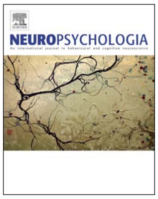
Neuropsychologia 108 (2018) 61–72

Contents lists available at ScienceDirect

Neuropsychologia

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



Are resting state spectral power measures related to executive functions in healthy young adults?

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ARTICLE INFO

Keywords:
Resting-state electroencephalogram
Theta
Upper alpha
Executive function
Power spectra

ABSTRACT

Resting-state electroencephalogram (rsEEG) has been found to be associated with psychopathology, intelligence, problem solving, academic performance and is sometimes used as a supportive physiological indicator of enhancement in cognitive training interventions (e.g. neurofeedback, working memory training). In the current study, we measured rsEEG spectral power measures (relative power, between-band ratios and asymmetry) in one hundred sixty five young adults who were also tested on a battery of executive function (EF). We specifically focused on upper Alpha, Theta and Beta frequency bands given their putative role in EF. Our indices enabled finding correlations since they had decent-to-excellent internal and retest reliability and very little range restriction relative to a nation-wide representative large sample. Nonetheless, Bayesian statistical inference indicated support for the null hypothesis concerning lack of monotonic correlation between EF and rsEEG spectral power measures. Therefore, we conclude that, contrary to the quite common interpretation, these rsEEG spectral power measures do not indicate individual differences in the measured EF abilities.

1. Introduction

Spontaneous brain activity is sometimes measured using Electro Encephalography at rest (rsEEG). This rsEEG demonstrates rhythmic activity that is quantified by means of spectral analysis (Dietsch, 1932; Buzsáki, 2006). Importantly, aspects of this rhythmic activity proved as stable individual traits related to a myriad of cognitive functions (Niedermeyer and da Silva, 2005; Schomer and Da Silva, 2012) including intelligence (Thatcher et al., 2005, 2007, 2008), academic performance (Cheung et al., 2014) and problem solving (Kounios et al., 2008). Accordingly, rsEEG was found to be associated with conditions characterized by cognitive impairment such as neuro-developmental disorders (Lansbergen et al., 2011), neurological disorders (e.g. epilepsy, Hacker et al., 2017), psychopathology (Putman, 2011; Canuet et al., 2011; Kim et al., 2013), and normal aging (Finnigan and Robertson, 2011; Caplan et al., 2015). In the present work, we asked whether oscillations at Alpha (7–13 Hz), Theta (4–7 Hz) and in some cases Beta (13–24 Hz) frequencies bands, in rest (the absence of a task) are related to executive functions (EFs). One reason to predict a correlation between these rsEEG spectral power oscillations and EF is the fact that intelligence, a construct closely linked to EF (Friedman et al., 2006) has been shown to be related to rsEEG (Thatcher et al., 2005, 2008), and specifically to Alpha waves (Thatcher et al., 2007). Another reason is that several training studies that attempted to enhance EF abilities, also demonstrated changes in rsEEG Theta band, as a result of training (e.g. Langer et al., 2013, Wang and Hsieh, 2013). And finally a relatively new study by Ambrosini and Vallesi (2016a) demonstrated a relation between asymmetry of Beta and Alpha ratio frequency bands (measured in resting-state) and task-switching, an EF ability. To the best of our knowledge, this is the first study investigating this relation in a relatively wide range of EF tasks in a relatively large sample of healthy young adults. Below we provide a brief review of the relevant literature.

1.1. Executive function

EF is defined as the ability to organize, monitor and regulate lower-level cognitive processes such as perceptual, motor, and memory processes to fit information processing demands of the current task (Friedman and Miyake, 2017). EFs are essential for successful functioning. People with good EF are characterized as being flexible since they are better able than those with poor EF in dealing with complex situations requiring creative, “out-of-the-box” solutions. In contrast, poor EF characterizes immaturity (e.g., Diamond et al., 2007) as well as

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https://doi.org/10.1016/j.neuropsychologia.2017.10.031
Received 8 April 2017; Received in revised form 19 October 2017; Accepted 27 October 2017

many forms of psychological dysfunction including psychopathology (ranging from obsessive-compulsive disorder to depression, e.g., see Kashdan and Rottenberg, 2010), rigid problem-solving style and poor reasoning ability (Friedman et al., 2006). Although not uniformly accepted (e.g., Baddeley, 1986, vs. Lehto, 1996), Miyake et al. (2000) taxonomy has become the standard in discussion of EF. According to Miyake et al. (2000), there are three main components of EF: working memory updating, switching, and inhibition. More recently, an alternative model was suggested by Friedman and Miyake (Friedman and Miyake, 2017; Miyake and Friedman, 2012), that also accounts for correlations between switching, inhibition and updating by proposing a general EF factor. In this model, "inhibition" is fully explained by the general EF factor. Hence, the new model postulated a general EF factor and unique switch-specific and updating-specific components. Since we used Friedman and Miyake's taxonomy only as a general guideline to ensure reasonable coverage of the EF domain, we described the three originally proposed functions here. ***Working memory updating*** – working memory (WM) is a system that holds temporarily relevant information in a state of high accessibility for the sake of goal achievement (Baddeley and Hitch, 1974; Baddeley, 2003; Oberauer, 2010). Amongst other things, WM is required to hold a behavioral goal in mind, to plan ahead, to keep track of one's progress on a task, to relate new information to old information, and to perform complex reasoning as required in tests of intelligence (e.g., Friedman et al., 2016; Gray et al., 2003). Since WM has a limited capacity (e.g., Cowan, 2001), its contents must be continuously updated. Thus, a distinction between two features of WM can be made, capacity and updating. Nonetheless, the distinction between them in terms of individual differences in ability may not be critical, given the near perfect correlation between the respective latent variables (Schmiedek et al., 2009). ***Inhibition*** –We are constantly facing situations in which pre-potent but inappropriate actions or thoughts must be inhibited in favor of a less potent but appropriate behavior. Studies suggest that inhibition can be sub-divided into at least: (a) inhibition of inappropriate motor responses and distractor inhibition, and (b) inhibition of proactive interference (Friedman and Miyake, 2004). ***Switching*** – The state of readiness of the cognitive system to execute a particular task or process information in a particular way is called a "mindset". Changing mindsets is one of the most significant challenges facing the cognitive system, and can be critical in situations in which the current mindset is not suitable and needs to be replaced. Currently, the method of choice for examining mindset changes is task-switching. In task-switching paradigms, participants are required to switch between simple tasks. Although the tasks themselves are simple, task-switching often leads to a significant decline in performance (for review see Kiesel et al., 2010; Meiran, 2010; Monsell, 2003; Vandierendonck et al., 2010). There are two prevalent switching-efficiency measures 1) *Switching-cost*, the drop in performance in trials involving a task-switch relative to trials in which the task is the same as in that of the preceding trial (repeat trials). 2) *Mixing-cost*, the drop in performance in repeat trials taken from a switching-task relative to single-task trials taken from experimental blocks without task-switching (single-task blocks). When these costs are combined (i.e., the performance decrement in switch trials relative to single-task conditions), the outcome is called "*alternation-cost*". Although it is commonly suggested that EF is mainly regulated by the frontal lobes (Miyake et al., 2000; Miller and Cohen, 2001), some non-frontal brain regions are necessary for EF (Alvarez and Emory, 2006; Friedman and Miyake, 2017) including the parietal cortex, the basal-ganglia and the cerebellum. Below we provide a brief review of the relevant rsEEG literature, starting with a more general review of rsEEG and cognitive functions and then a specific focusing on rsEEG and EF.

