Neuroscience Letters 550 (2013) 134–138

Contents lists available at SciVerse ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

# Spontaneous theta rhythm and working memory co-variation during child development

Elena I. Rodriguez-Martinez*, Catarina I. Barriga-Paulino, Maria A. Rojas-Benjumea, Carlos M. Gómez

*Human Psychobiology Lab, Experimental Psychology Department, University of Sevilla, Spain*

## HIGHLIGHTS

- A negative relationship was found between EEG power and WM during child development.
- This relationship was higher in the theta range.
- A bivariate model including RT and theta power explained most of the age-related variance in WM.

ARTICLE INFO

*Article history:*
Received 12 April 2013
Received in revised form 23 June 2013
Accepted 24 June 2013

*Keywords:*
Working memory
Maturation
Power spectral density
Phonological loop
Visuo-spatial sketchpad
Central executive

ABSTRACT

The present study examines possible relationships between changes in electroencephalogram (EEG) power and in working memory (WM) due to brain maturation. Scores on the phonological loop, visuospatial sketchpad and executive components of WM, measured by the Working Memory Test Battery for Children (WMTB-C), were correlated with the power spectral density (PSD) values on the spontaneous EEG from 1 to 46 Hz. In order to control for non-specific processes of visuomotor abilities, the reaction time (RT) variable was measured with an Oddball task. One hundred and sixty seven subjects (82 males and 85 females) between 6 and 26 years old participated in the study. Three minutes of spontaneous EEG were recorded. The WMTB-C and the Oddball task were also administered. The scores on each WM component increased and the RT in the Oddball decreased with age, while PSD values in the different frequencies decreased with age. Significant negative correlations between each of the components and the PSD were obtained. The maximal negative correlations were obtained in the theta (4–7 Hz) range. A bivariate linear model including theta PSD and RT explained most of the WM variance due to age. The results suggest that spontaneous EEG maturation is closely related to WM maturation, particularly in the theta range.



## 1. Introduction

Working memory (WM) is a cognitive operation used in our activities in everyday life, whether at the academic, professional or personal level. This operation is the ability to store and manipulate information during short periods of time. It allows one to sustain and use data needed for certain tasks.

Baddeley and Hitch's [2] WM model, proposes a multi-component structure that includes a central executive and two unimodal slave systems: the phonological loop and the visuospatial sketchpad. With this WM model, it is possible to measure a student's capacity to acquire knowledge, rather than measuring what the student has already learned.

The central executive is responsible for important high-level cognitive activities [3,4]. The phonological slave system comprises two components, a phonological store and an articulatory rehearsal system. Material that can be stored includes spoken and written language, but also pictures when translated into verbal format. The visuospatial sketchpad is dedicated to the storage and maintenance of visual (e.g., color, form) and spatial (e.g., position, movement) information. Both WM and the spontaneous EEG develop over time until reaching the typical adult pattern.

Delta rhythm is the main EEG activity in the first two years of life. In contrast, delta waves are not observed in a normal adult EEG, in waking and relaxed states. Theta rhythm is mainly seen in children, it decreases progressively with age, and it is enhanced while performing tasks involving attention and WM [11]. The visually

*Abbreviations:* WM, working memory; PSD, power spectral density; WMTB-C, Working Memory Test Battery for Children; Hz, Hertz; AM, ante meridian; PM, post meridian; KΩ, kilo-ohms; DC, direct current; AD, Analog Digital; AC, alternant current; μV, microvolts; FFT, Fast Fourier Transform; IQ, Intelligence Quotient; ERS, event-related synchronization.

* Corresponding author. Tel.: +34 954557800; fax: +34 954551784.
*E-mail addresses:* elisroma@us.es, cgomez@us.es (E.I. Rodriguez-Martinez).

0304-3940/$ – see front matter © 2013 Elsevier Ireland Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.neulet.2013.06.054

modulated alpha rhythm, which is the main characteristic of the adult human EEG, presents a progressive maturation in which an increase in frequency occurs with increasing age [29]. Beta rhythm has traditionally been linked to active information processing and arousal. Its amplitude increases up to a period that includes adolescence and adulthood [10].

The study of changes in the EEG power pattern due to maturation during development is particularly important because EEG rhythms can be affected or modulated by developmental disorders [12,6], socioeconomic status [32,35] and gender [24,22,23]. A decrease in absolute power in the delta, theta, alpha and beta bands appears during brain maturation. This result has been confirmed several times, and it seems to be an important landmark in EEG development [31,1]. The shift from low to high EEG frequencies in relative power is also a characteristic of brain maturation. Some studies have shown that brain maturation and cognitive development are intimately associated. For example, Hudspeth and Pribram [20] observed that through the development of cognitive functions during puberty, brain maturation progresses from posterior to frontal regions. This postero-anterior pattern would be related to the fact that gray matter shows progressive maturation in a postero-anterior gradient [17].

