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EEG correlates of cognitive load in a multiple choice reaction task

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The present study aimed to examine EEG correlates of cognitive load in a task, in which multiple stimulus-response mappings have to be maintained in working memory (WM) combined with selective inhibition of irrelevant stimulus-response mappings on every trial. Twenty-four healthy younger adults had to perform choice reaction tasks differed in the number of S-R mappings and motor response requirements. Performance was lower in the high load than in the low load condition. Performance decline at higher WM loads was accompanied by an increase of EEG power in delta, theta, and beta frequency bands and by a reduction in alpha band. The effect on alpha was generalized across all the electrodes. Correlations between EEG and performance were observed in the high load condition but not in the low load condition. Theta activity negatively correlated with reaction time, whereas positive correlations between beta activity and reaction time were found. The two frequency bands negatively correlated with each other at all electrodes. The results suggest that changes in alpha and theta power may be considered as the most sensitive indicators of cognitive load. The alpha reduction may be related to activation of widespread cortical areas which were recruited for performance of complex WM tasks. The beta increase, especially in the beta-2 range, may partly be associated with activation of motor cortex due to difficulties in preparation and execution of motor responses. Theta increases may be considered as an index of facilitation of information processing in WM and improvements in higher-order executive control, which in turn facilitates motor processes.

Key words: EEG, cognitive load, working memory, inhibition, multiple choice

INTRODUCTION

Modern work is characterized by an increase in cognitive load, multitasking and time pressure. These factors require the involvement of higher-order psychological functions of workers, especially working memory (WM), a system providing temporary storage and processing of information necessary for the currently relevant task (Baddely, 1992). This makes WM to an essential cognitive function providing flexible action regulation and adjustment to environmental demands. The ability to inhibit old or no more relevant information is considered to be critical for efficient WM functioning (Zacks and Hasher, 1994). Poor inhibition leads to intruding of irrelevant information into WM and reduces its capacity (Vogel and Machizawa, 2004; Borella, 2008). The inhibition is also critical for a situation in which multiple stimulus-response (S-R) associations (S-R mappings) or task sets should be maintained in WM and compete with each other for an access to a motor response. This kind of inhibition has extensively been investigated in the task switching paradigm when participants had to switch between two or three tasks (e.g. Kiesel et al., 2010; Schapkin et al., 2014). In the switching experiments both irrelevant tasks and S-R mappings have to be inhibited. The inhibition of the irrelevant S-R mappings per se has usually been examined in the choice reaction time tasks when participants have to decide between up to four response alternatives (e.g. Yordanova et al., 2004). However, these tasks were relatively easy due to small amount of S-R mappings which should be maintained in WM during task performance. In contrast, little is known about inhibition processes in choice reaction

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tasks with multiple S-R mappings, which maintenance would widely exceed the WM capacity (i.e. three chunks of associative information, see Cowan et al., 2012).

The electroencephalogram (EEG) is a widely acknowledged and valid method for assessing cognitive load. The majority of EEG studies have reported changes in spectral power of theta and alpha frequency bands during task performance. Theta power is usually enhanced in a variety of tasks with high WM demands (Gevins et al., 1997; 2000; Smith et al., 1999; McEvoy 2001; Deiber et al., 2007; Itthipuripat et al., 2013; Gärtner et al., 2014; Ozdemir et al., 2016).

The effects of mental load on alpha band power are inconsistent. Alpha power is usually reduced in attention demanding tasks (Gundel and Wilson, 1992; Ergenoglu et al., 2004) and under WM load (Gevins et al., 1997; McEvoy et al., 2001). However, there are studies reported an increase in alpha power with increased WM load (Jensen et al., 2002; Herrmann et al., 2004; Johnson et al., 2011; Ozdemir et al., 2016).

Findings on EEG beta oscillations as responses to cognitive demands are scarce. Gundel and Wilson (1992) found that beta activity (13.5-32 Hz) was lower for the higher difficulty level of a visual scanning task. In the n-back task (Kirchner, 1958) a higher parietal beta power (15-25 Hz) was associated with enhanced task difficulty (Deiber et al., 2007). Nevertheless, there are a body of research reporting a relationship between EEG beta activity and motor processes. Beta power usually decreases over the brain areas contra-lateral to the response hand before a movement and increases when the movement is completed (Pfurtscheller and Da Silva, 1992). Interestingly, similar effects were found not only for real hand movements but also for action imagination (Neuper et al., 2009) and action observation (Koelewijin et al., 2008).

Oscillations in the low frequency EEG band (1-3 Hz), labeled as delta activity, have predominantly been discussed in context of sleep research as an index of unspecific decrease in brain arousal level during transition from the waking state to sleep (see Knyazev 2012, for review). In this context it appears plausible that delta activity increases in prolonged tasks probably due to fatigue (Hoedlmoser et al., 2011). Nevertheless, there are studies which have consistently reported that delta activity also increased in short-term cognitive tasks (Fernández et al., 2002; Harmony et al., 2009; Dimitriadis et al., 2010; Ozdemir et al., 2016).