1.2. rsEEG & relevant cognitive functions

Studies have demonstrated that the human EEG is a stable trait over time (e.g., Kondacs and Szabo, 1999; Williams et al., 2005) and has a genetic basis (Smit et al., 2005). This led researchers to ask what other traits are related to rsEEG. A recent study conducted by Cheung et al. (2014), for example, found that rsEEG is related to academic performance. In that study, better academic performance was correlated with a decrease in rsEEG coherence measures. Kounios et al. (2008), found that high-insight participants had relatively reduced occipital rsAlpha-band activity and low-insight participants had relatively increased occipital Beta activity. Most importantly, and given the high correlation with EF (Kane and Engle, 2002), the correlations with intelligence are also relevant. Thatcher et al.'s (2005; 2007; 2008) showed that intelligent participants had a general increase in global power activity in all brain regions and had quicker processing times in frontal connections as reflected by shorter phase delays and decreased coherence. Thatcher et al. (2007), also found a positive relationship between amplitude measured during rsEEG and IQ, especially in the Alpha frequency range of 9–10 Hz. Further support for this idea comes from other groups of researchers (Başar, 2006; Doppelmayr et al., 2005) as well. Thus, it would seem that those individuals with higher frequency of rsAlpha power may be able to use this to actively inhibit irrelevant processes, depending on task-requirements. These findings are also interpreted as supporting the neural efficiency hypothesis (Haier et al., 1992), suggesting that intelligent participants are more efficient and thus require less neural activity (Jausovec and Jausovec, 2000, 2003). Additional but indirect support for the relation between cognitive abilities and rsEEG comes from studies that used neurofeedback and tailored transcranial magnetic stimulation (TMS). Klimesch et al. (2003) applied repetitive TMS in order to increase upper Alpha at posterior scalp sites. Results show a significant improvement in performance on the mental rotation task (a task known as related to visual WM, Just and Carpenter, 1985) in the treated group as compared to a sham group. Additionally, Nan et al. (2012) demonstrated that increasing upper Alpha through neurofeedback training improved performance on a WM capacity task in comparison to silent control. However, in that study rsEEG was not administrated before or after training. Another neurofeedback study conducted by Wang and Hsieh (2013), found that increasing frontal Theta in the middle frontal electrode (Fz) improved executive attention as measured by the ANT task (Fan et al., 2002). Moreover, enhanced rsTheta at frontal electrode (Fz) was only found in the neurofeedback group post-training as compared to the sham group.

1.3. rsEEG & Executive functions

While there are quite a few relevant studies that investigated rs*fMRI* and EF (i.e., Gordon et al., 2014; Kelly et al., 2008; Hampson et al., 2006), there are only very few studies that examined the relationship between rsEEG and EF. In regards to Alpha and Beta waves, Ambrosini and Vallesi (2016a) investigated the relation between rsEEG and task-switching performance. The asymmetry of the Beta (12.5–24 Hz) and Alpha (7.5–12.5 Hz) ratio frequency bands was assessed using source-based rsEEG spectral analysis. It was found that participants with stronger left Beta/Alpha activity in the middle frontal gyrus were better able to exert what the authors called "transient" cognitive control, measured behaviorally by the task switching-cost, whereas participants with stronger right Beta/Alpha activity in the same brain area were better able to exert "sustained" cognitive control, as measured by lower task mixing-cost scores. Ambrosini and Vallesi (2016b) additionally showed that participants with stronger resting-state left-lateralized activity in different pre-frontal cortex regions were better able to inhibit irrelevant information as measured by Stroop task. Lastly, in relation to Alpha in rsEEG, Clark et al. (2004) found a positive relationship between rsAlpha peak frequency and WM performance. Specifically, frontal rsAlpha peak frequency was found to be a significant predictor of the reverse digit span, with each 1 Hz increase in frequency associated with a .21 increase in reverse digit span score. Limited research

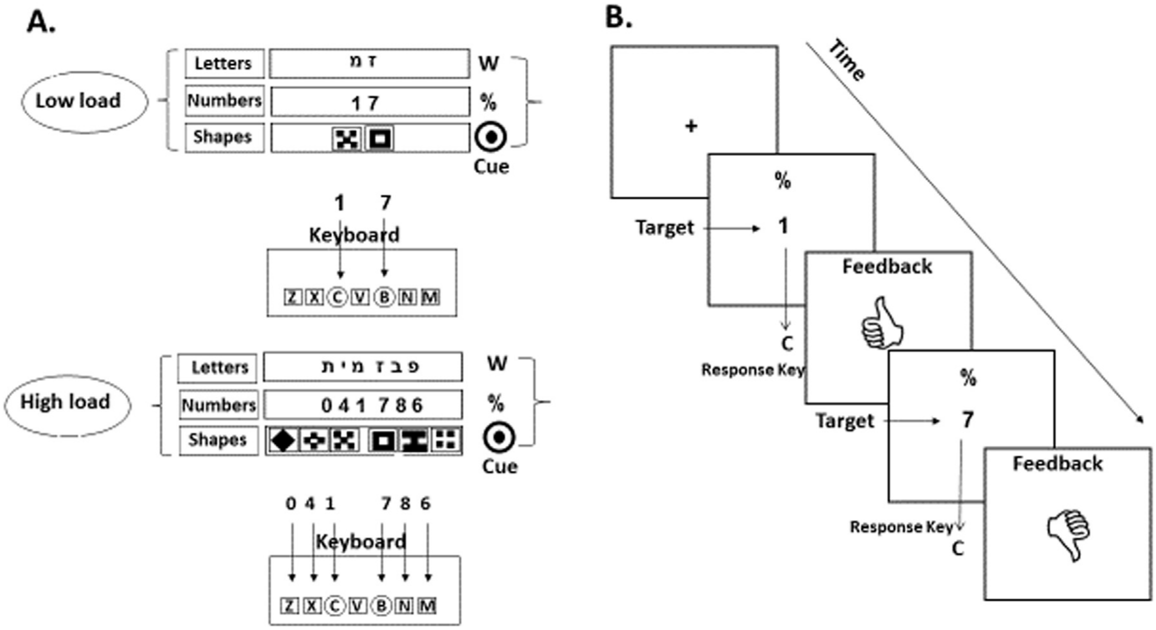

Fig. 1. The Choice Reaction Time Task. **A)** The two choice tasks (top) represent low working memory load and the six choice tasks (bottom) represent high working memory load. A task-cue was attached to every task (letters, digits or shapes). **B)** An example of the number-version of the two-choice reaction time task.

exists in regards to Theta waves as measured by rsEEG and it is mainly concerned with the relation between Theta and WM. One study by Finnigan and Robertson (2011), conducted on healthy older adults, found that frontal Theta power measured during eyes-closed rsEEG was positively correlated with a test of WM capacity. Additionally, Heister et al. (2013) measured resting-state magnetic power, which is closely linked to EEG, and used MEG (magnetoencephalography). These authors found that the right posterior frontal power and parietal Delta/Theta ratio were positively correlated with three-back WM performance. Additional but indirect support for the relation between Theta and WM comes from a training study by Langer et al. (2013), who analyzed the correlations between rsEEG measured before WM training across all frequency bands. A significant positive correlation was found between WM complex verbal span (taping WM storage and processing) and Theta power measured in the right anterior electrode cluster.[1]

1.4. The current study

The goal of the present investigation was to fill gaps in the literature of EF and rsEEG by using power spectral EEG measurements (relative power, ratio between frequency bands, asymmetry and coherence) and behavioral tasks of WM capacity, inhibition and task-switching. We explored the correlations between them in a relatively large sample of participants. We focused our investigation on Alpha and Theta in particular because accumulative evidence indicated that those frequency bands plays a critical role in EF. We also included asymmetry of the Beta/Alpha ratio as done by Ambrosini and Vallesi (2016a, 2016b) since it was found to be related to task-switching and inhibition. Based on the literature reviewed above, we tentatively predicted that better WM performance would correlate with increased Theta and Alpha specifically in frontal scalp locations and stronger resting-state Beta/Alpha left-lateralized activity in the frontal scalp regions may also correlate with inhibition. However, since we used in our EF battery a switching task that did not include task-repetition trials, this made it impossible to compute mixing- cost and switching-cost indices as did Ambrosini and Vallesi (2016b). Therefore, we did not have any specific prediction in regards to the relation between rsEEG and switching as measured here.

