INT. J. BIOAUTOMATION, 2018, **22**(3), 253-262 doi: 10.7546/ijba.2018.22.3.253-262

Effect of Proactive Mode of Processing on Event-related Oscillatory Brain Responses in Children

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Received: October 11, 2017 **Accepted: August 30, 2018**

Published: September 30, 2018

Abstract: *Proactive cognition is characterized by the formation and active maintenance of an internal task representation. The aim of this study was to explore if the internal task representation might affect the processing of incoming stimuli. For that aim, the effects of proactive and reactive modes of processing on sensory and cognitive information processing were compared by using event-related oscillatory responses in a developmental model. Thirty six children aged 7-10 years were studied in a sensorimotor task with fixed stimulus sequences. Children were divided into two groups according to their proactive or reactive mode. Auditory event-related potentials were recorded and decomposed in the time-frequency domain to analyze amplitude and phase synchronization of oscillatory responses. Major results demonstrated that proactive mode of processing was characterized by enhanced pre-stimulus theta activity accompanied by a significant decrease of the temporal synchronization of event-related theta/alpha oscillations in the first 300 ms after stimulus. These results provide evidence that maintaining internal task representations in working memory engages oscillatory circuits, which can modulate the processing of incoming sensory information.*

Keywords: *Time-frequency ERP components, Children, Cognition, Auditory modality.*

Introduction

Goal maintenance is a critical component of cognitive control that is required for successful performance in a wide variety of cognitive situations [2]. Braver et al. [3] suggest that there are two distinct cognitive processes that activate goal-relevant information to enable behavioral control. The first, proactive control, acts by actively maintaining goal-related information. The second, reactive control, acts by deriving goal-related information from the environmental context at the time a behavioral decision is required. Thus, the key neurophysiological difference between the two processing modes is the presence or not of the internal goal (task) representation. While the effects of the internal goal representation on behavior are well documented, the neurophysiological grounds of these effects are still to be clarified [6]. The present study aims at elucidating whether and how the continuous maintenance of an active internal task representation may affect sensory and cognitive stimulus evaluation. Previous research has typically applied cues in sensorimotor tasks, which either guided predictably subsequent performance or induced conflict by not informing correctly about upcoming events [5]. This approach relies largely on cognitive flexibility, which may modulate transiently the stability of internal goal representation. To overcome confounding from changing context, the present study used the design of the serial response time task (SRTT) [17, 22], where a fixed stimulus-response sequence could be used to guide and optimize performance in a sustained and durable way. In addition, a developmental model of 7-10 year-old children was employed to enable a condition, in which the capacity to form and sustain the internal task representation may not be developed in some children, to be contrasted with the condition, in which this ability has reached mature functionality [21, 22]. Finally, in the present study, the neurophysiologic effects of proactive and reactive control were assessed by analyzing event-related potentials (ERPs) which are well documented to reflect sensory and cognitive stimulus processing in both adults (e.g., [16]) and children [25]. It has been established that when analyzing ERPs in the time-frequency domain, new information about event processing can be obtained in terms of underlying frequency networks and their functional synchronization [13, 23, 25]. Therefore, ERPs were analyzed in both the time and time-frequency domains.

Materials and methods

Participants

A group of thirty-six normal healthy children from 7 to 10 years of age (20 boys) participated in the present study. Children had similar socio-economic status, IQ scores close to normal for their age, and were right-handed. Interviews with parents and teachers excluded any history of neurologic or psychiatric disorders, attentional or behavioral disturbances, or learning problems. All subjects were paid for their participation in the study.

Stimuli and procedure

Computer-generated auditory stimuli were delivered with intensity of 60 dB sound pressure level (SPL), duration of 50 ms (rise/fall time 10 ms), and random inter-stimulus intervals between 3.5 and 6.5 s. Participants executed SRTT, in which 800 Hz (Low, L) and 1200 Hz (High, H) tones were presented with equal probability ($p = 0.5$) and with determined sequence of appearance of six stimuli (H-H-L-H-L-L), which was repeated 16 times in a single run. Children were instructed to press a button to the low tones (targets) with the dominant (right) hand as quickly and accurately as possible. They were informed that the stimuli had a regular repeatable pattern of occurrence and were instructed to pay attention in order to comprehend it. In case of comprehending stimulus sequence, children were asked to announce verbally the moment of comprehension and to continue task execution to the end. During the experiment, EEG was recorded with children keeping their eyes closed and reaction times (RTs) to targets were measured. In a separate session, a simple reaction task (SRT) was performed.