Recovery from cognitive load is of high practical relevance. The comparison between the baseline and the recovery can provide information on possible after-effects of cognitive load such as fatigue or monotony. However, we did not find such data at all and can only capitalize on research used prolonged driving tasks. In these studies EEG during task performance was continuously recorded while time-on-task effects were analyzed. Authors consistently reported an increase in theta power (Lal and Craig, 2002; Hoedlmoser et al., 2011; Zhao et al., 2012; Wascher et al., 2014) and, in some cases, also increases in alpha and decreases in beta activity (Zhao et al., 2012). In addition, the overnight driving stimulation led to a sharp increase in delta power (Hoedlmoser et al., 2011).

Taken together, EEG oscillations in different frequency bands may be considered as valid indicators of WM load. The inconsistencies of results are probably due to a variety of experimental tasks differed in difficulty level and type of cognitive functions recruited. Nevertheless, following pattern of EEG responsivity to WM load appears to be mostly typical: the increase in theta and the decrease in alpha activity.

The aim of the present study was to examine EEG correlates of cognitive load in a multiple choice reaction task (MCRT, high load condition). First, the particularity of the task is the conflict between the long-term maintenance of nine S-R mappings and inhibition of currently irrelevant S-R mappings on every trial. Second, the number of S-R mappings widely exceeds the WM capacity (i.e. three chunks of associative information, see Cowan et al., 2012). Third, the S-R mappings are distributed across stimulus modalities (visual *vs.* acoustic) and type of motor responses (hand *vs.* foot). Finally, selective inhibition of currently irrelevant S-R mappings was strengthened by applying time pressure. To our knowledge, this is the first study devoted to EEG correlates of cognitive load in such type of tasks, which also have a great practical relevance for modern working conditions requiring continuous switching of attention under time pressure. To examine whether brain activity progressively changes with task difficulty we used a simple choice reaction task (SCRT, low load condition) as a "control" condition where only one relevant S-R mapping should be maintained in WM during task performance. The low load condition also contained low motor demands as participants had to use one response button only and no time pressure was applied.

In the high load condition lowered performance in terms of accuracy or reaction time (RT) was expected. An increase in theta and a reduction in alpha activity should be seen with increasing WM load. Keeping in mind a possible relation of beta activity to motor processes, the increase of beta power in a task with high motor demands was also expected. Finally, we examined the after-effects of cognitive load by the comparison of the baseline with the recovery condition. Following the studies of simulated driving we expected EEG changes with time on task which may indicate mental fatigue, e.g. the delta increase. Alternatively, EEG correlates of cognitive facilitation due to practice could also be obtained.

METHODS

Participants

Twenty-four healthy younger adults (20–42 years old, mean=25.16, standard deviation (SD)=4.59, 13 women, 11 men) participated in the experiment. The exclusion criteria were cardiovascular, neurological or psychiatric disorders, head injury, use of psychoactive medications, or drugs. All participants were right-handed according to Flinders Handedness survey (Nichols et al., 2013), native German speakers, and had normal or corrected-to-normal vision. Informed consent was obtained from all participants included in the study. The experiment was approved by the Ethics Council of University of Magdeburg.

Task

The low load condition was simulated by the simple choice reaction task (Original: The Reaction Test, form S3, Vienna Test System, Austria; Schuhfried, 2013) contained five stimulus types: red circle, yellow circle, tone of 2000 Hz, red circle with tone of 2000 Hz and yellow circle with tone of 2000 Hz. Visual stimuli appeared at two middle lower positions of the computer screen, while acoustic stimuli were presented via loudspeaker. Participants had to press the black button by the right middle finger when the yellow circle was accompanied by a tone and refrain from pressing when other four stimulus types were presented. Both speed and accuracy were emphasized in the instruction. Stimuli were presented for 1200 ms, the inter-stimulus interval randomly varied from 1500 to 4000 ms. The trial block consisted of 48 trials (16 targets) and lasted about 6 min.

The high load condition was simulated by the multiple choice reaction task (Original: The Determination Test, form S2, Vienna Test System, Austria) contained five circles (red, white, blue, green, yellow) randomly appeared at ten positions of the computer screen (Fig. 1). Additionally, two gray rectangles were randomly presented at the left and right lower corners of the screen. Finally, two acoustic signals of low (250 Hz) and high (1000 Hz) frequencies via loudspeaker were presented. Participants had to respond to the stimuli by pressing various buttons by the right middle finger and by the right and left feet according to following stimulus-response mappings, see Table I.

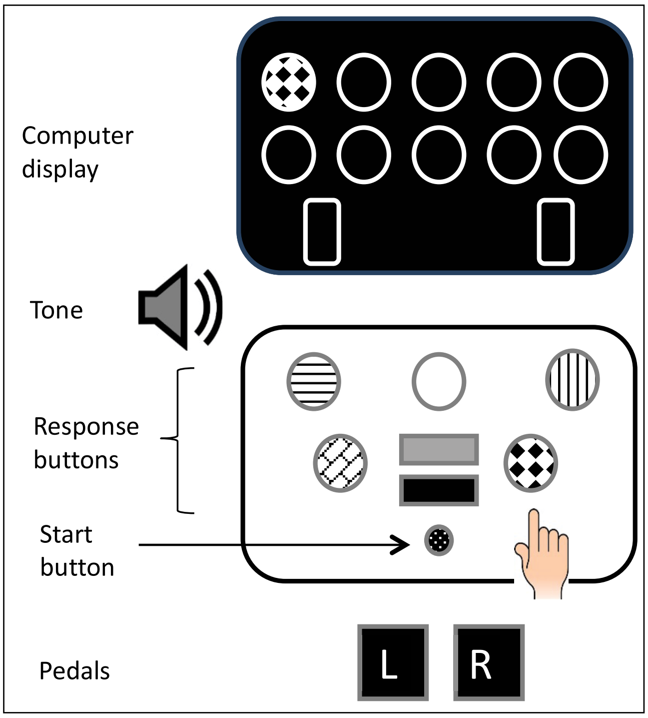

Fig. 1. Task equipment for the multiple choice reaction task. The colour response buttons and colour stimuli are presented in black-and-white patterns.