2. Methods

2.1. Participants and selection procedure

One hundred sixty-five participants (95 males, mean age = 22.12 years, $SD_{\text{age}} = 2.54$, range 19–28) were Israeli Defense Force (IDF) soldiers who were tested in this study as a part of a larger brain training study. The potential to improve brain functions was the main motivator, and no other compensation was provided for the study. However, it was made clear to the participants that the session used for the present study was solely for measuring capabilities and not for training. All participants gave informed consent prior to their participation. Additionally, they were informed that they could withdraw from the study at any time. All participants reported having normal or corrected-to-normal vision, with no history of psychiatric disorders, head trauma, central nervous system disorders or use of psychotropic medications. 86.5% were right handed.[2] Since it was a training study, another inclusion criterion was having at least an average Intelligence Rating Score [3] (IRS) of 50. The mean IRS in our sample was accordingly above average and showed restricted range (M = 68, $SD = 12.22$, as compared with $SD = 20$ in non-restricted populations). The institutional review board of the IDF Medical Corps approved the study. The study was conducted according to the guidelines of the declaration of Helsinki (Word Medical Association, 2013). Three participants were removed from the analysis due to bad EEG recordings that could not be corrected. The effective sample consisted of 162 participants (95 males). Their mean age was 22.5 years with a range of 19–28 years.

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[1] In that study, 204 electrodes were divided to 6 clusters: Three anterior and three posterior.

[2] Handedness was determined based on the preferred hand for writing, assessed on three-point scale (1 = right, 2 = left, 3 = either hand/ ambidextrous).

[3] The IRS comprises four sub-tests presented in a multiple-choice format: 1) the Otis- R, which measures the ability to understand and carry out verbal instructions; 2) Similarities-R, assesses verbal abstraction and categorization; 3) Arithmetic-R, which measures mathematical reasoning, concentration, and concept manipulation; and 4) Raven's Progressive Matrices-R, that measures non-verbal abstract reasoning and visual-spatial problem-solving abilities. The sum of the scores for the four tests forms a validated measure of general intelligence, scored on a 9-point scale, scaled between 10 and 90, with a 10-point increment at each score (Gal, 1986). The correlation between the general IRS score and the WAIS total IQ is > .90 (Kaplan et al., 2002).

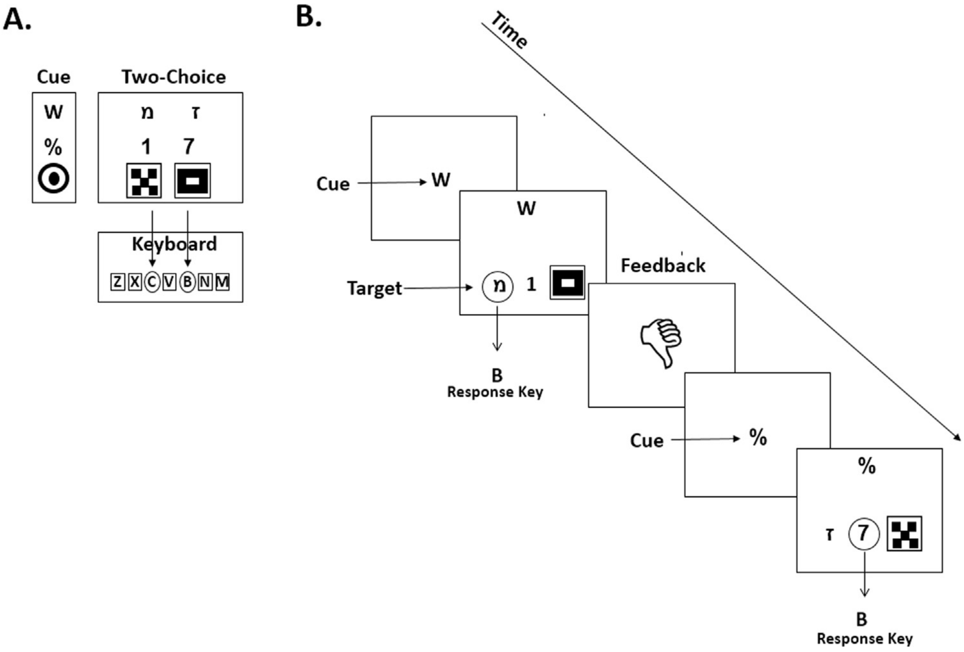

Fig. 2. The Switching Task. **A)** In the learning phase, cues and stimuli-response (S-R mapping) presented at the beginning of the task. There was no time limit for this screen. **B)** An example of the task with two steps of "word" that switched to "number" task. The cue-sign appeared in every trial, along with the target and two other distractors. Errors were followed by a visual feedback (thumbs down).

2.2. *Materials*

EF were assessed using the BEF [4] (Brief EF) battery including tests measuring switching, inhibition and WM capacity. We also included a mental rotation task since it was previously used by other authors in this field of investigation (Klimesch et al., 2003). The BEF battery consisted of:

2.2.1. *Choice Reaction Time (CRT)*

This test began with three six-choice-reaction tasks (high WM load) with tasks involving letters, digits and shapes, respectively (Fig. 1A, bottom) each task comprising of 72 trials preceded by 6 trials of practice. In all three tasks, the mapping between stimuli and response keys (on the keyboard) was arbitrary (Shahar et al., 2014) and thus required keeping this mapping information in WM. Participants used the index, middle and ring fingers of their right and left hands to respond in this task. In the next phase, three additional two-choice-reaction tasks (low WM load) were executed, with tasks involving letters, digits and shapes, respectively (Fig. 1A, top) and comprising 36 trials each, preceded by 2 trials of practice. Participants used just the index fingers of both hands, with the two choices mapped to the same stimuli as in the previous phase. Thus, WM-load was reduced in the 2-choice condition by both having fewer rules to keep in mind (two vs. six) and by the fact that these rules were trained beforehand. All the task-stimuli were presented at the center of a black 19-in. (48.26-cm) computer screen. The stimuli for the CRT were the Hebrew letters "ב,ג,ד,ז,ח,ט,כ,ל,מ,נ,ס,פ,צ,ק,ר,ש,ת" (Hebrew was the language of the participants), digits 0–9 which were presented using 48-point Times New Roman font. The shapes were 8 symmetrical shapes (Fig. 1) printed in white against a black background. Each shape was 64 × 64 pixels in size. Each trial included a fixation (500 ms), target (until response or until 6 s). Errors were followed by a 400 ms visual feedback (Fig. 1B). Two indices of WM efficiency were extracted from the CRT task: ***"Alternative-cost"*** which is the difference between the mean reaction time (RT) of high WM load (six choices) and the mean RT of low WM load (two choices). High scores represent compromised WM efficiency. ***"6-choice Tau"*** represents the rate of exceptionally slow reaction times of high memory load, as quantified with the Tau parameter from the ex-Gaussian model of reaction-time distributions. High Tau has been shown to have a very high correlation with individual differences in WM as estimated at the latent variable level (Schmiedek et al., 2007) Additionally, Shahar et al. (2014), using mathematical modeling of the decision process, showed that Tau is linked to WM retrieval rate with high Tau indexing slow retrieval of information from WM.

2.2.2. *The switching task*

This task was introduced after the CRT tasks and used the already learned two-choice stimulus-response mapping with task cues that were already familiar. The task began with a screen displaying the task cues and the stimulus-response mapping (Fig. 2A) and continued with a sequence of trials in which the task switched in every trial (Fig. 2B). Presentation of letters, shapes, and digits as well as error indication were the same as in the CRT task, with the only difference being that each target stimulus comprised of a combination of a shape, a letter and a digit. There were 201 trials in this task preceded by 6 practice trials. The task cues stimuli were "W" for letters, "%" for numbers and "○" for shapes. Each task cue was 64 × 64 pixels in size. Stimuli were presented in white on a black background. The task cues were presented at the center of a black 19-in. (48.26-cm) computer screen 500 ms prior to the presentation of the stimulus (Fig. 2B). Each stimulus appeared until response was given or after 6 s had elapsed. Two distracting effects were controlled for. Spatial compatibility was controlled for by having one third of the target stimuli being presented on the same side of the responding hand (spatially compatible), one third on the opposite side (incompatible) and one third in the middle. Task-rule congruency effects were controlled by the fact that in one third of the trials, all stimuli (target and two distractors) were mapped to the same response, in one third, one was mapped to the opposite response and in one third two were mapped to the opposite response. The related effects are not reported in this study. Two indices of switching were extracted from the Switching Paradigm: ***"Alternation – cost RT"*** represents the difference in reaction time between repeated trials taken from experimental blocks without task-switching ("single-task blocks") and switched trials (see

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[4] It is important to mention here that this BEF battery provided a relatively reasonable coverage of the EF-domain. However, this coverage was nonetheless incomplete. For example, instead of measuring WM updating, we indirectly measured other WM functions. One of them is conceptually related to capacity ("Alternative Cost"). The other ("Tau" in the 6-choice task) has been previously shown to be strongly correlated to WM performance at the level of individual differences (Schmiedek et al., 2009), and modeling work has linked it to the rate of retrieval from WM (especially Shahar et al., 2014).

