

Linking performance with brain potentials: Mental rotation-related negativity revisited

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ABSTRACT

It has been suggested that the amplitude of parietal event-related potentials (ERPs) provides a neural signature of imaginary object rotation. Here, we evaluated the relationship between the so-called rotation-related negativity and individual performance in the mental rotation of alphanumeric characters. The signals were averaged with respect to two time events, stimulus onset (ERP_{ONSET}) and response time (ERP_{RT}) indexing, respectively, an early and a late phase of the mental rotation. The amplitude of a slow parietal negativity varied with the rotation angle in both ERP_{ONSET} and ERP_{RT} . The amplitude of this potential correlated negatively with task performance, indexed by response time. This was the case in ERP_{RT} but not in ERP_{ONSET} . We further show that variations of the ERP_{ONSET} amplitude with the rotation angle might at least partially result from increased duration/latency jitter among single trials. These results suggest that late rather than early processing supports task solution in mental rotation.

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1. Introduction

Individual differences in cognitive functioning are of fundamental importance when searching for neural correlates of mental processes (Kosslyn et al., 2002). Mental rotation has been extensively used to assess individual visuo-spatial abilities as well as to study the nature of visual imagery and spatial cognition. If visual stimuli, such as letters and digits, are presented at an increasing angle of rotation from the upright position, the time required to identify the stimuli increases monotonically (Cooper & Shepard, 1973). Electrophysiological studies have repeatedly shown that the amplitude of event-related potentials (ERPs) recorded over the parietal cortex varies as a function of the rotation angle; in the interval ranging from approximately 350 to 800 ms the ERP amplitude is more negative for characters rotated away from the upright position (Peronnet & Farah, 1989). It has been suggested that this slow negativity, which is superimposed on a broad positive deflection (the late positive complex, LPC), is a specific correlate of the mental rotation process (Peronnet & Farah, 1989; Wijers, Otten, Feenstra, Mulder, & Mulder, 1989). Control experiments using various stimuli and task demands supported this interpretation (Heil, 2002).

It is unknown, however, whether the same view will hold if inter-individual differences in the performance of mental rotation

are the main source of variance when investigating this particular electrophysiological correlate of mental rotation. If parietal negativity were a true correlate of the rotation process, one would expect the amplitude to vary also with individual performance. Given that accuracy is usually high in the mental rotation of characters, inter-individual differences in performance are best captured by response time. It is well known that variability in response time increases with an increasing angle of stimulus rotation (see, e.g., Heil, Bajric, Rosler, & Henninghausen, 1996). This fact offers an alternative interpretation of changes in ERP amplitude; more negative ERP deflection (i.e. smaller absolute amplitude) with larger mental rotation could result from increased single-trial jitter in the latency and duration of components forming the LPC, which are averaged to yield the mean ERP (Peronnet & Farah, 1989; Regan, 1989; Kok, 2001).

In the present study, we tested the behavioral relevance of parietal ERP negativity in the context of mental rotation. We explored the association between ERP amplitude and concurrently measured response time (RT) to rotated alphanumeric characters. If slow parietal ERP negativity was a true correlate of imaginary character rotation, we would expect to find less negative amplitudes in subjects who perform better (i.e. faster) in the task.

Our results show that ERP amplitude is strongly associated with performance in mental rotation. The predicted association was found, however, only for ERPs time-locked to the response time (ERP_{RT}), reflecting a late phase of the mental rotation process. In contrast, no association with performance was observed for ERPs

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time-locked to the onset of stimuli (ERP_{ONSET}), which reflect an early phase of the cognitive process. We further suggest that the negative shift of the mean ERP_{ONSET} amplitude, widely considered a marker of mental rotation, might result from increased duration/latency jitter among single trials.