Table I. Stimulus-response mappings in the low and high load conditions.

Low load condition		High load condition	
Stimulus	Response	Stimulus	Response
yellow circle with tone	black button	red circle	red button
red circle with tone	no response	blue circle	blue button
yellow circle	no response	green circle	green button
red circle	no response	yellow circle	yellow button
tone	no response	white circle	white button
		low tone	black button
		high tone	gray button
		gray rectangle left	foot pedal left
		gray rectangle right	foot pedal right

In contrast to the SCRT, the stimuli in the MCRT were presented randomly using an adaptive algorithm. The presentation time of a stimulus was speeded up or down depending on the mean reaction time to eight antecedent responses. By this time pressure participants were kept at the limits of their processing capacity. The trial block lasted 8 min but the trail number per block varied across participants (range: from 484 to 686 trials, mean=567, SD=53) due to the adaptive presentation algorithm. Both speed and accuracy were emphasized in the instruction.

To control the response hand position in both tasks, participants had to keep the response finger (middle right finger) on the start button placed below the response buttons until a stimulus has been presented and return the finger to the start button after the response.

Ratings of perceived cognitive load

The perceived cognitive load was assessed by the Borg scale (Borg, 1982). Originally, the Borg scale was developed for measuring of exertion in sport exercises and is recommended by the guidelines of the American Heart Association as a tool for measuring an individual's exertion and fatigue during physical work. In the present study participants rated their cognitive load after each task by the scale from 6 – "no exertion at all" to 20 – "maximal exertion".

EEG recording

EEG was continuously recorded from 13 scalp electrodes (Fp1, Fp2, FT9, FT10, Fz, FCz, Pz, C3, C4, TP9, TP10, O1, O2) mounted on an elastic cap according to the "10–20" system against Cz and then re-referenced to averaged mastoids offline. The vertical EOG was recorded from FP2 and IO electrodes placed above and below the right eye. For assessing the horizontal EOG, FT9 and FT10 electrodes were used as they were placed next to the outer canti of eyes. Electrode impedance was kept below 10 kΩ. EEG and EOG were sampled with bandpass DC – 131 Hz and a rate of 500 Hz by the mobile LiveAMP recorder (Brain Products, Germany).

In the high load condition multiple eye movement artifacts strongly contaminated the EEG signal as participants had to look at the rapidly presented stimuli appeared at various positions of the computer screen. As artifacts of complex form could not be sufficiently eliminated by common correction algorithm (Gratton et al., 1983), they were corrected using the independent component analysis (ICA, Makeig et al., 1996) implemented in the Brain Vision Analyser (Brain Products, Germany). Additionally, 2 s EEG segments with the amplitude exceeded +/– 100 µV were rejected. The EEG was filtered digitally offline with a 30 Hz low and 1 Hz high pass. Thereafter the 2 s EEG segments were analyzed by fast Fourier transform (FFT) with the spectral resolution of 0.5 Hz. The total power (P_{total}, μV^2) was computed for each 2 s EEG segment in the range of 1-30 Hz and then each power value of the spectrum for each 2 s EEG segment was calculated as follows: $P_{normalized}=P_{freq} / P_{total} * 100$ (whereby P_{freq} is the power at each individual frequency bin). Thereafter, the normalized spectral power in 2 s EEG segments was averaged separately for each subject, frequency band (delta: 1-3 Hz; theta: 4-7 Hz; alpha: 8-13 Hz; beta-1: 14-19 Hz; beta-2: 20-30Hz), electrode, and experimental condition ("baseline", "low load", "high load", "recovery"). The frequency bands were separated by 1 Hz breaks for avoiding overlaps between the bands.

Procedure

After electrode application a training session for each task was given until participants learned stimulus-response mappings and correctly responded all the training trials. Thereafter, participants conducted the main trial block for each task. The task order was counterbalanced across participants. Before the tasks a 5 min baseline was recorded. Participants were instructed to sit quietly and relaxed with open eyes and look at the black computer screen. At the end of the experiment a recovery measurement of 5 min with the same instruction was conducted.

Statistical analysis

Performance and EEG measures were subjected to an ANOVA with "load" ("baseline", "low load", "high load", "recovery") as a within-subject factor. The Huynh-Feldt-corrected p-values were computed, if necessary. The Bonferroni corrected T-tests were applied to examine significant ANOVA effects. In addition, Pearson correlations between performance, perceived cognitive load, and EEG power spectra for each task and electrode were computed. The statistical analysis was conducted by IBM SPSS 24.0.

RESULTS

Performance

Participants responded slower in the high load condition (M=753.75; SD=63.51) than in the low load condition (M=517.08; SD=83.99; t=14.06; df=23; p <.001). The error percentage was higher under high load (M=8.38; SD=4.88) than in the low load condition (M=0.43; SD=1.06, t=8.03; df=23; p <.001).

