

# EEG-Rhythm Dynamics during a 2-back Working Memory Task and Performance

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**Abstract**—Working memory is an essential component of human cognition and determines to a large extent an individual's intellectual ability. In this paper, the human brain oscillatory response system associated with working memory performance is evaluated in an experimental and analysis setting involving 10 volunteers performing a visual 2-back task. Event-related dynamics in three bands: theta (3.5 - 7 Hz), alpha (7.5 - 12 Hz) and upper beta (17 - 29 Hz) at 32 locations distributed over the scalp are examined analyzing the event-related desynchronization (ERD)/synchronization (ERS) in these bands. Both global dynamics as well as trial- and subject-specific trends were considered. The overall across participants trend shows that the theta level synchronizes during working memory engagement, whereas beta and alpha desynchronizes. While common features seem to emerge, different subjects exhibit equally significant but opposite in direction correlation between reaction time and power dynamics.

## I. INTRODUCTION

Working memory (WM) is the brain system involved in the temporary storage and manipulation of information and coordination of resources needed for various cognitive processes such as learning, reasoning and language comprehension [1]. It has been suggested that various selectively distributed oscillatory systems control the integrative brain functions at all sensory and cognitive levels, playing an important role in functional communication in the brain [2]. Scalp recorded electroencephalogram (EEG) can reveal the functional role and the interaction between the different oscillatory systems involved in various mental states and processes. Frequency specific changes of the ongoing EEG activity reflect the decrease or increase in synchrony of the underlying neuronal populations and manifest as decreases or increases of power in given EEG frequency bands [3]. When those changes are time-locked to a specific event they are called the event-related desynchronization (ERD) or synchronization (ERS).

The frequency band most often linked to working memory and mental effort in general is the theta band (4 - 8 Hz) [4]. Increases in theta band power have been related to episodic memory demands [5]. Increases in theta oscillatory responses also reflect different memory load [6], [7] and task demands [8]. Correlations between theta band synchronization and performance have also been reported [9]. Alpha rhythms (8 - 12 Hz) often behave in the opposite way. Increasing task demands are associated with decrease in alpha power [5],

[7]. High tonic alpha band power levels are also significantly correlated with increased performance [9]. Beta oscillations (12 - 30 Hz) initially related to motor processes, lately have also been found in association with cognitive processing. Early appearing beta ERD has been observed, becoming longer with increased memory load [10].

A majority of the studies studying event-related dynamics rely on trial averaging, which assumes that most trials express single mode of activity time-locked to an event of interest plus some background activity. As [4] suggests, however, different modes of activity, due to task-unrelated mental effort or specific performance strategies for example, may occur in different trials. Therefore, the trial variability may be reflecting other factors accompanying the task execution. Thus, it is important to study the event-related brain dynamics on a per trial basis and try to identify possible features that would explain the inter-trial variability. Especially interesting is the question how differences in performance are manifested in the brain dynamics modulations.

The goal of this study is to evaluate the human brain oscillatory response system associated with working memory performance. Considering the rhythmic nature of the signals, we go beyond the studies that use event-related potentials (ERPs) and investigate the event-related power changes in three bands corresponding to the classical theta, alpha, and upper beta frequency bands both as global and trial-specific dynamics. We also study the link between the neurophysiological responses and their behavioral correlates, performance in particular.

This paper is organized as follows. First, we introduce our methods in Section II. Section III explains the data analysis and Section IV presents the results and discussion. We conclude the paper in Section V.

## II. METHODS

### A. Participants

Ten healthy volunteers (5 males and 5 females) in their twenties (average age 24 years) with normal or corrected to normal vision participated in the study. To minimize the effect of hemispheric biases, only right handed subjects were considered for participation. Half of the participants were asked to perform the experiment in the morning and half in the afternoon. All participants signed an informed consent and were rewarded for their participation at the end of the study.

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## B. Experimental paradigm

In recent years the n-back task has been employed in many studies to investigate working memory processing [11]. During the n-back task the subjects are presented with a series of items appearing on a screen one at a time. They are asked to decide whether each item in the sequence matches the one that was presented n-items ago. In our study we used the 2-back letter version of this task where the participants had to decide whether a letter currently presented on the screen is the same as the one presented two letters earlier (see Figure 1). The used test set consisted of 8 letters, namely B, F, K, H, M, Q, R and X. Vowels were not included in order to prevent semantic associations. The selected letters did not have common shape features to avoid errors due to shape confusions (e.g. V and W). Each letter was presented on the computer screen for 500 milliseconds. A fixation cross appeared on the screen between trials (a letter presentation) for a random duration between 1000 and 3000 milliseconds. When a trial was a target (the letter was the same as the one 2 letters ago), the participants had to press the button 1. In all other cases, the participants had to press the button 2.

