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Research report

Fast and slow brain rhythms in rule/expectation violation tasks: Focusing on evaluation processes by excluding motor action

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ABSTRACT

Theta rhythm has been connected to ERP components such as the error-related negativity (ERN) and the feedback-related negativity (FRN). The nature of this theta activity is still unclear, that is, whether it is related to error detection, conflict between responses or reinforcement learning processes. We examined slow (e.g., theta) and fast (e.g., gamma) brain rhythms related to rule violation. A time–frequency decomposition analysis on a wide range of frequencies band (0–95 Hz) indicated that the theta activity relates to evaluation processes, regardless of motor/action processes. Similarities between the theta activities found in rule-violation tasks and in tasks eliciting ERN/FRN suggest that this theta activity reflects the operation of general evaluation mechanisms. Moreover, significant effects were found also in fast brain rhythms. These effects might be related to the synchronization between different types of cognitive processes involving the fulfillment of a task (e.g., working memory, visual perception, mathematical calculation, etc.).

1. Introduction

From early childhood through adulthood and old age, a person needs to adapt and adjust to the surrounding. Monitoring of self-performance, meaning the capability to evaluate outcomes of self-actions and differentiate between correct and erroneous information, is a crucial process to this adjustment. Electro-physiological and brain-imaging studies have suggested that monitoring of self-performance, such as detecting an error response or evaluating outcomes and feedbacks, is related to theta activity involving the anterior cingulated cortex (ACC) [1–6].

Event related potentials (ERPs) studies of self-performance monitoring have investigated two main ERP components: the error-related negativity (ERN) and the feedback-related negativity (FRN). Both components seem to involve the ACC and have been related to theta activity (4–8 Hz) [5–8]. The ERN is a negative component over the medial frontal cortex that follows error commission in choice reaction tasks, even in the absence of explicit performance feedback [3,5,7,9–13], and the FRN relates to a negative electrical deflection similar to ERN, that follows feedback associated with unfavorable outcomes (e.g., winnings/losses) [6,8,14]. [15] suggested that both ERN and FRN components are functionally similar, and reflect the operation of an error-processing system [3,9–11,13,15].

However, other studies have suggested that the role of these components is not exclusively related to error detection, and involves response conflict monitoring [1,6,16] or/and reinforcement learning signals [8,14,17]. Moreover, a study of Yeung et al. [6] suggests that during errors, conflict arises between the executed incorrect response and activation of the correct response due to ongoing stimulus evaluation. Therefore, the response conflict theory can account for both error and conflict detection tasks [6]. Nevertheless, this theory cannot explain the finding of FRN in the absence of overt responses, as has been reported by Yeung et al. [8]. In their study the results were explained by adopting the reinforcement learning theory, which suggests that the ACC involves processing motivationally significant information concerning rewards and punishments, and therefore can explain these components even in the absence of overt responses [8]. However, a new discrepancy arises in this case, since the view of the negative medio-frontal components as related to motivational processes cannot explain the appearance of such components in situations where there is no motivational aspect, such as in "pure" conflict situations eliciting the N2 component in the flanker task [6,18].

A recent study of Tzur and Berger [19] showed that rule-violation tasks, such as distinguishing between correct and incorrect simple mathematical equations (e.g., "1 + 2 = ", correct solution "3" or incorrect solution "8"), are related to theta activity (4–8 Hz) that seems to involve the ACC. Their time frequency analysis suggested

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a phase-lock increase in theta power for incorrect solutions compared to correct ones. Tzur and Berger [19] suggested that this effect might be related to a violation of expectation, that is, a conflict arising between the expected rule (e.g., "1 + 2 = 3") and the presented information, which violated that rule (e.g., "1 + 2 = 8"). This idea was based on the conflict monitoring theory, according to which, as mentioned, the ACC monitors for the presence of conflict between simultaneously active but incompatible processing streams [1,6,16,20,21].

Tzur and Berger [19] proposed that this view of the ACC function, as reflected in theta activity, should be expanded and include not only the monitoring of response-conflicts, but also the monitoring of conflict between expectations. Nevertheless, it could still be argued that the theta activity observed by Tzur and Berger [19] relates to motor response planning and/or executing processes, since the task that was used included a verification motor response (e.g., press key "1" for the correct solution and key "4" for the incorrect solution).

Therefore, the first aim of the present study was to compare the effect of a phase-lock increase in theta activity (4–8 Hz) for an incorrect solution in a rule-violation task [19], to the one found even in the complete absence of overt responses [22]. Finding similar patterns of theta activity would strongly support the idea that this phase-lock theta activity relates also to an evaluation process, regardless of any motor response planning and/or execution. Participants were presented with mathematical equations, and were asked to distinguish between correct and incorrect solutions without any overt response, that is, just by looking passively at the mathematical exercises and their presented solutions (this will be referred to as the *passive group*).

The second aim was to evaluate similarities found between time–frequency analyses of rule-violation tasks (from this study) and analyses related to the ERN and FRN components [5,7,8,14]. Finding such similarities would suggest that these neural activities might reflect the operation of a generic evaluation mechanism, meaning that the cognitive processes which are related to the ERN and FRN [5,15,17] are also involved in situations of rule-violation.

The EEG (electroencephalogram) data collected from the passive group was partially obtained from the study of Berger et al. [22], and was analyzed with wider time–frequency analyses (i.e., analyzing the relative power and phase synchrony of frequency bands ranging from 1 to 95 Hz). These analyses were used also on the EEG data collected from Tzur and Berger [19] (this EEG data will be referred to as the *active group*), which were compared to the passive group analyses.