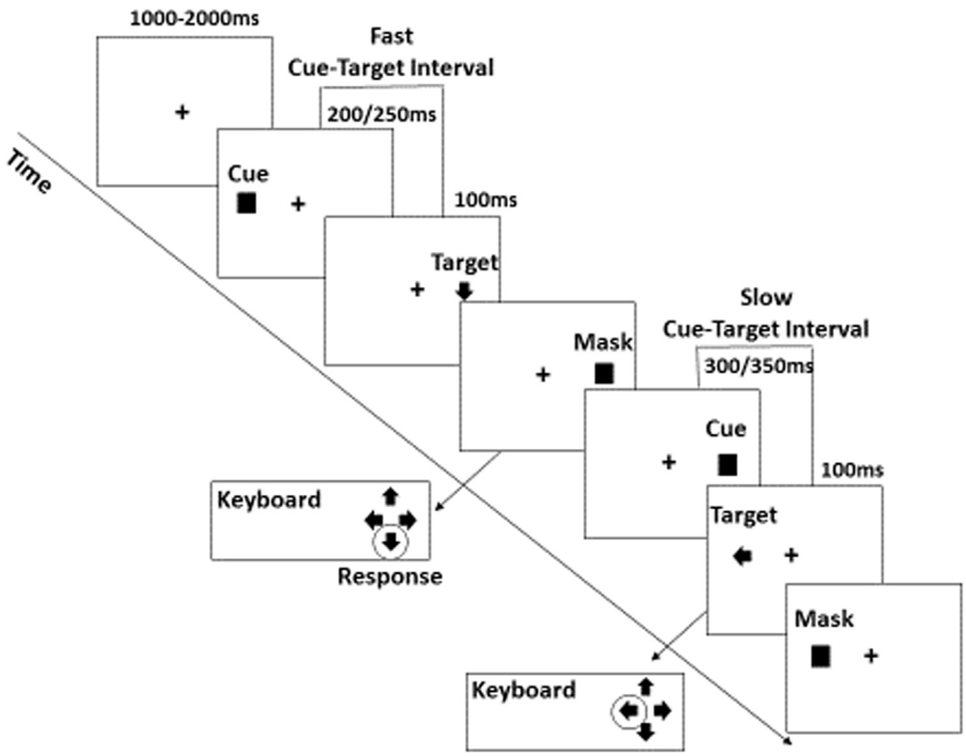

Fig. 3. The Anti-saccade Task. Each trial began with a centered fixation mark (+) for variable durations (1000 ms, 1500 ms, 2000 ms), followed by a cue/distractor presented on the right or the left side of the centered fixation mark for variable durations (200 ms, 250 ms, 300 ms, and 350 ms). Then, a target arrow appeared on the opposite side of the centered fixation mark for 100 ms and then masked until response or after 5 s.

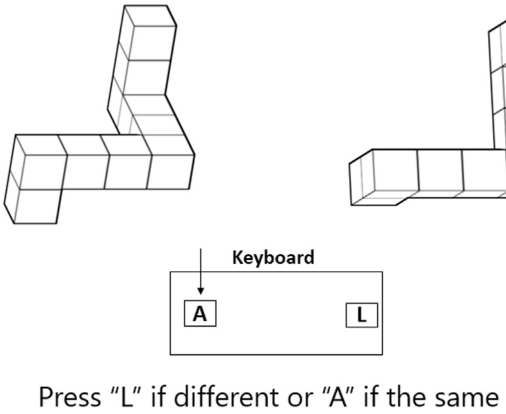

Fig. 4. The Mental Rotation task. The instructions presented on screen requested the participants to decide whether a pair of 3D shapes were identical (even if rotated) or different. The rotation of the 3D shape was on one axis only each time (horizontal or vertical). Accuracy and response times were recorded as a function of the rotation angle (55, 100, 145, and 190).

Meiran et al., 2000). High scores represent difficulty in switching. “***Alternation – cost in errors”*** represents the difference in errors between repeated and switched trials. High scores represent poor switching ability.

2.2.3. *The anti-saccade task (Miyake et al., 2000)*

This task measured inhibition success. 96 trials started with a centered fixation mark (+) that appeared for variable durations (1000 ms and 2000 ms in 500 ms intervals), followed by a visual cue presented on one side of the screen (e.g., left) for 200–350 ms in 50 ms intervals, followed by the presentation of a target stimulus on the opposite side (e.g., right) for 100 ms before being masked by gray cross-hatching that disappeared after response or after 5 s. The visual cue was a white square (64 × 64 pixels), and the target stimulus was a small white arrow (64 × 64 pixels). The participants' task was to indicate the direction of the arrow (left, up, down or right) with the keyboard's arrows (Fig. 3). Participants were required to inhibit the reflexive response of looking at the initial cue (a small white square) because doing so would make it difficult to correctly identify the direction of the arrow. The task started with 24 practice trials. We used the proportion of the incorrect responses as a measure of inhibitory control called ***“Anti- saccade***[5] ***in errors”***. High proportion of errors represents bad inhibition.

2.2.4. *The mental rotation task*

This task was a modification of the original task by Shepard and Metzler (1971) that was used in this study as a measure of visual WM. The instructions presented on the screen requested participants to decide whether a pair of 3D shapes, each composed of 10 cubes, were identical (even if rotated) or different. The rotation angle of the 3D shape was on one axis only each time (horizontal or vertical). Participants responded by pressing left (A) or right (L) on the keyboard. The assignment of keys (A, L) to YES and NO responses was counterbalanced between participants (Fig. 4). The participants received a visual example for correct rotation and incorrect rotation before entering the task. There was no time limit for the instructions screen. The task consisted of a single block of 64 trials, without practice trials. The stimuli were presented side by side, horizontally, with 20 pixels separation between them on a black 19-in. (48.26-cm) computer monitor. Each shape was 290 × 290 pixels in size. The stimuli were presented until a response was given or until 10 s passed. Accuracy and response times were measured as a function of the rotation angle (55, 100, 145, and 190). Each pair were presented such that one shape was on the right and the other was on the left with a 7.6° visual angle between the shapes centers. The interval between the response and the next pair of shapes was 500 ms. ***“Mental Rotation-RT***[6] ***”*** represents the reaction

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[5] Unlike in the original publication, we used a range of intervals to make the task suitable for use in a wide range of ability levels, such that poor ability individuals would also be able to detect some targets. The results indicate a steady increase in accuracy with increasing interval.

[6] We also extracted indices of the proportion of errors in the mental rotation task, and since similar results were found, and since reaction time measurement represent better working memory, we decided to stay with one index in that task.

time of the correct responses. High scores represent difficulty of visual WM (longer time to mentally rotate the shape in mind).

2.3. Design and procedure

During the EEG recording, participants were placed in a quiet, air-conditioned room, sat on a comfortable chair, in relaxed waking. rsEEG was recorded for a period of three minutes with eyes closed and three minutes with eyes open. In the eyes closed condition, participants were requested to stay relaxed as much as possible, while trying not to fall asleep, and not think of anything specific. In the eyes open condition, participants were requested to look straight at the white wall and not think of anything specific. After completing the EEG recording, participants performed the BEF battery (approximately 45 min). The order of administration was fixed for all participants to minimize any error due to participant by order interaction (Miyake et al., 2000). After performing the BEF battery, participants also filled out questionnaires, which will be reported elsewhere.

2.4. Resting-state EEG recording

EEG recordings were made using Discovery 24E (www.brainmaster.com). All electrode computerized electroencephalograph with 19 mono-polar leads were in accordance with the international 10–20 electrode distribution system (FP1, FP2, F3, Fz, F4, F7, F8, T3, C3, Cz, C4, T4, T5, T6, P3, Pz, P4, O1, O2). Impedance for each channel was measured and adjusted until they were kept below 5 kΩ before recording started. EEG activity was digitized at a sampling frequency-rate of 256 Hz and band pass filtered online between .5 and 100 Hz. An EEG cap (www.electro-cap.com), one of four different sizes (small, small-medium, medium-large, and large), was attached with a gel to the scalp and used to record EEG signals. In addition to these 19 electrodes, two earlobe electrodes (termed A1 and A2) were attached to the left and right ear. Electrodes were referenced to the left earlobe with the ground electrode at the CPZ location.