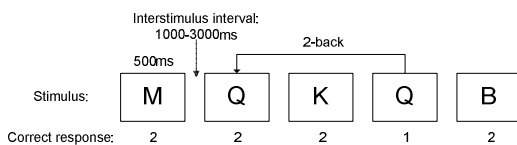


Fig. 1. Experimental paradigm: 2-back task.

The task was administered using the E-Prime application suite [12]. The participants had to complete 3 sessions of 30 trials (10 targets) each. Before starting they had a chance to practice the task. Behavioral performance (reaction time and accuracy) was recorded.

The total duration of the experiment was around 40 minutes, including 15 minutes for initial set up of the equipment, introduction of the subjects and informed consent signing, followed by two baseline EEG measurements of two minutes with eyes open and eyes closed.

## C. Signal acquisition

Brain activity was recorded with the BioSemi ActiveTwo signal acquisition system [13] using 32 electrodes mounted on an elastic cap at a sampling frequency of 2048 Hz. The electrodes were positioned according to the international 10/20 standard and were uniformly distributed over the scalp. The signal from a photo diode placed on the computer screen rendering the task, was jointly recorded with the EEG to annotate the letter presentation events.

## III. DATA ANALYSIS

The signals were subsampled to 1024 Hz, the DC component was removed using a 2 Hz high-pass FIR filter, and

the power line interference was attenuated applying a 1 Hz-wide band-stop FIR filter centered at 50 Hz. In order to minimize the effect of background neuronal activity in the area of interest and to localize the neural responses we re-referenced each channel to the average of all channels. This is known as common average re-referencing (CAR) [14], which was subtracted from each channel.

Eye blink artifacts were corrected using Independent Component Analysis (ICA) [15]. ICA is a technique used to separate linearly mixed, statistically independent sources, based on the assumption that the cerebral sources, generating the signals recorded on the scalp, are non-Gaussian and temporally independent. An eye-blink component has been identified for each subject and then the signals have been reconstructed excluding this component. No obvious distortions to the original underlying brain signals were observed.

To examine the event related dynamics of working memory processing we estimated the power of the signal in three frequency bands: 3.5 - 7 Hz, 7.5 - 12 Hz and 17 - 29 Hz by band-pass filtering the signal in each band, squaring the result, and applying a 150-ms long running average filter. The choice of the bands was made by taking into account the largest differences between pre and post letter presentation. These bands do also coincide with the classical EEG ranges theta, alpha, and upper beta. For convenience hereafter we refer to them as theta, alpha, and beta.

The original non-filtered (after eye-blink correction) and band-pass filtered signals were then segmented into 3000 millisecond-long epochs starting at 1000 milliseconds before a stimulus onset until 2000 milliseconds after a stimulus onset resulting in one epoch for each trial. The non-filtered epochs were screened one more time for extreme high amplitude values, high frequency muscle noise and other irregular artifacts generated by non-cerebral activity. We used an automatic procedure taking the average of the two extremes (the minimum and the maximum) across all epoch plus twice their standard deviation as rejection thresholds.

## IV. RESULTS AND DISCUSSION

The summary of the behavior results is shown in Table I. The average reaction time (RT) for targets was slightly faster than that of non-targets. The percentage of correct responses was 86.89% on average, 81% for targets and 89.83% for non-targets. This results are comparable to that of other studies using a similar experimental paradigm.

Only trials with correct responses were considered for further analysis. This resulted in 23 target and 51 non-target trials on average per participant.

TABLE I  
BEHAVIOR RESULTS

	Targets	Non-targets	Total
Mean RT (SD) [ms]	690 (223)	815 (228)	776 (220)
Hits (SD) %	81.00 (9.56)	89.83 (7.22)	86.89 (6.74)

To examine stimulus- and response-induced global trends in the EEG, we have computed the grand average power across all subject in each of the bands identified above and for each electrode location. The proportional power change with respect to the baseline reference interval (set between 1000 and 500 milliseconds before stimulus onset) in each channel was then averaged for every 200-millisecond long interval starting from 400 milliseconds before the letter presentation until 1000 milliseconds after the letter presentation. The result is visualized as a topographic map in Figure 2.