Ratings of perceived cognitive load

The subjective task difficulty was higher under high load (M=15.17; SD=1.55) than in the low load condition (M=10.00; SD=2.06; t=13.29; df=23; p <.001). Qualitatively, the subjective exertion in the high load condition was rated by the participants between "high" and "very high", while in the low load condition between "low" and "very low". According to the rating, the high load condition remained within the limits of participant's cognitive capacity and exerted only moderate subjective load. The majority of participants described this task as "interesting" some of them also as "amusing" despite of its high difficulty.

EEG power spectra

In this section the F and p values for significant effects on EEG power spectra are described as follows. First, general effects for each frequency band are reported which were observed for the majority of electrodes. Then, specific effects seen at particular electrodes only are described. Detailed information about means, SDs of EEG power spectra as well as results for paired comparisons between experimental conditions for different frequency bands is presented in the Table II.

Delta (1-3 Hz)

Delta power increased in both tasks compared with the recovery. The effect was significant at C3 ($F_{(2,50)}$=8.10, p<.001), C4 ($F_{(2,50)}$=6.58, p<.002), Fz ($F_{(2,39)}$=6.67, p<.005), FCz ($F_{(2,40)}$=8.19, p<.009), Cz ($F_{(2,47)}$=14.06, p<.001), Pz ($F_{(2,54)}$=14.30, p<.001), TP9 ($F_{(2, 49)}$=10.00, p<.001), and TP10 ($F_{(2,34)}$=6.65, p<.007). Delta power was also larger in the low load condition than in both baseline and recovery at TP10 ($F_{(2,34)}$=6.65, p<.007) as well as it was larger under low load than in the recovery at Cz ($F_{(2,47)}$=14.06, p<.001) and Pz ($F_{(2,54)}$=14.30, p<.001). In addition, delta power increased under high load compared with the recovery at FP1 ($F_{(2,50)}$=6.09, p<.003) and FP2 ($F_{(2,53)}$=5.89, p<.003). Delta power also decreased in the recovery relative to the baseline at FCz ($F_{(2,40)}$=8.19, p<.009), Cz ($F_{(2,47)}$=14.06, p<.001), Pz ($F_{(2,54)}$=14.30, p<.001), and TP10 ($F_{(2,34)}$=6.65, p<.007) as well as under low load compared with the baseline at O1 ($F_{(2,43)}$=4.17, p<.03). Finally, delta power was larger under low load relative to the baseline at Cz ($F_{(2,47)}$=14.06, p<.001) and Pz ($F_{(2,54)}$=14.30, p<.001).

Theta (4-7Hz)

Two effects of experimental conditions on theta power were obtained. First, theta power was larger in the high load condition than in both baseline and recovery. The effect was significant at FP1 ($F_{(3,55)}$=7.95, p<.001), FP2 ($F_{(2,57)}$=6.88, p<.001), C3 ($F_{(2,47)}$=7.21, p<.002), Fz ($F_{(2,40)}$=6.40, p<.005), FCz ($F_{(2,46)}$=7.25, p<.002), Cz ($F_{(2,53)}$=8.08, p<.001), Pz ($F_{(3,62)}$=13.10, p<.001), TP9 ($F_{(2,51)}$=4.56, p<.01), and TP10 ($F_{(2,41)}$=5.20, p<.01). Also at lower loads an increase in theta power relative to the recovery was found. The effect was significant at C3 ($F_{(2,47)}$=7.21, p<.002), C4 ($F_{(2, 51)}$=3.40, p<.04), TP9 ($F_{(2,51)}$=4.56, p<.01), TP10 ($F_{(2,41)}$=5.20, p<.01). Theta power also increased in the high load condition compared with the low load condition at Pz ($F_{(3,62)}$=13.10, p<.001), and under high load compared with the recovery at FT9 ($F_{(2,45)}$=5.81, p<.004). In contrast, a decrease in theta power at lower loads as compared to the baseline at O1 ($F_{(2,45)}$=7.90, p<.001) and O2 ($F_{(2,39)}$=7.27, p<.003) was observed.

Alpha (8-13Hz)