Group selection: reactive vs. proactive mode of processing

According to their performance, participants were assigned to a group with reactive (RE) or with proactive (PRO) mode of processing. Two criteria were used for group selection: (1) Explicit knowledge about the regular sequence in the SRTT, and (2) RT decrease after regularity comprehension as compared to RTs before regularity comprehension. Children recovering the full structure of the regularity would have maintained an internal representation of stimulus sequence to optimize their behavior by predicting next stimulus appearance, which would shorten their RTs after regularity comprehension. This processing strategy refers to *proactive mode of processing*, opposite to the *reactive mode* of processing where a mental representation of stimulus sequence is not created so that responses are only selected after stimulus appearance. Therefore, only those children with explicit knowledge about stimulus regularity were selected for the PRO group who reduced RTs with 100-200 ms after comprehension. This final group selection resulted in 19 children with reactive and 17 children with proactive mode of processing. Table 1 demonstrates that children from the PRO group tended to be older than those from the RE group ($F(1/35) = 3.9$, $p = 0.056$) and did not differ significantly with respect to gender distribution ($\chi^2(1/36) = 0.1$, $p > 7$). Fig. 1 illustrates the validation of group selection. In the PRO group, RTs were significantly shorter after than before sequence comprehension (*F*(1/16) = 286.5, $p < 0.0001$), although RTs after comprehension were still longer than simple RTs (*F*(1/16) = 7.2, $p = 0.02$). Accordingly, the speed of responses did not differ between the two groups before comprehension (*F*(1/35) = 0.02, $p > 0.8$), but it was significantly faster in the PRO than in the RE group after comprehension (*F*(1/35) = 11.4, $p = 0.002$).

Table 1. Distribution of participants in the study

	Proactive	**Reactive**
Number	17	19
Mean age (months)	105	97
Age range (months)	86-120	87-111
Gender (boys/girls)	8/9	10/9

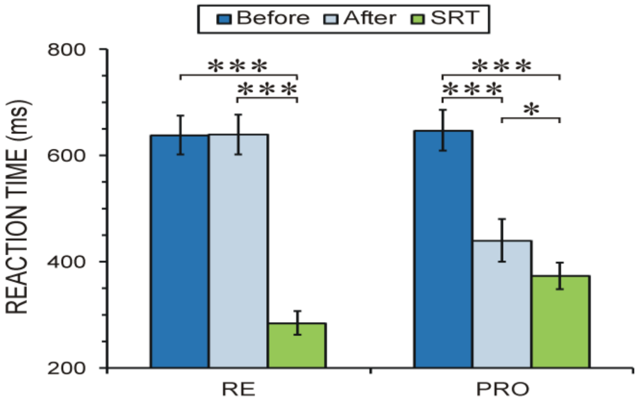

Fig. 1 Mean reaction time ± standard error (SE) for the two groups,
with reactive strategy and with proactive strategy,
in the SRTT (before and after comprehension of stimulus regularity),
and in SRT. * $p \leq 0.05$, *** $p \leq 0.001$.

Data collection and pre-processing

EEG data were recorded at midline frontal, central and parietal electrodes (Fz, Cz and Pz), with linked mastoids as a reference, forehead electrode as ground, and electrode impedance less than 10 kΩ. The electrooculogram (EOG) also was recorded [9]. EEG was amplified with cut-off frequencies of 0.5 and 70 Hz and digitized with a sampling rate of 250 p.s. Raw EEG traces with a length of 1024 ms before and after stimulus were selected for analysis of average and single-sweep ERPs. Raw single sweeps were inspected visually offline to eliminate EEG segments contaminated with blink, muscular, or any other type of artifact activity, with any EEG or EOG trial exceeding ±100 μV also being excluded. Thus, the number of artifact-free sweeps analyzed for each subject in each stimulus condition was between 35 and 47.

Analysis of averaged ERPs

Individual averaged ERPs were computed for each lead and stimulus condition. A 200 ms interval before stimulus was used as a baseline. Fig. 2 demonstrates that auditory ERPs in children during explicit learning of auditory regularities were characterized with N1, P2, N2 and P3 components followed by a slow negative wave at anterior locations. For analysis in the time domain, peak amplitudes of N1, P2, N2 and P3 components were measured according to the baseline.