In the first 200 milliseconds after stimulus onset, the theta band shows increase in occipital sites, most probably related to the initial processing of the visual stimulus. We can also observe theta synchronization localized over fronto-central sites, which diminishes around 600 milliseconds. At the same time over parietal and occipital sites theta desynchronizes. Alpha band shows desynchronization in the first 600 milliseconds, primarily over frontal and occipital sites. Around the average reaction time (776 milliseconds) we can observe the focal ERD/surround ERS phenomena [16], which reflects sensorimotor activation and deactivation. Since all our participants were right handed, the ERD in the alpha band is, as expected, lateralized to the left hemisphere in central electrode positions. Beta band shows stable desynchronization appearing first over central, parietal and occipital sites, and later around 400 milliseconds after the stimulus onset also propagating over frontal electrode locations. After the average reaction time across participants we can observe another sensorimotor effect, a beta ERS, over parietal and occipital sites.

Figure 2 confirms the relevance of frontal sites but also shows the potential involvement of central and parietal sites. The grand average of the instantaneous power (*power dynamics*) for theta, alpha, and beta along the midline, which includes frontal (Fz), central (Cz) and parietal (Pz) sites, is shown in Figure 3. We distinguish the power dynamics of target and non-target stimuli. Similarly to Figure 2, the power at each time point was normalized and related in percentage to the power in the reference interval. The average power changes in the interval from 0 to 600 milliseconds after stimulus presentation was compared to a baseline interval from 1000 to 400 milliseconds before stimulus presentation using the non-parametric Wilcoxon signed-rank test. The results show that theta and beta dynamics are statistically significant at level  $p \leq 0.01$  for all sites and stimulus types.

Overall, an initial rise of the theta level can be observed upon presentation of the stimulus. This is more prominent at the central site Cz and for the target stimuli. For the frontal and central locations, the theta power returns to reference levels before the reaction time has elapsed. After the reaction time, the theta level increases and decreases again in the parietal location Pz, which may be indicative of the subject's expectancy of presentation of the next letter.

The decrease of the alpha level on presentation of the stim-

ulus indicates the active engagement of the corresponding cortical site in processing the stimulus and the retrieval of the answer in working memory. For both targets and non-targets, and for Fz, Cz, and Pz, the alpha level decreases after presentation of the letter. The alpha level returns to the reference level few hundred milliseconds after the reaction time and more slowly than theta does.

Beta also appears to evolve in an opposite direction of theta. Beta desynchronizes after stimulus presentation and returns to its reference level faster than alpha overall and slightly faster than theta at the parietal site Pz.

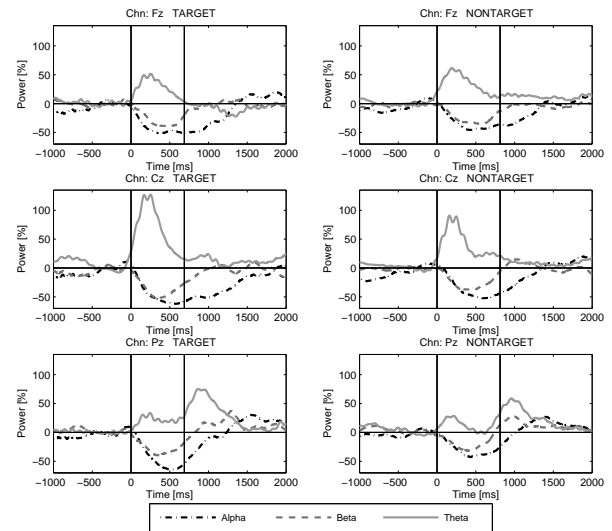


Fig. 3. Grand average of the power changes for all subjects in the three bands: theta, alpha and beta at midline sites Fz, Cz, and Pz for target and non-target stimuli. The second vertical line between 500 and 1000 milliseconds correspond to the average reaction time. The statistical significance, as estimated by Wilcoxon signed-rank test, of the average power levels in theta and beta band in the time interval from 0 to 600 milliseconds after stimulus presentation compared to the baseline interval from 1000 to 400 milliseconds before stimulus presentation was  $p \leq 0.01$  for all sites and stimulus types.