The effect of experimental conditions on alpha power was the greatest and more widespread across electrodes as compared with other frequency bands. A clear-cut decrease in alpha power under high cognitive load relative to other experimental conditions was obtained. The effect was significant at FP1 ($F_{(2,57)}$=17.65, p<.001), FP2 ($F_{(3,60)}$=20.55, p<.001), FT9 ($F_{(3,51)}$=21.94, p<.001), FT10 ($F_{(3,69)}$=16.93, p<.001), C3 ($F_{(3,63)}$=53.98, p<.001), C4 ($F_{(3,69)}$=41.43, p<.001), Fz ($F_{(2,49)}$=39.85, p<.001), FCz ($F_{(2,54)}$=49.71, p<.001), Cz ($F_{(3,63)}$=71.28, p<.001), Pz ($F_{(3,62)}$=50.80, p<.001), TP9 ($F_{(3,61)}$=44.08, p<.001), TP10 ($F_{(2,49)}$=41.09, p<.001), O1 ($F_{(2,46)}$=15.89, p<.001), and O2 ($F_{(2,55)}$=15.42, p<.001). Moreover, alpha power was smaller at lower loads than in the recovery at all the electrodes except FT9, O1 and O2: FP1 ($F_{(2,57)}$=17.65, p<.001), FP2 ($F_{(3,60)}$=20.55, p<.001), FT10 ($F_{(3,69)}$=16.93, p<.001), C3 ($F_{(3,63)}$=53.98, p<.001), C4 ($F_{(3,69)}$=41.43, p<.001), Fz ($F_{(2,49)}$=39.85, p<.001), FCz ($F_{(2,54)}$=49.71, p<.001), Cz ($F_{(3,63)}$=71.28, p<.001), Pz ($F_{(3,62)}$=50.80, p<.001), TP9 ($F_{(3,61)}$=44.08, p<.001), and TP10 ($F_{(2,49)}$=41.09, p<.001). Finally, alpha power increased in the recovery compared with the baseline at all the electrodes: FP1 ($F_{(2,57)}$=17.65, p<.001), FP2 ($F_{(3,60)}$=20.55, p<.001), FT9 ($F_{(3,51)}$=21.94, p<.001), FT10 ($F_{(3,69)}$=16.93, p<.001), C3 ($F_{(3,63)}$=53.98, p<.001), C4 ($F_{(3,63)}$=41.43, p<.001), Fz ($F_{(2,49)}$=39.85, p<.001), FCz ($F_{(2,54)}$=49.71, p<.001), Cz ($F_{(3,63)}$=71.28, p<.001), Pz ($F_{(3,62)}$=50.80, p<.001), TP9 ($F_{(3,61)}$=44.08, p<.001), TP10 ($F_{(2,49)}$=41.09, p<.001), O1 ($F_{(2,46)}$=15.89, p<.001), and O2 ($F_{(2,55)}$=15.42, p<.001)

Table II. Means, SDs (in parenthesis), F-values, and T-tests for EEG power spectra. * – p<0.05; ** – p<0.01; ***–- p<0.001; ns – non-significant.