2. Methods

2.1. Subjects and procedure

Fourteen healthy volunteers (7 females, mean age 24 ± 2 years) participated in the study. The study was approved by the local ethical committee and informed consent was obtained from all volunteers. Subjects were seated 100 cm in front of a computer monitor. Alphanumeric characters ('P', 'R', 'S', 'F', 'G', '1', '2', '4', '5', '7'), extending $2 \text{ cm} \times 1 \text{ cm}$, were presented in the center of the screen. The characters (stimuli) were displayed in regular or mirror-reversed form, rotated clockwise by 0° (no rotation), 60° , or 120° ; they were presented in random order, with a total of 180 (3×60) trials per subject. Subjects indicated, with a key press, in which form the characters were presented using a two-alternative forced choice: regular vs. mirror. Accuracy of the judgment and RT were registered. Subjects were instructed to focus on accuracy but to respond as quickly as possible. The trial started with presenting a central fixation-point, which was replaced after 1000–1500 ms by a target character. The stimulus remained displayed until the subject's response. A series of practice trials was administered before the experiment. Recording of ERPs proceeded only if the subject made at least 19 of 20 (95%) correct consecutive judgments.

2.2. ERP recording

ERPs were recorded using standard procedures (Picton et al., 2000) from positions P3, P4, T3, T4, F3, F4, referenced to linked mastoids. The signal was analog filtered (0.1–70 Hz), A/D converted with a sampling rate of 1000 Hz and 14 bit precision, and digitally filtered in the range 0.5–45 Hz. An epoch lasted from -500 to 1500 ms, relative to the stimulus onset. Trials with EEG artifacts (identified by inspection), incorrect trials and trials with exceptionally short (<300 ms) or long RTs (>3000 ms) were removed. Mean activity prior to stimulus onset (-500 to 0 ms) was subtracted from the signal. Signals were averaged with respect to two time points: stimulus onset (ERP_{ONSET}) and response time (ERP_{RT}). Average ERP_{ONSET} amplitude was calculated in the interval between 350 and 700 ms, which has been previously attributed to mental rotation process (Peronnet & Farah, 1989; see Introduction). Due to limited epoch duration, trials with RTs ranging between 600 and 1500 ms were selected and an average ERP_{RT} amplitude was computed in the interval between 600 and 250 ms before the key press. Critically, this time interval is expected to include the mental rotation process, since ~ 50 – 100 ms are required for subsequent decision and response selection and ~ 150 ms for motor programming (Mordkoff & Grosjean, 2001; Masaki, Wild-Wall, Sangals, & Sommer, 2004; Heil, 2002). Mean number of trials to average per subject and condition were 51 ± 5 for ERP_{ONSET} and 44 ± 7 for ERP_{RT} .

2.3. Data analysis

A one-way repeated measures analysis of variance (RM ANOVA) was calculated for the RT data and a two-way RM ANOVA (factors Angle: $0^\circ/60^\circ/120^\circ$ and Channel: P3/P4) was calculated for the ERP data. The Greenhouse–Geisser correction for sphericity violation was applied when appropriate. Correlations between ERP amplitude and RT as well as RT dispersion (interquartile range) were assessed by the Pearson correlation coefficient. Individual performance in mental rotation was fitted by a linear regression model in the form: $RT = \beta_0 + \beta_1 \times ERP_{RT} + \beta_2 \times ERP_{RT0^\circ} + \beta_3 \times RT_{0^\circ}$, where RT and ERP_{RT} are, respectively, the subject's RT and ERP_{RT} amplitude for rotated characters; and RT_{0° and ERP_{RT0° are, respectively, the subject's RT and ERP_{RT} amplitude for unrotated stimuli (control condition). The model was further adjusted by entering the stimulus rotation-angle as additional covariate.