To visualize the trial-specific dynamics of the three power bands at the frontal midline location Fz, we represent in Figure 4(a) and Figure 4(b), for two participants in the study (subjects S2 and S7 respectively) the individual trials sorted in ascending order by their corresponding reaction time. The trials are represented in the time period spanning from 1000 milliseconds before stimuli presentation up to 2000 milliseconds after stimulus presentation and are smoothed using a 10-trial moving average window. The thick black curve represents the reaction time and the color code is commensurate with the instantaneous level. The level is simply the ratio between the current power and the power of the reference interval. As in Figure 3, we distinguish the target and non-target stimuli.

These two participants exhibit signal dynamics that are qualitatively different from each other in the sense that for

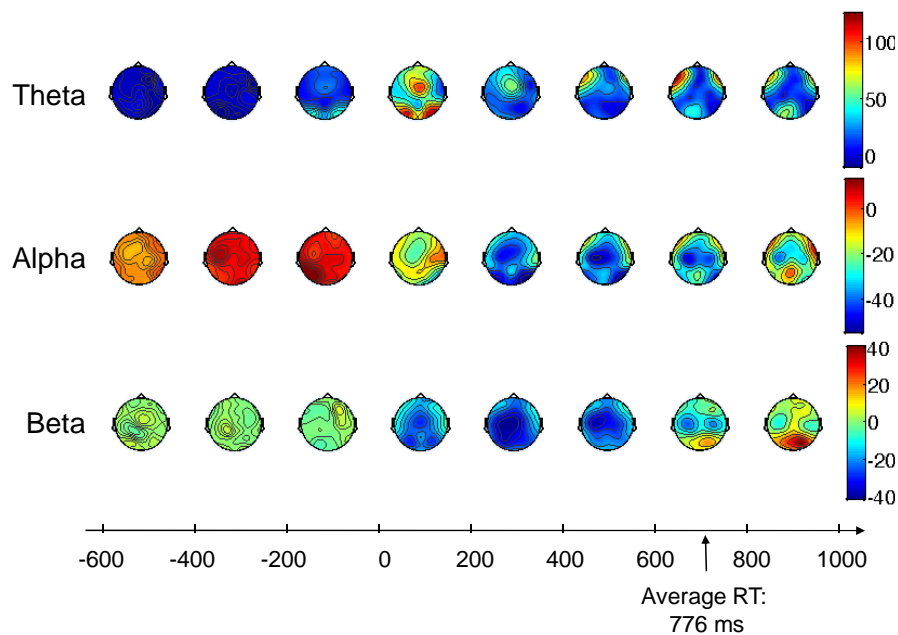


Fig. 2. Topographic representation of the grand average of the power changes for all subjects in the three bands: theta, alpha and beta. The values represent an average percentage change from a baseline [-500 -1000 ms] in intervals of 200 ms. For ease of visualization the color map has been adjusted for each band separately.

subject S2, fast reaction times for both target and nontarget stimuli are characterized by a more pronounced theta synchronization while the opposite holds for subject S7. S2 behavior was common to five participants in the study. The correlation between reaction time and the average theta, alpha, and beta levels in the interval spanning from 0 to 600 milliseconds after stimulus presentation for nontargets is reported in Figure 5 for subjects S2 and S7. For this analysis we consider nontarget trials due to the higher confidence resulting from the higher number of trials. The Pearson's correlation coefficient and its statistical significance level for each location and band are also reported in the figure. The estimated trends confirm the fundamental difference in the brain dynamics of these two participants while performing the 2-back task. Individual specificities in brain functioning have been extensively documented in several studies and clearly manifests in our results.

## V. CONCLUSION

Working memory is an essential component of human cognition that can be studied through the n-back task. In this study we asked 10 participants to engage in a 2-back memory task using a set of (consonant) letters. Instead of considering ERP based features as generally done in literature, we focus on patterns of brain activity in three frequency bands, namely theta, alpha, and beta at 32 locations distributed over the scalp. In particular, we identified significant correlations between performance indicators and single trial dynamics.