Electrode	Experimental condition				F	T-Tests (Paired comparisons)
	1-Baseline	2 -Low Load	3- High Load	4 -Recovery		
Delta (1-3Hz)						
Fp1	11.26 (3.46)	11.36 (3.79)	14.03 (3.62)	10.68 (2.39)	6.09**	3 *vs.* 4 (t=3.30, p<.003)
Fp2	11.75 (3.54)	11.98 (4.22)	14.20 (3.66)	10.76 (2.64)	5.89**	3 *vs.* 4 (t=3.43, p<.002)
FT9	12.57 (3.99)	11.33 (4.44)	13.21 (3.39)	11.04 (3.32)	2.70*	ns
FT10	12.61 (4.50)	12.62 (4.56)	13.74 (3.42)	11.60 (2.69)	ns	ns
C3	10.16 (3.30)	11.83 (3.41)	11.85 (3.51)	8.97 (2.73)	8.10***	2 *vs.* 4 (t=6.60, p<.001); 3 *vs.* 4 (t=3.37, p<.003)
C4	10.20 (3.26)	11.60 (3.67)	12.03 (3.81)	9.47 (2.73)	6.58**	2 *vs.* 4 (t=5.36, p<.001); 3 *vs.* 4 (t=3.32, p<.004)
Fz	11.52 (3.16)	12.74 (3.52)	13.21 (3.39)	10.43 (2.57)	6.67**	2 *vs.* 4 (t=6.14, p<.001); 3 *vs.* 4 (t=3.30, p<.003)
FCz	11.90 (3.74)	12.94 (3.52)	13.98 (4.53)	10.45 (2.87)	8.19**	1 *vs.* 4 (t=3.35, p<.003); 2 *vs.* 4 (t=5.40, p<.001); 3 *vs.* 4 (t=4.28, p<.001)
Cz	11.33 (3.10)	13.16 (3.69)	13.25 (3.49)	9.94 (2.45)	14.06***	1 *vs.* 2 (t=-3.41, p<.002); 1 *vs.* 3 (t=-2.97, p<.007); 1 *vs.* 4 (t=3.94, p<.001); 2 *vs.* 4 (t=7.83, p<.001); 3 *vs.* 4 (t=4.84, p<.001)
Pz	10.98 (3.19)	12.68 (3.97)	12.76 (3.91)	9.26 (2.50)	14.30***	1 *vs.* 2 (t=-3.46, p<.002); 1 *vs.* 3 (t=-2.56, p<.02); 1 *vs.* 4 (t=4.45, p<.001); 2 *vs.* 4 (t=6.56, p<.001); 3 *vs.* 4 (t=4.54, p<.001)
TP9	11.05 (3.56)	12.54 (3.68)	13.34 (4.23)	9.71 (2.59)	10.00***	2 *vs.* 4 (t=6.04, p<.001); 3 *vs.* 4 (t=4.38, p<.001)
TP10	10.90 (2.80)	12.44 (3.44)	11.97 (3.33)	9.74 (2.44)	6.65**	1 *vs.* 2 (t=-3.71, p<.001); 1 *vs.* 4 (t=3.48, p<.002); 2 *vs.* 4 (t=7.02, p<.001)
O1	9.02 (3.15)	7.81 (3.22)	7.02 (3.98)	7.98 (2.74)	4.17*	1 *vs.* 2 (t=2.86, p<.009)
O2	9.11 (3.48)	8.25 (3.93)	7.36 (4.31)	8.11 (2.71)	ns	ns
Theta (4-7Hz)						
Fp1	7.30 (2.28)	7.81 (2.75)	9.11 (2.59)	7.14 (2.02)	7.95***	1 *vs.* 3 (t=-2.83, p<.01); 3 *vs.* 4 (t=3.29, p<.003)
Fp2	7.39 (1.88)	8.02 (2.45)	9.02 (2.59)	7.39 (1.94)	6.88**	1 *vs.* 3 (t=-2.43, p<.02); 3 *vs.* 4(t=3.42, p<.002)
FT9	6.37 (1.71)	6.38 (1.78)	7.43 (2.20)	5.86 (1.66)	5.81**	3 *vs.* 4 (t=2.07, p<.05)
FT10	5.96 (1.75)	6.37 (1.69)	6.65 (1.61)	6.24 (1.59)	ns	ns
C3	6.78 (2.00)	7.48 (1.98)	7.94 (2.59)	6.47 (1.76)	7.21**	1 *vs.* 3 (t=-2.05, p<.05); 2 *vs.* 4 (t=6.60, p<.001); 3 *vs.* 4 (t=3.36, p<.003)
C4	6.85 (1.91)	7.33 (1.99)	7.50 (2.41)	6.57 (1.69)	3.40*	2 *vs.* 4 (t=5.36, p<.001)
Fz	8.40 (2.28)	9.10 (2.52)	9.69 (2.82)	8.21 (2.15)	6.40**	1 *vs.* 3 (t=-2.04, p<.05); 2 *vs.* 4 (t=6.14, p<.001); 3 *vs.* 4 (t=3.25, p<.003)
FCz	8.51 (2.22)	9.23 (2.34)	9.75 (2.68)	8.26 (2.01)	7.25**	1 *vs.* 3 (t=-2.47, p<.02); 2 *vs.* 4 (t=5.40, p<.001); 3 *vs.* 4 (t=4.28, p<.001)
Cz	7.98 (2.05)	8.46 (2.04)	9.15 (2.35)	7.61 (1.73)	8.08***	1 *vs.* 3 (t=-2.96, p<.007); 2 *vs.* 4 (t=7.83, p<.001); 3 *vs.* 4 (t=4.84, p<.001)
Pz	6.50 (1.59)	6.66 (1.77)	7.80 (2.34)	6.04 (1.58)	13.10***	1 *vs.* 3 (t=-2.56, p<.01); 2 *vs.* 3 (t=-6.56, p<.001); 3 *vs.* 4 (t=4.54, p<.001)
TP9	8.08 (2.32)	8.96 (2.64)	9.08 (2.67)	7.96 (2.21)	4.56*	1 *vs.* 3 (t=-2.59, p<.01); 2 *vs.* 4 (t=6.84, p<.001)
TP10	8.25 (2.14)	8.90 (2.13)	9.33 (2.55)	7.92 (1.84)	5.20*	2 *vs.* 4 (t=7.02, p<.001)
O1	6.21 (2.27)	4.97 (1.93)	6.56 (2.20)	5.77 (1.90)	7.90***	1 *vs.* 2 (t=3.21, p<.004)
O2	6.32 (2.37)	4.97 (1.95)	6.80 (2.82)	5.95 (2.03)	7.27**	1 *vs.* 2 (t=2.17, p<.04)