The present study examines possible relationships between changes in EEG power and in WM due to brain maturation. To test this hypothesis, scores on the three WM components were measured (phonological loop, visuospatial sketchpad and central executive) and correlated with the PSD of frequencies between 1 and 46 Hz in 30 electrodes in a population of 167 subjects between 6 and 26 years old. Additionally, a bivariate regression model that includes EEG PSD in the theta band and RT in an Oddball paradigm was tested. The RT term would make it possible to include a general factor of visuomotor performance in the regression model. Determination coefficients of the bivariate regression model would assess the proportion of age-related WM variance explained by the model during development.

## 2. Materials and methods

### 2.1. Experimental human subjects

The study included a sample comprising 172 human subjects between 6 and 26 years old (4 females and 4 males for each birth age). Five subjects were excluded due to excessive EEG artifacts. Of the total, 154 were right-handed and 13 left-handed. The left-handed subjects were maintained to increase the generalizability of the results. The group of males consisted of 82 subjects (mean ± SD age: 15.94 ± 6.06), 75 right-handed and 7 left-handed. The female group consisted of 85 subjects (mean ± SD age: 15.73 ± 6.10), 79 right-handed and 6 left-handed.

Subjects did not report any neurological diseases or psychological impairments. Both groups were extracted from middle class socioeconomic backgrounds. The children had normal academic records, and the young adults were college students. Experiments were conducted with the informed and written consent of each participant (parents/tutors in the case of the children) following the Helsinki protocol. The study was approved by the Ethical Committee of the University of Seville.

### 2.2. Methods

#### 2.2.1. Working Memory Test Battery for Children

For measuring WM, a Spanish adaptation of the Working Memory Test Battery for Children (WMTB-C) [16] was used. The WMTB-C has 9 subtests that assess each component of WM.

This neuropsychological test has to be administered in the following order: (1) Digit Recall, (2) Word List Matching, (3) Word List Recall, (4) Block Recall, (5) Non-word List Recall, (6) Listening Recall, (7) Counting Recall, (8) Mazes Memory and (9) Backward Digit Recall. Subtests 1, 2, 3 and 5 measure the phonological loop, subtests 4 and 8 measure the visuospatial sketchpad, and subtests 6, 7 and 9 measure the central executive. The Digit Recall, Block Recall, Counting Recall, Mazes Memory and Backward Digit Recall subtests were applied as in the original battery. Phonological subtests were adapted to the Spanish language.

The scores on each subtest were weighted, and the mean value of the subtests was obtained for each component of the WM model, and expressed in percentages. The weighting was introduced in order to obtain the same range of values on the nine sub-tests of the WMTB-C. The weighting was computed taking into account the maximum possible score on each subtest.

#### 2.2.2. Oddball task

The subjects also performed an Oddball task. The Oddball task was composed of a total of 120 trials; 25% were novel stimuli, and 75% were standard. The stimuli were presented for 700 ms. The inter-stimulus interval lasted 700 ms. The stimuli covered a visual angle of 4.56°, and they were situated in the center of the screen. All the stimuli, both standard and novel, were cartoons. Subjects were instructed to press the button only when a novel stimulus appeared. The response window was 1400 ms. There was only one block, and the presentation order was random. The variables recorded were mean RT, false alarms, misses and anticipations (responses faster than 200 ms). Only correct trials were used to compute the RT mean.

#### 2.2.3. EEG record

The EEG was recorded during three minutes of spontaneous activity while keeping the eyes open. This period is sufficient recording time, given that test–retest reliability for EEG periods of 60 s is 92% [27].

Subjects were asked to blink as little as possible and keep their eyes focused on a cross presented at the center of the screen. Subjects were recorded at different times of the day, between 12 AM and 8 PM. No information about previous sleep was required. Recordings were obtained from an average reference of 32 scalp sites from the international system (Fp1, Fpz, Fp2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, M1, T7, C3, Cz, C4, T8, M2, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, POz, O1, Oz, O2,), using tin electrodes mounted in an electrode cap (ELECTROCAP). Ocular movements were recorded by two electrodes at the outer canthus of each eye for horizontal movements, and electrodes placed above and below the left eye for vertical movements. All the scalp electrodes were re-referenced off line to the mastoid average (M1 + M2)/2. Impedance was maintained below 10 kilo-ohms (kΩ). Data were recorded in direct current (DC) mode at 512 Hz, with a 20,000 amplification gain using a commercial Analog Digital (AD) acquisition and analysis board (ANT). Data were not filtered during registration. We asked subjects to stay calm and look at the screen for three minutes while blinking as little as possible.

### 2.3. Data analysis

EEG recordings were analyzed with the EEGLAB [13] and Matlab 2010a software packages. To eliminate alternant current (AC) power line interference and blink artifacts on the EEG, an independent components analysis [7,8,13] was performed. These components were discarded, and the EEG signal was reconstructed. The segmented epochs lasted 2000 ms. All the epochs for which the