rotation phase, controls had a larger ERP for the right upright hand than for the left upright hand, while amputees had a larger ERP for the left (intact) upright hand than for the right (affected) upright hand.
Conclusions: Early visual processing was not affected by limb amputation. However, the perceptual salience of hand pictures decreased and the intact hand gained more significance in the amputees.
Significance: Event-related potentials had the capability of showing the differences in categorization and mental rotation phases between amputees and controls.

1. Introduction

Mental rotation of body parts has been previously used to investigate whether motor imagery ability is affected by limb amputation. However, the results are not consistent. For example, some studies observed slower responses in amputees than healthy controls (Nico et al., 2004; Reinersmann et al., 2010), while others reported comparable performances (Curtze et al., 2010). Using the high temporal resolution of electroencephalography (EEG), our previous study indicated that only amputees with phantom limb perceptions during the task showed a prolonged response time in mental rotation, and their performances were related to attenuated brain oscillatory activity during the mental rotation process (Lyu et al., 2016). The process of mental rotation has sequential and partly overlapping phases, i.e., a) visual encoding, b) analysis of the orientation difference between the target and mental

Abbreviations: EEG, electroencephalography; MRI, magnetic resonance imaging; ERP, event-related potential; RRN, rotation-related negativity; ANOVA, analysis of variance; PLP, phantom limb pain.

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template, c) mental rotation of the corresponding body part from the current to the target position, and d) laterality judgment and response execution (Heil, 2002; Parsons, 2003). Nevertheless, how the time course and the neural activity in each sub-stage are affected in amputees remains unknown.

For the high temporal resolution, EEG and event-related potential (ERP) have been useful tools in studying the temporal patterns of the cognitive processes and neurodynamics. Several ERP components could be particularly indicative in the different phases of the mental rotation task. First, early waves within 100 ms, termed 'sensory' or 'exogenous' ERPs, depend largely on the physical parameters of the stimulus (Sur and Sinha, 2009). For example, the occipitoparietal P100 component reflects early visual processing and has been shown to be modulated by the spatial distribution of a visual stimulus (Herrmann and Knight, 2001). For this component, we did not expect any difference in amputees as the visual pathway is less affected by an amputation. The later waves, which are termed 'cognitive' or 'endogenous' ERPs, mainly reflect information processing (Sur and Sinha, 2009). The anterior N200 relates to the perceptual salience of a stimulus, i.e. unfamiliarity or deviation of a stimulus from a long-lasting mental template (Folstein and Van Petten, 2008), probably corresponding to the stimulus categorization process. Since amputees need more visual guidance of their body in their daily life, we hypothesized that they have a decreased N200 compare with controls in the categorization phase. Then, during the mental rotation time window from about 400 to 600 ms (Horst et al., 2012; Yan et al., 2012), the stimuli should evoke a complex ERP in the parietal area, i.e., a P300 component superimposed by a rotation-related negativity (RRN) component. The P300 component reflects the evaluation of the stimuli (Polich, 2007) and the formation of the decision (O'Connell et al., 2012), while the superimposed RRN, which becomes more negative as the rotation angle of the target increases, probably represents the actual mental rotation process (Heil, 2002). Since the amplitude of the RRN relates to the mental rotation effort, i.e., a decreased RRN reflects the facilitation of the mental rotation process (Núñez-Peña et al., 2005; Riečanský and Jagla, 2008; Liesefeld and Zimmer, 2011), we expected an increased RRN for the right (affected) hand and a decreased RRN for the left (intact) hand stimuli as amputees loose the sensorimotor function of the missing limb and alternatively use the intact limb more frequently in their daily life. In the present study, therefore, we aimed to investigate how the time course of hand mental rotation is affected in amputees in respect of the aforementioned ERP components in comparison with healthy controls.