Alpha (8-13Hz)						
Fp1	10.42 (3.27)	10.58 (4.05)	7.55 (1.61)	12.54 (4.19)	17.65***	1 *vs.* 3 (t=4.02, p<.001); 1 *vs.* 4 (t=-3.35, p<.003); 2 *vs.* 3 (t=3.61, p<.002); 2 *vs.* 4 (t=-3.66, p<.001); 3 *vs.* 4 (t=-6.15, p<.001)
Fp2	10.82 (3.40)	10.78 (4.06)	7.78 (1.77)	12.99 (4.57)	20.55***	1 *vs.* 3 (t=4.73, p<.001); 1 *vs.* 4 (t=-3.44, p<.002); 2 *vs.* 3 (t=3.85, p<.001); 2 *vs.* 4 (t=-4.13, p<.001); 3 *vs.* 4 (t=-6.23, p<.001)
FT9	10.62 (3.15)	11.64 (4.11)	7.85 (1.89)	12.71 (4.60)	21.94***	1 *vs.* 3 (t=4.62, p<.001); 1 *vs.* 4 (t=-4.36, p<.001); 2 *vs.* 3 (t=5.09, p<.001); 3 *vs.* 4 (t=-6.05, p<.001)
FT10	10.19 (3.61)	10.59 (3.74)	7.88 (2.05)	12.37 (4.35)	16.93***	1 *vs.* 3 (t=3.59, p<.003); 1 *vs.* 4 (t=-3.71, p<.001); 2 *vs.* 3 (t=4.48, p<.001); 2 *vs.* 4 (t=-3.34, p<.003); 3 *vs.* 4 (t=-6.25, p<.001)
C3	13.67 (4.13)	12.04 (3.78)	8.23 (2.03)	15.61 (4.72)	53.98***	1 *vs.* 3 (t=8.99, p<.001); 1 *vs.* 4 (t=-4.15, p<.001); 2 *vs.* 3 (t=6.72, p<.001); 2 *vs.* 4 (t=-6.26, p<.001); 3 *vs.* 4 (t=-10.67, p<.001)
C4	13.33 (4.00)	12.39 (4.12)	8.73 (2.34)	14.71 (3.88)	41.43***	1 *vs.* 3 (t=7.99, p<.001); 1 *vs.* 4 (t=-2.60, p<.02); 2 *vs.* 3 (t=6.72, p<.001); 2 *vs.* 4 (t=-6.26, p<.001); 3 *vs.* 4 (t=-10.67, p<.001)
Fz	11.55 (3.71)	10.74 (3.77)	7.84 (1.77)	13.45 (4.34)	39.85***	1 *vs.* 3 (t=6.45, p<.001); 1 *vs.* 4 (t=-6.41, p<.001); 2 *vs.* 3 (t=4.62, p<.001); 2 *vs.* 4 (t=-6.74, p<.001); 3 *vs.* 4 (t=-8.16, p<.001)
FCz	11.42 (3.40)	10.61 (3.71)	7.45 (1.71)	13.39 (3.89)	49.71***	1 *vs.* 3 (t=7.53, p<.001); 1 *vs.* 4 (t=-6.18, p<.001); 2 *vs.* 3 (t=5.10, p<.001); 2 *vs.* 4 (t=-7.31, p<.001); 3 *vs.* 4 (t=-9.83, p<.001)
Cz	12.18 (3.15)	11.07 (3.52)	7.88 (1.84)	14.33 (3.73)	71.28***	1 *vs.* 3 (t=9.93, p<.001); 1 *vs.* 4 (t=-6.29, p<.001); 2 *vs.* 3 (t=6.11, p<.001); 2 *vs.* 4 (t=-8.56, p<.001); 3 *vs.* 4 (t=-12.08, p<.001)
Pz	14.77 (4.04)	13.87 (4.79)	9.50 (2.70)	17.84 (4.89)	50.80***	1 *vs.* 3 (t=7.71, p<.001); 1 *vs.* 4 (t=-6.49, p<.001); 2 *vs.* 3 (t=5.94, p<.001); 2 *vs.* 4 (t=-6.22, p<.001); 3 *vs.* 4 (t=-9. 90, p<.001)
TP9	11.34 (3.46)	10.30 (3.62)	7.56 (1.98)	13.19 (3.91)	44.08***	1 *vs.* 3 (t=7.19, p<.001); 1 *vs.* 4 (t=-4.69, p<.001); 2 *vs.* 3 (t=4.86, p<.001); 2 *vs.* 4 (t=-7.27, p<.001); 3 *vs.* 4 (t=-9.03, p<.001)
TP10	12.16 (3.47)	11.30 (3.87)	8.39 (1.97)	14.08 (4.18)	41.09***	1 *vs.* 3 (t=6.83, p<.001); 1 *vs.* 4 (t=-6.76, p<.001); 2 *vs.* 3 (t=4.38, p<.001); 2 *vs.* 4 (t=-6.93, p<.001); 3 *vs.* 4 (t=-8.52, p<.001)
O1	13.41 (3.18)	14.44 (3.69)	11.14 (1.96)	15.63 (4.71)	15.89***	1 *vs.* 3 (t=3.56, p<.002); 1 *vs.* 4 (t=-4.20, p<.001); 2 *vs.* 3 (t=5.13, p<.001); 3 *vs.* 4 (t=-4.61, p<.001)
O2	13.08 (3.22)	13.99 (3.64)	10.83 (1.93)	15.16 (4.25)	15.42***	1 *vs.* 3 (t=3.46, p<.002); 1 *vs.* 4 (t=-3.96, p<.001); 2 *vs.* 3 (t=4.96, p<.001); 3 *vs.* 4 (t=-4.84, p<.001)