Our results show a pronounced relevance of location Fz and the theta dynamics to exhibit changes related to the

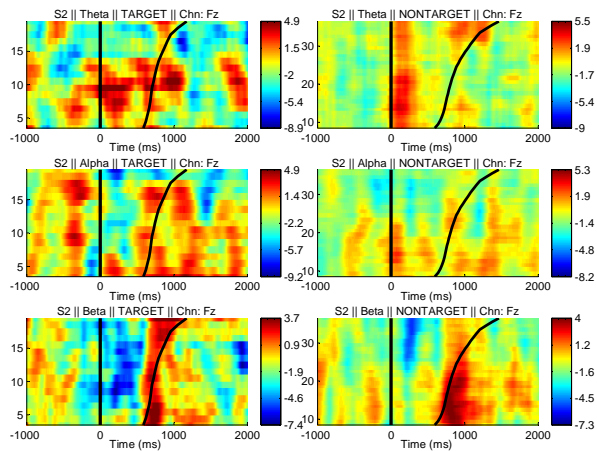
execution of the working memory task. For both targets and nontargets the theta level raises immediately after stimulus presentation. The magnitude of such a raise appears to correlate with the speed to which subjects react to a stimulus presentation.

Alpha exhibits overall desynchronization immediately after stimulus presentation and returns to pre-stimulus levels few hundred milliseconds after reaction time. From the overall alpha desynchronization, it seems that intake of the information to encode in the participant's working memory and the retrieval to compare with the item that was presented two trials ago engages several cortical sites.

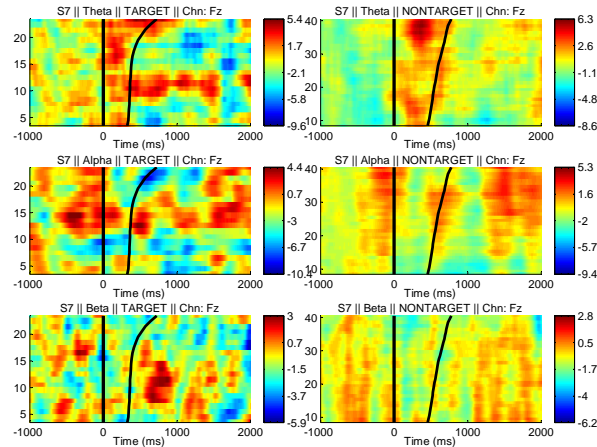
Traditional ensemble averaging across subjects and trials, however, does not fully model the actual brain dynamics. Individual specificities in brain activity manifest in our results as illustrated by the fact that different trends of dynamics correlate with reaction time in different subjects. Therefore, identifying relevant factors accounting for the variability in the signals and studying trial and subject specific dynamics could prove valuable. Additional insights about the link between brain dynamics and performance could be found by varying the task difficulty and looking into the accuracy of responses. Further research needs to be granted in order to correctly model the relation between working memory and brain rhythm dynamics.

## VI. ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of Alina Weffers and Mark Jaeger for their relevant suggestions



(a) Subject S2, Channel Fz



(b) Subject S7, Channel Fz

Fig. 4. Theta, alpha and beta dynamics for each trial at frontal midline site Fz smoothed and sorted by reaction time. Trials are represented horizontally. The level estimate results from taking the logarithm of the ratio between the instantaneous power in the band and the power in the reference period. Red values show ERS, blue values show ERD. The black curve represent the RT for each trial.

to improve this paper and our participants for their kind collaboration.

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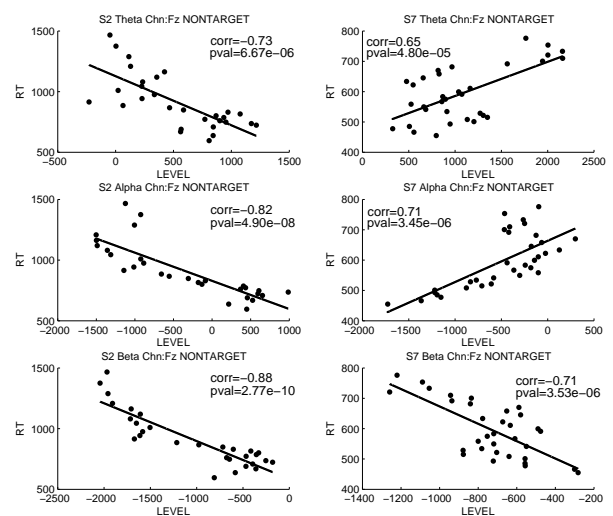


Fig. 5. RT versus average alpha, theta, and beta levels in the time interval from 0 to 600 milliseconds after stimulus presentation. The level estimate results from taking the logarithm of the ratio between the instantaneous power in the band and the power in the reference period.

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