To identify major phase-synchronized frequency components, averaged wide-band (0.5-14 Hz) ERPs were decomposed in the time–frequency domain by means of a continuous wavelet transform (details in [24]). Fig. 2 illustrates time-frequency decomposition plots of grand average ERPs and shows that ERPs comprised of a major phase-locked time-frequency component from the theta/slow alpha band (4-10 Hz) which appeared in the first 300 ms after stimulus. Also, a phase-synchronized delta (0.5-4 Hz) component was generated in a broad time range after stimulus. With this regard, single-sweep analyses of ERPs were performed for theta/alpha and delta frequency ranges.

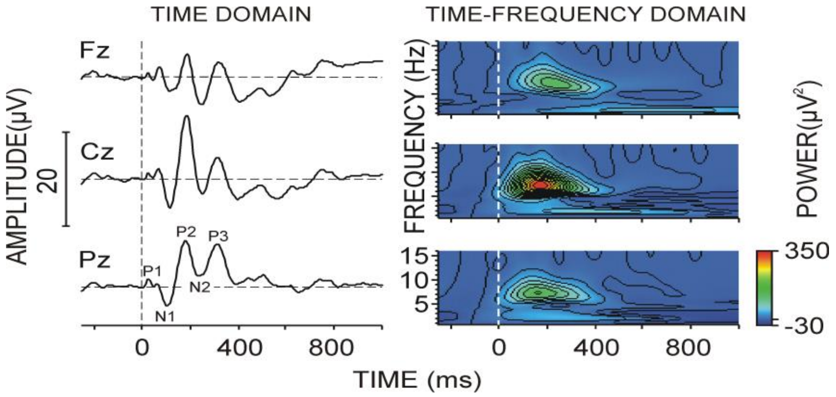

Fig. 2 Event-related potentials averaged in time domain (left) and their time-frequency decompositions (right). Stimulus occurs at 0 ms. Positivity upwards.

Single-sweep analysis

Single-sweep ERPs were band-pass filtered in delta (0.5-4 Hz), theta (4-7 Hz), slow (7-10 Hz) and fast (10-14 Hz) alpha frequency ranges by means of a modified linear band-pass filter with zero phase shift. Fig. 3 presents a schematic illustration of the methodology used to quantify amplitude variations independently of phase-synchronization of event-related oscillations (details in [12, 23]).

Amplitude

Amplitude was analyzed for pre- and post-stimulus epochs. The amplitude of pre-stimulus activity (500 ms before stimulus) was calculated as the root mean square (*rms*) value of the ongoing EEG (Fig. 3A) for theta, slow and fast alpha frequency bands. These frequency bands were chosen to reflect the effects of the mode of processing on preparatory EEG activity in relevant frequency bands established previously (e.g., [8, 15]). As shown in Fig. 3A, the magnitude of single oscillatory responses after stimulus was measured as the difference between the most positive and the most negative oscillatory deflections (Amax), maximal peak-to-peak amplitude, in the time window 0-300 ms after stimulus on-set. Because of their broad time localization single delta responses were measured as the mean amplitude values in consecutive time windows 0-200, 200-400, 400-600, and 600-800 ms after stimulus.

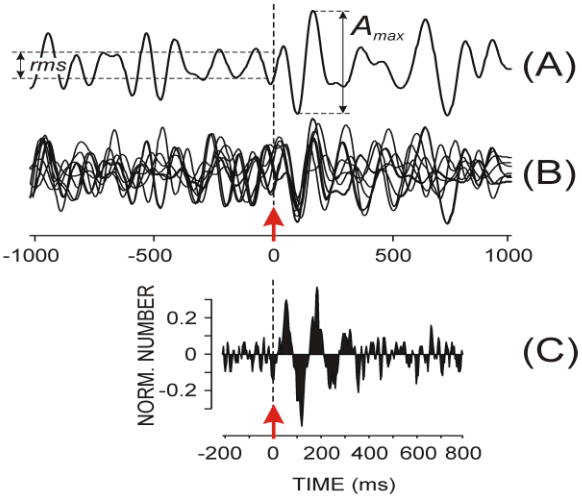

Fig. 3 Method for single sweep analysis and measurable parameters:
(A) amplitude measures: root mean square amplitude of the pre-stimulis activity (*rms*),
and maximal peak-to-peak amplitude (Amax) in the post-stimulus period;
(B) example for phase synchronization of superimposed single sweeps
filtered in the theta frequency range; (C) single-sweep wave identification histogram.
Stimulus occurs at 0 ms.