We hypothesized that the time–frequency analyses of both groups (passive and active) would reflect similar neural processing patterns, related to an increase in theta frequency band (4–8 Hz) phase-lock power and phase synchrony, for incorrect solutions compared to correct ones.

We used a time–frequency decomposition analysis, from which one can obtain estimates of instantaneous power, that is, energy at different frequencies [23], and inter-trial phase synchrony, that is, consistency of oscillation onset across trials [24]. This was done on a wide frequency band (1–95 Hz), including upper gamma, which to our knowledge has not yet been used to examine rule-violation tasks. This new approach of time–frequency analyses has presented a novel view of understanding brain activity related to cognitive processes, beyond the classic averaged ERPs [25,26]. Examining neural synchronization and its related energy at a wider frequency band (1–95 Hz) should contribute to a better understanding of these neural cognitive processes. Cohen et al. [14] reported an increase in power and phase synchrony in both theta and gamma frequency bands (over the medial frontal cortex) when participants received negative feedback (i.e., FRN) on their actions. Following this and our second aim, we expected to find an increased power and phase synchrony in the gamma frequency band as well.

2. Materials and methods

2.1. Participants

There were 2 groups of participants: *passive group*—28 participants (20 females and 8 males), with a mean age of 24.16 years (SD = 2.35); *active group* (from Tzur and Berger, [19])—17 participants (14 females and 3 males), with a mean age of 23.8 years (SD = 1.3). All participants were right-handed and were students at Ben-Gurion University of the Negev. They were all healthy with no history of neurological illnesses and had normal or corrected-to-normal vision. Participants gave informed consent and participated in the study as partial fulfillment of course requirements.

2.2. Procedure

Participants were presented with 360 trials (plus 30 practice trials) of simple mathematical equations (addition or subtraction), which were followed by either correct solutions (180 trials) or incorrect solutions (180 trials). Within the incorrect solution condition, there were three possible levels of deviation, appearing with equal probability. For example, for the equation "1 + 2 =", the incorrect solution could be either "4" (L1), "6" (L3) or "8" (L5). The number of positive and negative deviations (of incorrect solutions from correct ones) was equal. Equations that had identical operands (e.g., 3 + 3, 4 + 4) were excluded. The 360 trials were presented in a random order in four blocks (45 correct and 45 incorrect trials in each block).

Each trial began with a fixation point (500 ms), followed by an equation (1,500 ms), then a black screen (600 ms—for baseline calculation), and ended with a solution (1,500 ms). Random inter-trial intervals (ITIs; 200/400/600 ms) were inserted in order to reduce a monotonous task rhythm.

Participants were seated 60 cm in front of a computer monitor and asked to be as relaxed as possible in order to reduce muscle tension. They were told at the beginning of the experiment that they were participating in cognitive research in the field of numerical processing, and that they would be presented with simple mathematical equations followed by either correct or incorrect solutions. They were asked to silently distinguish between correct and incorrect solutions, that is, just by looking at exercises and the presented solution without any overt response.

Except for the absence of an overt response, this passive procedure is identical to the active one used by Tzur and Berger [19].

2.3. Electroencephalogram (EEG) recording

The EEG was recorded from 128 scalp sites using the EGI Geodesic Sensor net and system [27]. Electrode impedances were kept below 40 kΩ, an acceptable level for this system [28]. All channels were referenced to the Cz channel and data was collected using a 0.1–100 Hz bandpass filter. Signals were collected at 250 samples per second and digitized with a 16-bit A/D converter.

2.4. Time–frequency analysis

Time–frequency analysis of the data was conducted using a wavelet-based analysis [23,24]. Before the wavelet analysis, each participant's raw (0.1–100 Hz) EEG data was segmented into trials, time-locked to the presentation of the solution. The segmented data was inspected for artifacts (e.g., bad-channels resulting from channel-saturation, muscle movement, etc.) while excluding channels within each segment that exceeded the fast average amplitude of 200 μV or the differential average amplitude of 100 μV. Segments having 10 or more bad channels were excluded, and segments with fewer than 10 bad channels were included after replacing the bad-channel data with spherical interpolation of the neighboring channel values.

Prior to wavelet analysis, the data of each trial was re-referenced to the average of all of the sensors at each time point. For calculating the phase-lock power values, trials were averaged into correct and three incorrect (i.e., L1, L3, L5) conditions (stimulus-locked to the solution presentation) [29]. For calculating the total power (that is, phase- and non-phase-lock) and phase synchrony values between trials [24,30], trials were kept unaveraged. Following this, a family of Morlet wavelets was constructed at intervals of 0.5 Hz frequency, ranging from 1 to 95 Hz. Our wavelet family was computed using a f_0/σ_f ratio of 7 [23,31]. The power values (i.e., squared amplitude) and phase synchrony values (range from "0"—no synchrony, to "1"—full synchrony) were normalized with respect to a −200 to 0 ms pre-solution baseline. The time–frequency analysis was conducted for the frequency bands raging from 1 to 45 Hz and 65 to 95 Hz, excluding the 45–65 Hz band, since this was in the range of our electrical power network frequency and might have been vulnerable to electromagnetic interference (EMI).

The statistical analyses were done on the mean of a group of four channels, located between Cz and Fz of the 10–20 system (of electrode placement). This localization is comparable to the ERN and FRN components [5,8,14], see Fig. 1 (top row).

The wavelet power and phase synchrony analyses of both groups (active and passive) were conducted in the following way: For each condition (i.e., correct, L1, L3, L5), the adaptive-mean (calculated from a time-window of ±50 ms centered around a local maxima) of the power and phase synchrony from each frequency band