3. Results

As typically observed for mental rotation, RT increased with an increasing angle of character rotation (Table 1; $F_{2,13} = 27.428$,

Table 1
Mean performance in mental rotation of alphanumeric characters ($N = 14$)

	0°	60°	120°
Response time (mean \pm S.D., ms)	972 ± 161	1045 ± 180	1264 ± 288
Accuracy (mean \pm S.D., %)	98.8 ± 1.7	98.0 ± 2.5	94.7 ± 4.0

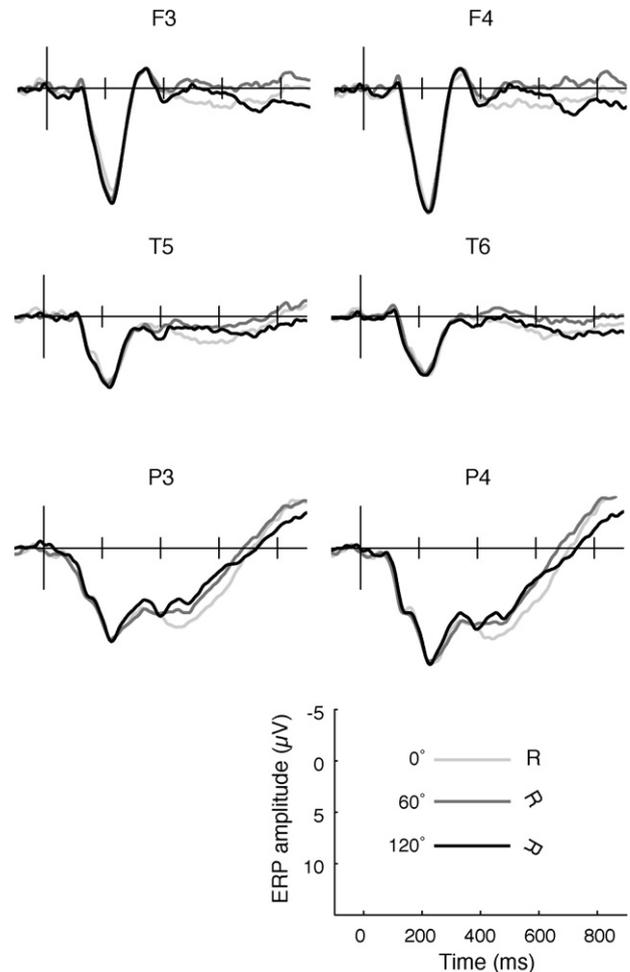


Fig. 1. Event-related potentials time-locked to the onset of visual stimuli (ERP_{ONSET}) during the mental rotation of alphanumeric characters. Grand average ERP_{ONSET} ($N = 14$) in all channels.

$\varepsilon = 0.581$, $P < 0.001$). Response accuracy was very high across all subjects and conditions (Table 1) so that RT was the only useful index of task performance.

Fig. 1 shows grand-average ERPs for signals time-locked to the onset of rotated characters in all leads. The ERP_{ONSET} amplitude varied systematically as a function of the angular deviation of a stimulus only in the parietal channels (P3, P4). Therefore, further analysis was restricted to the parietal leads. As expected from previous studies, the amplitude of the parietal ERP_{ONSET} , measured in the interval 350–700 ms from the stimulus onset, was more negative for the larger rotation angle (Fig. 2A; factor Angle: $F_{2,26} = 3.687$, $\varepsilon = 0.915$, $P = 0.044$). Since the Channel \times Angle interaction was not significant, indicating similar effects of stimulus rotation in both parietal channels, we pooled the data from the two parietal electrodes. We found that absolute mean ERP_{ONSET} amplitude was negatively correlated with the interquartile range of RT (IQR_{RT} ; $r = -0.340$, $P = 0.028$, $N = 42$). In addition, IQR_{RT} significantly increased with an increasing angle of rotation (0° : 266 ± 109 ms, 60° : 375 ± 162 ms, 120° : 437 ± 176 ms; $F_{2,13} = 10.147$, $\varepsilon = 0.876$, $P < 0.001$).

More importantly, we found no correlation between RT to the rotated stimuli and the ERP_{ONSET} amplitude (Fig. 2B; $r = -0.082$, $P = 0.678$, $N = 28$). In order to control for potential non-specific influences of inter-individual differences in psychomotor speed and mean ERP magnitude, both ERP_{ONSET} and RT data were refer-

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