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Research Report

Brain oscillatory 4–30 Hz responses during a visual *n*-back memory task with varying memory load

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A B S T R A C T

Brain oscillatory responses of 4–30 Hz EEG frequencies elicited during the performance of a visual *n*-back task were examined in 36 adult volunteers. Event-related desynchronization (ERD) and event-related synchronization (ERS) responses were examined separately for targets and non-targets in four different memory load conditions (0-, 1-, 2- and 3-back). The presentation of all stimuli in all memory load conditions elicited long-lasting theta frequency (~4–6 Hz) ERS responses which were of greater magnitude for the target stimuli as compared to the non-target stimuli. Alpha frequency range (~8–12 Hz) ERD responses were observed in all memory load conditions for both targets and non-targets. The duration of these alpha ERD responses increased with increasing memory load and reaction time. In all memory load conditions, early appearing beta rhythm (~14–30 Hz) ERD responses were elicited, and with increasing memory load, these beta ERD responses became longer in duration. Additionally, beta ERS responses were observed in the 0- and 1-back memory load conditions. The current results reveal a complex interplay between brain oscillations at different frequencies during a cognitive task performance.

1. Introduction

Working memory can be considered as a cluster of dynamic modules (a central executive with slave systems, such as a phonological loop and a visuospatial sketchpad) operating on a time scale of seconds (Baddeley, 1986, 2003). Working memory is necessary for “online” information processing and information storage needed for complex cognitive processing, such as language comprehension, learning and reasoning (Baddeley, 1986, 2003). Cognitive processing requires the transient integration of numerous, widely distributed, constantly interacting areas of the brain (Basar, 2005; Basar et al., 2001a; Fuster, 2000; Klimesch, 1996; Ward, 2003). It has been proposed that such complex cognitive processes could be implemented by synchronization of neurons into transient oscillatory assemblies (Singer, 1999; Varela et al., 2001), i.e., the formation of dynamic links mediated by neuronal synchrony. Such neuronal synchrony (or desynchrony) can be assessed by means of scalp recorded electroencephalogram (EEG).

The EEG signal can be decomposed into oscillatory components of different frequencies and the wavelet analysis method allows for the inspection of the EEG signal simultaneously as a function of time and frequency (e.g., in Basar et al., 2001b). It is now acknowledged that human scalp recorded EEG oscillatory responses at different frequencies can be related to several aspects of cognitive functioning ranging

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from stimulus processing, attention, working memory to long-term memory (Basar et al., 1999, 2001a; Klimesch, 1999; Ward, 2003). For example, increased theta frequency range (~3–8 Hz) oscillatory responses have been reported in association with working memory functions (see e.g., Bastiaansen and Hagoort, 2003; Kirk and Mackay, 2003; Klimesch, 1996; Rizzuto et al., 2003), responding to e.g., memory load (Jensen and Tesche, 2002) and task demands (Gevins et al., 1997; Raghavachari et al., 2001). Also target stimulus detection has been reported to be associated with increased theta responses (Klimesch et al., 2000; Mazaheri and Picton, 2005). Event-related responses of the alpha frequencies (~6–12 Hz) have been related to e.g., attention, alertness (Klimesch et al., 1998) and memory processes (Klimesch, 1999; Krause et al., 1996; Krause et al., 1999). Typically, increased cognitive load is associated with decreases in alpha power (Gevins et al., 1997; Krause et al., 2000; Stipacek et al., 2003). The responses of the beta frequencies (~20 Hz) were first associated with the activity of the motor cortices in relation to movement (Pfurtscheller et al., 1998; Stancak and Pfurtscheller, 1996), movement planning (Alegre et al., 2003; Kaiser et al., 2001) and motor imagery (Pfurtscheller and Neuper, 1997). Recently, beta rhythm responses have been reported also in association with cognitive processing (Karrasch et al., 2004; Kopp et al., 2004; Pesonen et al., 2006; Tallon-Baudry, 2003; Weiss and Rappelsberger, 1998).