2.5. EEG pre-processing & analyses

EEG processing and analyses were performed offline using the Neuro-guide v-2.5.2 software (Applied Neuroscience Inc., St. Petersburg, FL, USA) program. We analyzed our data relative to linked ears references. All EEG recordings were carefully and individually checked for artifacts (eye blinks, muscle artifacts) by visual inspection and then edited to be removed from the data. A minimum of 90 s[7] of EEG recording was obtained for each participant, with all subsequent calculations being based on the average EEG spectrum computed from these minimum 90 s. Test re-test and split-half reliability for the entire EEG recording, as well as for all 19 electrode locations separately, were generated automatically by the Neuro-guide software for every EEG recording. Split-half reliability coefficients were calculated as the ratio of variance of all the even 1-second segments of EEG recording divided by all the odd 1-second segments of EEG recording. Variance was calculated as the sum of the square of the deviation of each time point from the mean of all selected time points. Test re-test reliability coefficients were calculated by dividing the EEG recording in half, treating each half as a separate occasion, and comparing the two to each other. Reliability was calculated by comparing the variance of the beginning half of the selected EEG recording to the variance of the end half of the selected EEG recording. Variance was calculated as the sum of the square of the deviation of each time point from the mean of all selected time points. Good split-half and test re-test reliability is considered > .90 with an edited sample length of more than 60 s. All test–retest and split-half reliability coefficients used in the analysis were above .90. A Fast Fourier Transform (FFT) was computed on 2-seconds epochs thus yielding a .5 Hz frequency resolution over the frequency range from 0 to 30 Hz for each epoch. The 75% sliding window method of Kaiser and Sterman (2001) was used to compute the FFT in which successive 2-seconds epochs (i.e. 256 points) were overlapped by 500 ms steps (64 points) in order to minimize the effects of the FFT windowing procedure. Relative power was computed from the 19 scalp locations in the following frequency bands: Theta (4–7 Hz); Alpha (7.0–13 Hz); low Alpha (7–10 Hz); upper Alpha (10– 13 Hz) and Beta (12– 24 Hz). Relative power was the ratio of power in a given band/sum of power from 1 to 30 Hz (i.e. total power) × 100. Relative power ratios of the different frequency bands of EEG from a specific electrode were computed for Theta/Alpha, Theta/low Alpha, Theta/upper Alpha, Beta/Alpha, Beta /low Alpha, Beta /upper Alpha. The advantage of using relative power values and not absolute power values is that it eliminates the potential contribution of individual differences in skull thickness and volume conduction.

3. Results

3.1. Behavioral and electrophysiological data handling

Only correct responses were taken into account in calculations of response time (RT) measures. Trials with RT shorter than 100 ms, or higher than 4 SD from the mean score in every RT index and also trials after error were discarded. As a result, 8.7% of the trials were discarded from the Choice Reaction Task, 16% of the trials were discarded from the Switching Task, and 25% of the trials were discarded from the Mental Rotation Task. Most of the discarded trials were post-error trials, but these had to be excluded since it is known that after an error there is a post-error slowing (Laming, 1979; Rabbitt, 1966). We computed six indices extracted from the BEF battery as mentioned in the method Section (2.2). We also added three electrophysiological measures. Two global power activation- one for eyes closed and one for eyes open. These two measures represents the mean power activity of all brain (with activity in each band transformed into z-score before averaging), between 1–40 Hz, as recorded from 19 leads (across-electrodes). Additionally, and we extracted for each participant the individual Alpha frequency (IAF). We used peak (i.e., maximum amplitude) frequency in determining the individual Alpha frequency. The Alpha-range maximum peak frequency was measured over a 4–14 Hz band, using .1 Hz jumps. We computed eyes closed spectrum and eyes open spectrum and then calculated the difference between them and extracted the individual value for the frequency of the maximum alpha activity peak. The frequency of the maximal power in the difference spectrum was taken as an anchor representing the individual peak of the participant (for more details see Klimesch, 1999). Table 1 presents the descriptive statistics of indices as measured from 162 participants. We used a non-parametric correlation (Kendall's tau) analyzing our data. Retest correlations were performed on the 140 participants that accomplished the training program and were therefore tested twice (pre and post-training). Standard deviation in brackets represent the proportion of the *SD* relative to the *SD* based on a nation-wide representative sample (n = 543). These values enable the assessing of the degree of range restriction (which limits the ability to find correlations), with 1.00 indicating no range restriction and values below 1.00 indicating range restriction. As can be seen, our EF indices results indicate a negligible range restriction relative to a large representative sample of the entire Israeli population of young adults. We also added correlation with group intelligence (IRS) in order to demonstrate that although there was a range restriction of high intelligence scores in our study sample in respect to a nation-wide representative sample, it did not affect our EF indices. The correlation between the EF indices and IRS scores (marked in brackets) were taken from the nation-wide representative sample (n

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[7] In general, the test re-test reliability of qEEG is an exponential function of sample length in which 20 s epochs are approximately .8 reliable, 40 s approximately .9 reliable and 60 s asymptotes at approximately .95 reliability (Burgess and Gruzelier, 1993; Van Albada, and Robinson, 2007).

Table 1

Descriptive statistics and retest reliabilities (n = 162). Retest correlations are based on 140 participants who accomplished the training program and were tested twice (pre and post training). Global power activation represents the mean power activity from all brain-placed electrodes (19 leads), between 1–40 Hz. Standard deviation in brackets represent the proportion of the *SD* relative to the *SD* based on a nation-wide representative sample (n = 543). IRS represents intelligence rating score. Correlation with group IRS represents correlations of the indices with IRS. The correlation in brackets represents correlations of the indices with IRS taken from the large representative sample (n = 543).

Measures	*Mean*	*Std. Dev.*	*Correlation with group IRS*	*Median*	*Max*	*Min*	*Skewness*	*Kurtosis*	*Retest*	*α-Cronbach*
Alternative-Cost RT (ms)	521	158 (.59)	−.17** (−.29)***	502	1,182	214	1.30*	2.77*	.69***	.79
6-Choice Tau (ms)	449.80	178 (.88)	-.19** (-.26)***	416	1,218	153	1.20*	2.37*	.70***	.78
Alternation -Cost RT (ms)	1,019	396 (.77)	.13**- (-.08)**	994	2,360	-83	.36	.58	.61 ***	.91
Alternation -Cost in Error proportion	.07	.13 (.91)	-.30*** (-.33)***	.03	.60	-.11	2.41*	5.17*	.52***	.95
Anti-Saccade Error proportion	.29	.16 (1.14)	-.19** (-.32)***	.27	.77	.01	.80*	.30	.77***	.93
Mental Rotation RT (ms)	4,878	1241	.08	5070	8643	912	-.84*	1.40*	.71 ***	.95
Global Power Eyes Closed	9.81	5.88	-.00	8.62	31.85	1.19	1.75*	1.72*	.86***	–
Global Power Eyes Open	5.69	3.09	.05	4.90	20.35	1.61	1.25*	4.02*	.86***	
IAF	9.85	1.00	-.02	9.9	13.00	7.3	-.09	.47	.74***	

* The asterisk represents when Skewness / kurtosis divided by their std. error is greater than > 1.96 or < −1.96.