2. Materials and methods

2.1. Participants

The data used in this study correspond to those in our previous study (Lyu et al., 2016). In total, 27 right-sided upper-limb amputees took part in this study. Two subjects (A5 and A16) were excluded due to extremely low signal-to-noise ratio, preventing us from detecting the early components such as P100. We therefore also included 25 control subjects. Age, level of education and gender ratio did not significantly differ between the two groups (age: amputees, 48.04 ± 9.56 years, controls, 47.48 ± 10.04 years, $T(48) = -0.20$, $p = 0.84$; level of education: amputees, 9.52 ± 2.64 years, controls, 10.88 ± 3.12 years, $T(48) = 1.66$, $p = 0.10$; male/female: amputees, 19/6, controls, 18/7, $\chi^2(1) = 0.10$, $p = 0.75$). Detailed demographic information of the participants is summarized in Supplementary Table S1. Each subject signed a written informed consent after the study had been explained to him or her. The experimental protocols were in compliance with the Declaration of Helsinki. This study was approved by the institutional ethics committee of Shanghai Jiao Tong University.

2.2. Hand mental rotation task

The participants took part in a hand mental rotation task (Lyu et al., 2016). A left or right back-view of the picture of a hand (9 cm × 9 cm) at a predefined orientation (0°, 60°, 120°, 180°, 240° or 300°) was presented randomly in the center of the display which was approximately 60 cm in front of the participants (i.e., a visual angle of 8.6°). The participants were asked to judge whether the picture was a left or right hand, and press the left foot pedal using their left foot for left hand stimuli or the right foot pedal using their right foot for right hand stimuli. The stimuli did not disappear until the participants responded, and they were followed by an interval of 800 ms with a black fixation cross in the center of the screen. The photographic hand pictures were taken from Ionta et al. (2007). The experiment consisted of 4 blocks of 384 pictures in total after 1 training block. Each stimulus was repeated 8 times in a block.

Trials with incorrect responses or response times exceeding each participant's mean by more than two standard deviations (8.82% of all trials) and trials with artifacts (6.53%) were excluded from the subsequent analysis.

2.3. EEG acquisition and analysis

EEG signals were continuously recorded and amplified using a 32-channel EasyCap™ (based on the 10–10 system) connected to BrainAmp MR Plus amplifier (Brain Products GmbH, Munich, Germany), sampled at 1000 Hz and filtered online with a 100 Hz high cut-off filter. Vertical and horizontal electro-oculograms were monitored for detecting eye movements and blinks. The impedances were kept below 20 kΩ and all electrodes were referenced to FCz.

Raw EEG signals were preprocessed offline with BrainVision Analyzer (v2.0, Brain Products GmbH, Munich, Germany). We removed the global trend from the raw data and then filtered the data using a 0.5–30 Hz band-pass filter. The filtered data were re-referenced to the average of TP9 and TP10 (left and right mastoids). Ocular artefacts were corrected using a semi-automatic procedure based on the algorithm of independent component analysis (Jung et al., 2000). Our previous study (Lyu et al., 2016) revealed no significant differences in behavior for symmetric angles (i.e., 60° vs. 300°, 120° vs. 240°). Therefore, all orientations were collapsed into four categories (i.e., 0°, (±)60°, (±)120° and 180°) in subsequent statistical analyses. The EEG data were segmented into 8 categories (left or right hand × 4 orientations) ranging from 200 ms prior to the stimulus to 950 ms after the stimulus. Trials with motion artefacts (EEG amplitude value exceeding ± 200 μV or gradient value of more than 50 μV/ms, 6.54% of all trials) were excluded by semi-automatic detection. Baseline correction (from −200 ms to 0 ms prior to the stimulus onset) was applied afterwards. For each subject, ERPs were obtained by averaging the segments in all kinds of stimuli. Accordingly, the aforementioned ERP components, i.e., P100 (at O1 and O2: 80–150 ms after the stimulus onset), N200 (at F3, Fz, F4, C3, Cz and C4: 220–320 ms) and the mental rotation ERP (at C3, Cz, C4, P3, Pz and P4: 400–600 ms), were identified. ERP latencies of P100 and N200 were measured at the maximal peak/trough in the corresponding time windows and their amplitudes were estimated by the average around the peak (window size: 11 ms). The amplitude of the mental rotation ERP was calculated as the mean amplitude within the 400–600 ms window.