Event-related oscillatory EEG responses can be quantified e.g., by means of the event-related desynchronization method (ERD) (Pfurtscheller and Aranibar, 1977; Pfurtscheller and Lopes da Silva, 1999). In this method, a relative decrease in the power of a certain frequency band during stimulus processing (as compared to a no-stimulation reference) is called event-related desynchronization (ERD), whereas the opposite, a relative increase in the power is called event-related synchronization (ERS) (Pfurtscheller and Lopes da Silva, 1999). The ERD/ERS values are within-subject measures of relative changes in the EEG (Krause, 2003; Pfurtscheller and Lopes da Silva, 1999). As is the case with the EEG, also the ERD/ERS technique is characterized by a relatively good temporal resolution and provides a suitable method to assess dynamic brain oscillatory responses during cognitive processing.

In cognitive neuroscience, one widely used experimental paradigm in studies of working memory is the so-called *n*-back task, in which the subjects are instructed to monitor a sequence of stimuli and to respond whether a stimulus presented is the same as the one presented *n* trials previously (where *n* is a pre-specified integer, varying usually from 0 to 3). During the performance of this working memory task the stimuli are sequentially registered and stored, and the task performance requires continuous updating of stimulus information. The increase of memory load in the *n*-back task is typically witnessed on the behavioral level as increased reaction times and as enhanced number of incorrect responses.

Reports on brain oscillatory responses during the performance of the *n*-back task are hitherto scarce. In year 2000, Krause et al. reported of brain oscillatory (ERD/ERS) responses of the 4–12 Hz EEG frequencies during a visual *n*-back task utilizing the 0-, 1- and 2-back memory load conditions (Krause et al., 2000). In that study, the ERD/ERS responses of the theta frequencies (4–6 Hz) were found to dissociate between targets and non-targets such that these responses were greater for the target stimuli. In contrast, the ERD/ERS responses of the alpha frequencies (8–12 Hz) distinguished between the different memory load conditions such that the alpha ERD responses were of greatest magnitude and of longest duration in the highest memory load condition (Krause et al., 2000).

The aim of the current study was to evaluate the human brain oscillatory response system associated with cognitive processing by means of assessing the ERD/ERS responses of the 4–30 Hz EEG frequencies during a visual working memory task with four memory load conditions. Thus, we partially replicated the study by Krause et al. (2000), however, using four memory load conditions (as compared to the three levels in the year 2000 study). In addition, in the current study we analyzed the responses of a broad EEG frequency band (4–30 Hz) as a function of time (0–1800 ms) and for five electrode sites. This experimental and analysis setting allowed us to make more detailed observations on the brain oscillatory system during working memory processing.

2. Results

The behavioral results (mean RTs and percentages of correct answers) are displayed in Table 1.

As can be seen from Table 1, the reaction times increased and the number of correct responses decreased with increasing memory load. Due to these observations, the main effect for the factor LOAD was statistically significant on both reaction times ($F(1.168,40.9)=34.1$, $p<0.001$) and percentages of correct answers ($F(1.83,64.1)=56.175$, $p<0.001$).

The statistically significant ($p<.01$) mean ERD/ERS values for the four memory load conditions (0-, 1-, 2- and 3-back), separately for the non-target and target stimuli and for the five electrode locations, are displayed in Fig. 1 (in A) for the non-targets and (in B) for the targets. In addition, in Fig. 1, the statistically significant differences ($p<0.01$) between the ERD/ERS responses elicited in different memory load conditions (in C) for the non-targets and (in D) for the targets and between the ERD/ERS responses elicited for the target and non-target stimuli (E) are presented.

As can be seen in Fig. 1, in general, ~4–6 Hz ERS responses were elicited at 0–1800 ms in all memory load conditions for both targets and non-targets. Higher frequency (~14–23 Hz) ERS responses were witnessed only in the 0- and 1-back memory load conditions at ~500–1800 ms. As a function of

Table 1 – Mean (SD) reaction times (s) and percentages of correct answers for the four different memory load conditions

Memory load condition	0-back	1-back	2-back	3-back
Correct responses % (SD)	98.71 (1.00)	96.95 (1.90)	96.08 (2.72)	92.55 (4.13)
Reaction time (s) (SD)	0.432 (0.105)	0.514 (0.164)	0.832 (0.450)	1.344 (0.924)