** $p < .01$.

*** $p < .001$.

= 543) that performed the BEF. As can be seen in Table 1, similar correlations were found between the EF indices and IRS scores in both samples. Moreover, despite of the medium correlations of the indices with IRS, the proportion of *SD* between the samples remained high. Therefore, it seems that our indices are good representative of the Israeli population of that age range. We also computed Cronbach's alpha (using the three different stimuli - letters, digits and shape- as variables) for the EF indices (alternative cost, alternation-cost, 6-choice Tau). Cronbach's alpha for anti-saccade was computed using the separate cue-target intervals (200, 250, 300, 350 ms) as variables. Cronbach's alpha for the Mental Rotation Test was computed using the separate rotation angle (55, 100, 145, and 190) as variables. The Mental Rotation Test was added to the training study and is not considered as a pure EF index. Moreover, it was not included in the nation-wide representative sample, meaning that we cannot tell whether or not there was range restriction there. All measures were both sensible (in the sense of reproducing well established findings such as alternation-cost and alternative-cost) and reliable. Additionally, and as demonstrated, range restriction was minimal. Since range restriction and low reliability compromise correlations, the present results indicate that if there were true correlations between the constructs that the measures represent, our reliable measures and non-restricted sample enabled us to detect them.

Table 2 presents the correlation coefficients between frequency bands power recorded with eyes closed and eyes open, computed separately for each band. Anterior power activation (mean power from 7 leads: Fp1, Fp2, F3, F4, Fz, F7, F8). Posterior power activation (mean power from 7 leads: O1, O2, P3, P4, Pz, T5, T6). As can be seen the correlations between eyes closed and eyes open were quite high (.49–.93). The lowest correlation was found in the upper Alpha band, and is in line with previous studies indicating that upper Alpha is mostly pronounced during eyes closed (Niedermeyer, 1993; Başar, 2012). These results provide additional support for the validity and reliability of our EEG measures.

When computing the core correlations between rsEEG measures and EF indices, we used, aside from standard significance tests, also Bayes Factors (Rouder et al., 2012) using JASP 0.8.1.2 (Love et al., 2015). In "standard" null hypothesis testing (NHT), one can either reject H0 or remain undecided. The advantage of Bayesian statistics and especially Bayes Factor (BF) statistic is that they lead to three outcomes: accepting H0, accepting H1, or remain undecided. Specifically, when multiplying the prior odds (the a-priori belief regarding the relative odds of H1 and H0) by BF, one obtains the posterior relative odds of H0 and H1, given the data. For simplicity, and since we did not have grounds to assume otherwise, the prior odds ratio was assumed to be one, meaning that the BF represents the posterior odds of H0 and H1 given the data. We report BF_{01} (indicating by how much H0 is more probable than H1), but readers should keep in mind that BF10 (the relative odds in favor of H1) equals 1/BF01. The accepted criteria are for BF > 3 (and for H1, BF01 < .333) to indicate some support for the hypothesis, and BF > 10 (and for H1, BF01 < .10) to indicate strong support. We also computed the credible intervals (CI, upper and lower 95%) for each correlation in order to evaluate the likelihood of our sample's results in respect to the population. Specifically, credible intervals are a part of the Bayesian inference system, and indicate the range of correlation values that have 95% posterior probability given the data. However for brevity, we decided only to report the general trend of CI and not to present it for every correlation.

We computed the ratio between Theta and Alpha (Table 3 *A&B*) and the relative power of Alpha and Theta (Table 4 *A&B*) that were correlated (Kendall's tau and Kendall's tau-b) with our EF indices. As can be seen in Tables 3 and 4, H0 was deemed more likely than H1 given these

Table 2

Correlations between frequency bands power recorded with eyes closed and eyes open, computed separately for each band. Global power activation represents the mean power activity of all brain (between 1–40 Hz, across-electrodes). Anterior power activation (mean power from 7 leads: Fp1, Fp2, F3, F4, Fz, F7, F8). Posterior power activation (mean power from 7 leads: O1, O2, P3, P4, Pz, T5, T6).

Band	1–4 Hz *Delta*	4–8 Hz *Theta*	8–10 Hz *Low Alpha*	10–12 Hz *Upper Alpha*	12–15 Hz *Low Beta*	12–25 Hz *High Beta*	30–40 Hz *Gamma*	1–40 Hz *All bands*
Global Power	.79*	.93*	.85*	.49*	.85*	.82*	.60*	.79*
Anterior Power	.79*	.91*	.86*	.47*	.84*	.72*	.50*	.81*
Posterior Power	.76*	.90*	.79*	.49*	.82*	.84*	.77*	.78*

* $p < .001$.

Table 3
Correlations between EF indices and Theta/Alpha ratio in global (mean power activity between 1–40 Hz, across electrodes), frontal location (mean of relative power from 5 leads: Fp1, Fp2, F3, F4, Fz), parietal location (mean of power from 3 leads: P3, P4, Pz) and occipital location (mean of relative power from leads: O1, O2. (A) Eyes open and eyes closed (B). Kendall's tau-b (BF01 in italic) indicates *-moderate or ** strong support for H0.

A. Eyes Open Indices	Alternative Cost RT	6-Choice Tau	Alternation Cost RT	Alternation Cost in Errors	Anti-saccade in Errors	Mental Rotation RT
Global Theta/Alpha	−.01	−.02	.01	−.09	.05	−.07
BF01	9.49	8.67	9.50	2.85	6.16	4.50
Frontal Theta/Alpha	−.03	−.05	−.02	−.10	.02	−.09
BF01	8.42	6.60	8.95	2.41	9.05	2.46
Parietal Theta/Alpha	.00	−.02	.02	−.08	.08	−.05
BF01	9.60	9.21	8.91	3.39	3.07	6.22
Occipital Theta/Alpha	.01	−.03	.02	−.09	.09	−.05
BF01	9.32	8.50	8.98	2.66	2.14	6.22

B. Eyes Closed Indices	Alternative Cost RT	6-Choice Tau	Alternation Cost RT	Alternation Cost in Errors	Anti-saccade in Errors	Mental Rotation RT
Global Theta/Alpha	.06	.03	−.02	−.06	.04	−.05
BF01	8.22	13.42*	13.75*	8.82	11.82*	10.48*
Frontal Theta/Alpha	.05	.01	−.01	−.07	.03	−.06
BF01	10.61*	14.51*	14.58*	7.20	12.40*	8.82
Parietal Theta/Alpha	.06	.04	−.04	−.05	.03	−.05
BF01	8.41	12.01*	10.93*	10.22*	12.56*	9.41
Occipital Theta/Alpha	.07	.03	−.03	−.01	.09	.00
BF01	6.73	13.05*	13.17*	14.43*	3.68	14.91*

results, especially in eyes closed conditions. We add an analysis (Table 5*)* of the correlation between IAF and EF indices since previous studies (e.g. Klimesch, 1999; Hanslmayr et al., 2005; Nan et al., 2012) claimed that there are individual differences between participants in peak Alpha and also since previous study (Clark et al., 2004) found a positive relationship between Alpha peak frequency and WM performance. However, and as can be seen in Table 5, the results indicate support for H0.

We also add an analysis of the Beta and Alpha asymmetry since Ambrosini and Vallesi (2016a) demonstrated a dissociation between mixing-cost and switching-cost that was reflected in frontal asymmetry. It is important to add that there are several non-negligible differences between their study and ours including the use of source localization in their study, which was impossible in our study given the small number of electrodes. We therefore used scalp location in our analysis. Another difference is that Ambrosini and Vallesi (2016a) used separate indices for mixing- cost and switching-cost and we used a single index, "alternation-cost" since our switching task had 100% switching trials, without repeat trials. This made it impossible to compute separate mixing- cost and switching-cost indices. Arguably, since the Beta/Alpha ratio arguably represents a quantitative measure of brain dynamics at rest reflecting increased attentional investment and cortical engagement in information processing (Laufs et al., 2006), we decide to test this measure as well. Furthermore, we used the relative power of Beta (12–24 Hz) and Alpha (8–12 Hz) in the eyes closed condition as in Ambrosini and Vallesi (2016a) study. Beta/Alpha was computed for each electrode (FP1, FP2, F3,F4,F7,F8, P3, P4, O1,O2). Asymmetry was computed as the right – left difference for each pair of scalp electrodes (FP2-FP1, F4-F3, F8-F7, C4-C3, P4-P3, O2-O1). Therefore, higher (i.e., more positive) Beta/Alpha asymmetry values represent a strongly right lateralized brain activity at rest, whereas lower (i.e., more negative) Beta/Alpha asymmetry values represent a strongly left-lateralized brain activity at rest. Table 6 presents the correlations between the EF indices and β/α asymmetry values (A) in frontal, parietal and occipital scalp locations. The Bayesian analysis indicated support for H0 as well. We did the same procedure to Theta/Alpha ratio (B), and found similar results with support for H0.