Phase-synchronization

Fig. 3B shows several representative raw-data sweeps which are superimposed to visualize the stimulus-locked synchronization. For a quantitative evaluation of phase-locking, a modification of the single-sweep wave identification (SSWI) method was used [12]. As a result, a histogram was built and absolute integral values of the normalized (to the number of single-sweeps included) SSWI-histograms were calculated for the time window 0-300 ms post-stimulus, thereby giving information about the strength of single-sweep phase-locking in the above mentioned post-stimulus period (Fig. 3C). These measures were used for analysis of the phase-locking of theta/alpha responses, whereas for analysis of delta phase-locking, the maximal values of SSWI histograms in the averaged waveform in the interval 100-500 ms were measured, consistent with the length of the slow delta activity.

Statistical analysis

Measurable parameters of time-domain ERPs were N1, P2, N2 and P3 amplitudes. Measurable parameters of time-frequency ERPs were pre-stimulus *rms*-values, maximal peak-to-peak single-response magnitudes, and inter-trial phase-locking. All parameters were measured for each subject, stimulus type, and electrode and were subjected to a three-way analysis of covariance (ANCOVA) with repeated measures with two covariates. The between-subjects factor was Group (RE vs. PRO). The within-subjects factors were Stimulus (non-target vs. target) and Lead (Fz, Cz and Pz). Since children from the PRO group tended to be older than those from the RE group (Table 1) and gender in children has been previously shown to affect time and time-frequency ERPs [7, 17, 18], age in months and gender were included as covariates. The Greenhouse-Geisser correction was applied to the Lead factor with more than two levels. In the results, only main and interactive effects of Group (processing mode) will be presented.

Results

Pre-stimulus EEG activity

Significant effects of Group were yielded only for the theta frequency band, for which a significant Group×Stimulus×Lead interaction was found ($F(2/64) = 3.7$, $p = 0.03$). Fig. 4A illustrates this interaction and shows that pre-stimulus theta activity was larger in the PRO than in the RE group, but this effect was only expressed at centro-parietal electrodes and was more pronounced for targets than non-targets.

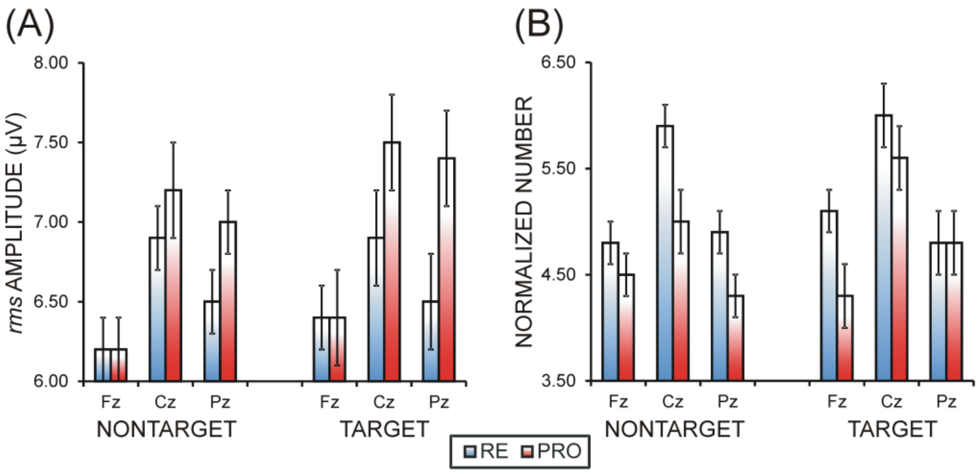

Fig. 4 Group mean values ± SE for the two groups (reactive, RE, and proactive, PRO), for nontargets and targets at three electrodes (Fz, Cz, Pz): (A) root mean square amplitude; (B) phase-locking measured as normalized number of synchronized waves in the single epochs.

Time-domain ERPs

For none of the time-domain components was any significant main or interactive effect of the Group factor found ($p > 0.1$).

Time-frequency ERPs

Amplitude

Single-sweep amplitudes of theta/alpha and delta time-frequency components did not differentiate the mode of processing as reflected by non-significant main and interactive Group effects ($p > 0.2$).

Phase-synchronization

In contrast to amplitude, the phase-locking of theta/alpha ERP component was substantially reduced in children from the PRO as compared to the RE group, but differently for targets and non-targets (Group×Stimulus×Lead, $F(2/64) = 5.6$, $p = 0.006$) (Fig. 4B). For non-targets, the proactive strategy was associated with phase-locking reduction at central and parietal locations, whereas for targets, phase-locking was significantly reduced at the frontal location, as revealed by MANCOVA at single electrodes ($F(1/35) > 4.0$, $p < 0.05$). No Group effects were found for the synchronization of the delta responses.