We also computed the correlations between EEG coherence measures and EF. The results of this analysis also led to the endorsement of H0 and are reported in the *supplementary materials* online. Overall, we performed 1110 correlations (185 rsEEG measures × 6 indices). In most cases (630 out of 1110) that were examined in this study, the credible interval fell between −.10 and +10, suggesting that even if there is a correlation, it is weak by Cohen's (1988) standards. In 394 cases, the credible interval extended beyond .14 and reached up to .20 and in 43 cases (3.9% of the correlations), the credible interval extended beyond .20 and reached up to .24 in four cases, suggesting that if there is a correlation, it was weak-to-moderate at the most. Summarizing the results section, Bayesian statistical inference indicated support for the null hypothesis concerning lack of monotonic correlation between EF and rsEEG spectral power measures. However, we cannot rule out the possibility of small correlations given the sample size that we used.

4. Discussion

The aim of the present study was to investigate the relationship between individual differences in rsEEG and EF. In our study, we tested a relatively large sample of participants, and conducted examination of power spectra measurements and focused on upper Alpha and Theta bands in particular given their putative role in EF. We also computed the ratio and relative power of these bands before correlating them with our EF indices, so as to eliminate the potential contribution of individual differences in skull thickness and volume conduction between participants which can influence rsEEG power. We used a non-parametric correlation (Kendall's tau) for all analysis. We employed Bayesian statistics (Kendall's tau-b) that enabled us to endorse both H0 and H1. Our results predominantly support H0, concerning lack of monotonic correlation between rsEEG measurements (relative, ratio, coherence and asymmetry of Beta/Alpha and Theta/Alpha) and EF. There were very few cases where H0 could not be endorsed, but neither could H1. An alternative approach involves asking what is the range of plausible correlations in the population, given the present results? This range is indexed by the credible intervals which show that even if there is a correlation between the current rsEEG and EF measures, it is weak. Therefore, we conclude that, at least among young healthy adults, the rsEEG indices that we examined are unrelated (monotonically) or weakly related to the measured EF. It is important to add that lack of correlation could be due to faulty study design, namely lack of reliability and range restriction. However, this is not the case since our results indicate excellent psychometric reliability of the measures and negligible range restriction relative to a large representative sample of the entire Israeli population of young adults. Coupled with the predominantly high Bayes factors, the acceptance of the null hypothesis is

Table 4

Correlations between EF indices and relative Alpha and Theta in different scalp locations: global (mean relative power activity between 1–40 Hz, across electrodes), frontal location (mean of relative power from 5 leads: Fp1, Fp2, F3, F4, Fz), parietal location (mean of power from 3leads: P3, P4,Pz) and occipital location (mean of power from 2 leads: O1, O2. (A) Eyes open and eyes closed (B). Kendall's tau-b (BF01 in italic) indicates *-moderate or ** strong support for H0.

A. Eyes Open Indices	**Alternative Cost RT**	**6-Choice Tau**	**Alternation Cost RT**	**Alternation Cost in Errors**	**Anti-saccade in Errors**	**Mental Rotation RT**
Global Alpha	−.01	.01	−.06	.08	−.06	.05
BF01	*9.28*	*9.51*	*5.40*	*3.57*	*4.72*	*6.14*
Frontal Alpha	.00	.02	−.06	.07	−.05	.04
BF01	*9.61*	*9.02*	*5.17*	*3.89*	*6.60*	*7.04*
Parietal Alpha	−.01	.02	−.05	.06	−.06	.05
BF01	*9.58*	*9.22*	*6.19*	*4.77*	*5.29*	*6.78*
Occipital Alpha	−.02	.01	−.04	.08	−.08	.05
BF01	*8.78*	*9.51*	*7.00*	*3.43*	*3.33*	*6.40*
Global Low Alpha	.01	.02	−.07	.06	−.03	−.01
BF01	*9.39*	*9.15*	*4.67*	*5.49*	*8.67*	*9.48*
Frontal Low Alpha	.01	.02	−.07	.07	−.01	.01
BF01	*9.29*	*8.70*	*4.27*	*3.86*	*9.56*	*9.50*
Parietal Low Alpha	.04	.04	−.06	.06	−.02	−.02
BF01	*7.74*	*7.73*	*5.45*	*5.58*	*9.10*	*9.02*
Occipital Low Alpha	−.02	−.01	−.06	.06	−.02	.00
BF01	*9.08*	*9.41*	*5.01*	*5.38*	*9.12*	*9.55*
Global Upper Alpha	−.01	.01	−.02	.04	−.08	.08
BF01	*9.31*	*9.55*	*9.19*	*7.22*	*3.39*	*3.34*
Frontal Upper Alpha	−.02	.02	−.01	.06	−.07	.07
BF01	*9.06*	*9.08*	*9.44*	*5.53*	*4.11*	*3.90*
Parietal Upper Alpha	−.01	.00	−.01	.02	−.07	.06
BF01	*9.44*	*9.61*	*9.30*	*8.87*	*4.61*	*4.73*
Occipital Upper Alpha	.00	.04	−.01	.04	−.07	.06
BF01	*9.60*	*7.42*	*9.35*	*7.46*	*4.13*	*5.59*
Global Theta	−.02	−.03	−.09	−.06	.05	−.08
BF01	*9.18*	*8.46*	*2.29*	*5.11*	*6.72*	*2.96*
Frontal Theta	−.02	−.03	−.10	−.07	.01	−.09
BF01	*8.70*	*8.41*	*2.47*	*4.14*	*9.60*	*2.54*
Parietal Thetax	.00	−.02	−.05	−.06	.09	−.04
BF01	*9.60*	*9.19*	*6.45*	*5.00*	*2.14*	*7.68*
Occipital Thetax	.03	.00	−.02	−.06	.07	−.02
BF01	*8.45*	*9.59*	*9.13*	*4.82*	*4.03*	*9.00*

B. Eyes Closed Indices	**Alternative Cost RT**	**6-Choice Tau**	**Alternation Cost RT**	**Alternation Cost in Errors**	**Anti-saccade in Errors**	**Mental Rotation RT**
Global Alpha	−.05	−.02	−.01	.04	−.03	.04
BF01	*8.98*	*14.05**	*14.94**	*11.23**	*12.70**	*11.04**
Frontal Alpha	−.04	−.01	.00	.04	−.02	.04
BF01	*11.12**	*14.67**	*14.99**	*10.74**	*13.97**	*11.07**
Parietal Alpha	−.06	−.03	.00	.03	−.02	.05
BF01	*8.79*	*13.01**	*14.95**	*12.91**	*14.39**	*10.43**
Occipital Alpha	−.07	−.02	.01	.02	−.07	.01
BF01	*7.17*	*13.83**	*14.86**	*13.50**	*6.22*	*14.70**
Global Low Alpha	−.02	−.01	−.04	.03	−.02	−.01
BF01	*13.83**	*14.98**	*11.45**	*12.32**	*14.34**	*14.72**
Frontal Low Alpha	−.04	−.02	−.03	.02	−.01	−.01
BF01	*12.10**	*14.28**	*13.17**	*13.44**	*14.71**	*14.89**
Parietal Low Alpha	.00	.03	−.04	.05	.00	−.01
BF01	*15.00**	*13.38**	*12.17**	*9.62*	*15.09**	*14.65**
Occipital Low Alpha	−.02	.02	−.02	.03	−.02	−.02
BF01	*14.13**	*14.40**	*14.25**	*12.81**	*13.77**	*14.00**
Global Upper Alpha	−.03	−.03	.03	.01	−.04	.06
BF01	*12.31**	*13.49**	*12.76**	*14.74**	*12.06**	*8.49*
Frontal Upper Alpha	−.03	−.01	.03	.02	−.04	.05
BF01	*13.00**	*14.68**	*13.40**	*13.44**	*10.78**	*9.60*
Parietal Upper Alpha	−.04	−.03	.05	−.02	−.02	.05
BF01	*12.00**	*12.43**	*9.52*	*13.96**	*14.42**	*9.27*
Occipital Upper Alpha	−.03	−.02	.03	.01	−.06	.01
BF01	*12.49**	*13.92**	*12.65*	*14.37**	*7.46*	*14.72**
Global Theta	.03	.01	−.07	−.05	.04	−.02
BF01	*12.68**	*14.78**	*7.12*	*10.44**	*11.46**	*13.58**
Frontal Theta	.01	−.01	−.06	−.06	.04	−.05
BF01	*14.60**	*14.98**	*8.91*	*7.57*	*10.68**	*9.46*
Parietal Theta	.05	.03	−.07	−.03	.03	−.04
BF01	*9.67*	*12.46**	*6.14*	*13.21**	*13.25**	*11.98**
Occipital Theta	.07	.03	−.04	.00	.08	−.01
BF01	*7.28*	*12.34**	*11.08**	*14.80**	*5.19*	*14.89**

warranted in the present case. Although resting-state oscillations arguably act as a functional repertoire from which the brain executes tasks, the spectral analysis approach that is still popular in training studies may be too simplistic to capture behavior-related regularities, as also noted in Gruzelier (2014a) (2014b) reviews. Furthermore, although several studies were able to demonstrate some significant