Regression analysis

A multiple regression stepwise analysis was run to establish if RT decrease after sequence comprehension would be predicted by the variables differentiating the RE and PRO groups, theta *rms* amplitude and theta/alpha phase-locking. The reduced theta/alpha phase-locking was selected by the model as a predictor of response speeding after sequence comprehension (R = 0.516, B = –65.2, $Beta$ = –0.516, t = –2.8, p = 0.01, $F(1/22)$ = 7.9, p = 0.01). No correlations existed between theta *rms* amplitude and theta/alpha phase-locking.

Discussion

The results of the present study reveal that the mode of cognitive control modulates (1) the state of event expectation as reflected by pre-stimulus theta activity, and (2) the early mechanisms of stimulus processing as reflected by phase-stability of event-related theta/alpha oscillations in the first 300 ms after stimulus. The reliability of these findings is supported by a stringent group selection based on the application of two criteria, explicit knowledge about task structure and performance speeding, both of which verify the functioning of a task representation. Also, the ERPs elicited in the present SRTT condition are fully consistent with ERP component structure and frequency content reported in children at that age in similar sensorimotor tasks [17, 18, 25, 26]. In addition, the covariates in the statistical design controlled for possible confounding effects of developmental and gender-related changes in spectral EEG activity and ERP parameters.

The observation that proactive control acts already during stimulus/response expectation is in line with findings on the contingent negative variation (CNV) in cognitive control conditions (e.g., [11]). The CNV was not analyzed here due to the application of random inter-stimulus intervals. The current analysis revealed that proactive control was accompanied by an increase in theta activity at posterior locations before both targets and non-targets. Increased theta activity has been regarded as a cognitive control signal originating from the mid-frontal and dorsolateral frontal regions [4], but the currently found posterior distribution is not consistent with this interpretation. Rather, the increased pre-stimulus theta in the proactive group may reflect a pre-activation of motor-related networks because increased pre-stimulus theta has been reported to correlate with motor response speeding [8], as well as with failed response inhibition in sensorimotor tasks [1]. Alternatively, basing on reports of increased theta/alpha activity during retention of memorized information [10] and strong associations between ongoing theta oscillations and successful memory [20], the increased pre-stimulus theta may signify the active maintenance of task-related information in working memory during proactively controlled preparation [15].

The phase-locking analysis further reveals that the temporal stability of theta/alpha responses is significantly weaker under proactive as compared to reactive control. Critically, the destabilization of phase synchronization emerged within the first 300 ms after stimulus when early processing mechanisms take place. These effects could not be detected by time-domain ERP components possibly because of their complex heterogeneous composition not allowing for a precise extraction of overlapping phenomena [13].The early destabilization may not indicate impaired auditory perception as evidenced by superior performance after sequence comprehension. Rather, it can be explained with an overlapping interference. One source is an autonomic response-related theta pattern [14, 24], which may emerge earlier for faster motor responses in the proactive group [19] and may interact with the preceding stimulus-related theta/alpha oscillations. Indeed, according to the present results, performance speeding after regularity comprehension was predicted by a decrease of theta/alpha phase-locking. However, the early temporal desynchronization was pronounced not only for target (motor-related) but also for non-target (motor-unrelated) stimuli, suggesting that a motor-related pattern is not the only factor. A complex interference with pre-activated oscillatory networks well may be an additional source of the temporal destabilization of stimulus-locked theta/alpha oscillations. This assumption is supported by the currently observed modulations of pre-stimulus activity during proactive control and previously established engagement of theta networks during sustained working memory [10]. However, as indexed by RT in the proactive group after regularity comprehension, the neural task representation may not be sustained with strong stability in children thus increasing the internal representation variability. Overlapping with a variable pattern might have reduced the coupling of early theta/alpha oscillations.

Conclusion

Using a developmental model the present study provides evidence that maintaining internal task representations in working memory modulates both the background activity and the processing of incoming sensory information.

Acknowledgements

Work was supported by the National Research Fund (Project DN 13/7-2017) and by the Institute of Neurobiology at the Bulgarian Academy of Sciences, Sofia, Bulgaria. Authors are thankful to Lora Lyamova for help in data collection and processing.

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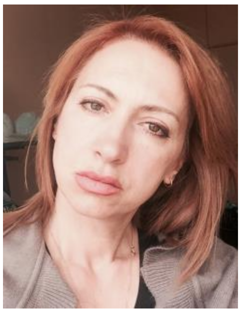

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