Table 5
Correlations between EF indices and the individual Alpha frequency (IAF) computed to each participant. Kendall's tau-b (BF01 in italic) indicates *-moderate or ** strong support for H0.

	Alternative Cost RT	6-Choice Tau	Alternation Cost RT	Alternation Cost in Errors	Anti-saccade in Errors	Mental Rotation RT
IAF	.03-	.03-	−.00	−.08	.02-	.04
BF01	*12.42**	*12.54**	*14.72**	*4.75*	*11.82**	*11.66**

Table 6
Correlations between EF indices and Beta/Alpha (A), Theta/Alpha (B) asymmetry in eyes closed condition only. Alpha represent low Alpha and Alpha2 represent upper Alpha. Kendall's tau-b (BF01 in italic) indicates *-moderate or ** strong support for H0.

A. Beta/Alpha Asymmetry	Alternative Cost RT	6-Choice Tau	Alternation Cost RT	Alternation Cost in Errors	Anti-saccade in Errors	Mental Rotation RT
FP2-FP1	.03	−.02	−.02	−.02	.00	−.05
BF01	*8.19*	*9.06*	*9.15*	*8.75*	*9.61*	*6.29*
F4-F3	.07	.04	.02	−.05	−.01	.02
BF01	*4.31*	*7.65*	*8.82*	*5.87*	*9.32*	*9.15*
C4-C3	.01	−.01	.02	−.05	−.01	−.06
BF01	*9.52*	*9.29*	*8.85*	*5.87*	*9.31*	*5.54*
P4-P3	.03	−.02	.03	.01	.05	.02
BF01	*8.61*	*9.23*	*7.90*	*9.34*	*6.27*	*9.08*
F8-F7	.10	.05	.04	−.06	.02	.02
BF01	*3.12*	*6.70*	*7.71*	*5.58*	*9.00*	*9.00*
O2-O1	.07	.04	.03	−.01	.13	.03
BF01	*3.87*	*7.12*	*8.05*	*9.39*	*.76*	*8.25*

B. Theta/Alpha and Theta/Alpha2 Asymmetry	Alternative Cost RT	6-Choice Tau	Alternation Cost RT	Alternation Cost in Errors	Anti-saccade in Errors	Mental Rotation RT
FP2-FP1 Theta/Alpha	.01	.00	−.02	−.06	−.04	.00
BF01	*9.52*	*9.60*	*8.69*	*5.02*	*7.43*	*9.55*
FP2-FP1 Theta/Alpha2	.07	.03	.01	−.06	.04	.01
BF01	*4.03*	*8.65*	*9.50*	*4.89*	*7.22*	*9.34*
F4-F3 Theta/Alpha	.01	.02	.06	−.05	.00	.07
BF01	*9.54*	*9.09*	*5.17*	*6.02*	*9.64*	*4.18*
F4-F3 Theta/Alpha2	.06	.01	.06	−.01	.02	.07
BF01	*5.72*	*9.37*	*5.03*	*9.21*	*9.11*	*4.39*
F8-F7 Theta/Alpha	.03	−.04	.03	.07	.06	.03
BF01	*8.58*	*7.32*	*8.33*	*3.97*	*4.77*	*7.97*
F8-F7 Theta/Alpha2	.04	−.04	.00	.07	.06	.03
BF01	*7.63*	*7.22*	*9.56*	*4.21*	*4.94*	*7.94*
P4-P3 Theta/Alpha	−.06	−.07	−.01	.11	.01	−.01
BF01	*5.29*	*4.51*	*9.46*	*2.33*	*9.41*	*9.26*
P4-P3 Theta/Alpha2	−.05	−.05	−.03	.08	.01	−.03
BF01	*6.11*	*6.25*	*8.62*	*3.33*	*9.30*	*8.29*
O2-O1 Theta/Alpha	.02	.03	−.04	.05	.05	.02
BF01	*9.05*	*8.25*	*7.55*	*6.27*	*6.29*	*8.90*
O2-O1 Theta/Alpha2	.02	.05	−.05	.04	.05	.02
BF01	*8.88*	*6.60*	*6.72*	*7.24*	*6.43*	*9.20*

connections between rsEEG spectral power measures and WM or switching, our data could not support such connections.

Two implications of the present results come to mind. One is the use of neurofeedback to change rsEEG in an effort to improve EF. Our results suggest that at least among young healthy individuals, neurofeedback, at least that involving Alpha and Theta power is unlikely to improve EF, again, at least those EFs that we measured. An outstanding challenge is to explain how some Alpha neurofeedback training studies led to improved mental-rotation ability (Hanslmayr et al., 2005; Zoefel, Huster, & Herrmann, 2011) and how Wang and Hsieh (2013) improved executive attention (closely related to inhibition) using neurofeedback targeting increasing frontal middle Theta.

The other implication concerns the difference between rsEEG and task-evoked EEG. For example, while the current results indicate lack of correlation between EF and Theta power, several studies show increase Theta power during EF task performance (e.g. Roux and Uhlhaas, 2014; Sauseng et al., 2004; Cavanagh and Frank, 2014; Sauseng et al., 2006). One hypothesis is that perhaps, the neurofeedback studies mentioned in the previous paragraph trained participants to increase Alpha or Theta on demand rather than during rest. This hypothesis should be tested in future studies.

5. Limitations

Several limitations of the current study must be acknowledged. First, due to EEG characteristics, we can only refer to electrode locations and not to brain locations. We used only 19 electrodes, a fact that limited our ability to employ localization procedures. Second, our conclusions are valid for the parameters that were examined and not to rsEEG in general, meaning that we cannot rule out the possibility that other parameters would have yielded correlations with EF. The same holds true for our EF testing that provide a decent but of course incomplete coverage of the domain. Thus, it may be beneficial to explore in the future other rsEEG parameters especially those related to network connectivity. Finally, and as mentioned before we cannot rule out the possibility of very small correlations given the sample size that we used).

6. Conclusion

In a large group of healthy young adults, we demonstrate a lack of monotonic correlation between rsEEG measurements (relative power, ratio, asymmetry, coherence) and EF.

Acknowledgments

The study was supported by the Israel Defense Forces (IDF) Medical Corps and Directorate of Defense Research & Development, Israeli Ministry of Defense (IMOD DDR&D). We would like to thank Col. Dr. Erez Carmon, Col. Dr. Eyal Fructer and Lut. Idit Oz for supporting this study. Dr. Arik Eisenkraft and Dr. Linn Wagnert-Avraham and Mr. Raeed Kayouf from the Institute for Research in Military Medicine, the Hebrew University Faculty of Medicine, Jerusalem. And also to Mr. Erez Gordon and Prof. Robert Thatcher for their invaluable help and professional knowledge.

Author contributions

Shirley Gordon had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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Analysis and interpretation of data

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Conflict of interest disclosures

All authors report no financial, personal or other relationships with commercial interests.

Indications of previous presentation

No previous presentation, nor date(s) or location of meeting

Funding/ support

The study was supported by the Israel Defense Forces (IDF) Medical Corps (394721) and Directorate of Defense Research & Development, Israeli Ministry of Defense (IMOD DDR&D) (4440587607).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.neuropsychologia.2017.10.031.

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