Beta-1 (14-19Hz)						
Fp1	5.38 (1.46)	5.19 (1.97)	4.85 (1.41)	5.32 (1.48)	ns	ns
Fp2	5.10 (1.41)	4.85 (1.81)	4.76 (1.50)	5.18 (1.43)	ns	ns
C3	5.39 (1.80)	5.06 (1.51)	5.74 (1.67)	5.65 (1.81)	ns	ns
C4	5.50 (1.69)	5.13 (1.70)	5.69 (1.83)	5.70 (1.66)	ns	ns
FT9	5.34 (1.42)	5.53 (2.27)	5.51 (1.39)	5.64 (1.73)	ns	ns
FT10	5.56 (1.55)	5.29 (1.80)	5.39 (1.53)	5.59 (1.61)	ns	ns
Fz	4.91 (1.38)	4.38 (1.44)	4.74 (1.57)	4.96 (1.24)	ns	ns
FCz	4.73 (1.47)	4.20 (1.33)	4.42 (1.66)	4.94 (1.27)	4.09*	2 *vs.* 4 (t=-3.47, p<.002)
Cz	4.84 (1.44)	4.24 (1.31)	4.72 (1.66)	5.05 (1.29)	4.52*	1 *vs.* 2 (t=3.80, p<.002); 2 *vs.* 4 (t=-3.80, p<.002)
Pz	5.26 (1.68)	4.74 (1.61)	5.33 (1.61)	5.22 (1.76)	ns	ns
TP9	5.01 (1.40)	4.40 (1.48)	4.78 (1.70)	5.32 (1.50)	3.54*	1 *vs.* 2 (t=2.96, p<.007); 2 *vs.* 4 (t=-3.06, p<.005)
TP10	5.22 (1.55)	4.51 (1.55)	5.23 (1.78)	5.21 (1.41)	3.47*	1 *vs.* 2 (t=4.06, p<.001); 2 *vs.* 4 (t=-3.23, p<.004)
O1	6.43 (1.86)	7.10 (1.83)	7.78 (1.88)	6.46 (2.11)	7.68***	1 *vs.* 3 (t=-2.81, p<.01); 3 *vs.* 4 (t=2.50, p<.02)
O2	6.48 (1.91)	7.05 (2.16)	7.70 (2.03)	6.54 (2.07)	4.74**	1 *vs.* 3 (t=-2.80, p<.01); 3 *vs.* 4 (t=2.51, p<.02)
Beta-2 (20-30Hz)						
Fp1	7.72 (5.18)	6.75 (5.32)	6.02 (3.26)	6.32 (4.15)	ns	ns
Fp2	6.93 (5.02)	6.03 (5.18)	5.80 (3.07)	5.70 (3.48)	ns	ns
C3	6.07 (3.99)	5.14 (3.10)	7.94 (4.29)	5.61 (3.47)	9.21***	1 *vs.* 2 (t=2.17, p<.04); 1 *vs.* 3 (t=-2.85, p<.009); 2 *vs.* 3 (t=-4.61, p<.001); 3 *vs.* 4 (t=3.11, p<.005)
C4	6.09 (3.87)	5.09 (3.10)	7.86 (4.85)	5.64 (3.42)	8.75***	1 *vs.* 2 (t=2.15, p<.04); 1 *vs.* 3 (t=-2.79, p<.01); 2 *vs.* 3 (t=-4.85, p<.001); 3 *vs.* 4 (t=2.85, p<.009)
FT9	7.33 (4.27)	7.07 (5.70)	8.00 (4.37)	7.24 (5.12)	ns	ns
FT10	8.02 (5.20)	7.13 (4.85)	8.44 (4.47)	6.47 (3.87)	ns	ns
Fz	5.18 (3.27)	4.11 (2.69)	5.91 (3.60)	4.60 (2.63)	5.96**	2 *vs.* 3 (t=-3.88, p<.001); 3 *vs.* 4 (t=2.16, p<.04)
FCz	4.94 (3.18)	3.92 (2.29)	5.76 (3.74)	4.52 (2.51)	6.33**	2 *vs.* 3 (t=-3.76, p<.001); 3 *vs.* 4 (t=2.10, p<.05)
Cz	5.28 (3.36)	4.25 (2.60)	6.38 (4.10)	4.79 (2.82)	8.24***	1 *vs.* 2 (t=2.70, p<.01); 1 *vs.* 3 (t=-2.42, p<.02); 2 *vs.* 3 (t=-4.35, p<.001); 3 *vs.* 4 (t=2.63, p<.01)
Pz	4.60 (3.29)	4.03 (2.89)	6.22 (4.24)	4.09 (2.84)	11.26***	1 *vs.* 3 (t=-3.40, p<.002); 2 *vs.* 3 (t=-4.91, p<.001); 3 *vs.* 4 (t=3.57, p<.002)
TP9	6.05 (4.43)	4.76 (3.72)	6.71 (4.91)	5.44 (3.84)	4.36*	1 *vs.* 2 (t=2.62, p<.02); 2 *vs.* 3 (t=-3.35, p<.003)
TP10	5.09 (2.75)	3.88 (1.83)	6.48 (3.47)	4.72 (2.40)	9.51***	1 *vs.* 2 (t=3.24, p<.004); 1 *vs.* 3 (t=-2.36, p<.03); 2 *vs.* 3 (t=-5.01, p<.001); 3 *vs.* 4 (t=2.55, p<.02)
O1	6.96 (4.67)	8.09 (4.67)	9.46 (3.70)	6.41 (4.66)	7.94***	1 *vs.* 3 (t=-3.48, p<.002); 2 *vs.* 3 (t=-2.21, p<.04); 3 *vs.* 4 (t=3.66, p<.001)
O2	7.05 (5.05)	8.28 (4.84)	9.20 (3.98)	6.51 (4.57)	7.43**	1 *vs.* 3 (t=-2.83, p<.01); 2 *vs.* 4 (t=2.71, p<.01); 3 *vs.* 4 (t=3.71, p<.001)

Beta-1 (14-19Hz)

Beta-1 power was reduced under low load compared with the baseline at Cz ($F_{(3,57)}$=4.52, p<.01), TP9 ($F_{(3,67)}$=3.54, p<.02), and TP10 ($F_{(2,45)}$=3.47, p<.04). Beta-1 power increased under high load relative to the baseline and thereafter decreased in the recovery at O1 ($F_{(3,61)}$=7.68, p<.001) and O2 ($F_{(2,56)}$=4.74, p<.009). Beta-1 power also decreased under low load compared with the recovery at FCz ($F_{(3,58)}$=4.09, p<.02), Cz ($F_{(3,57)}$=4.52, p<.01), TP9 ($F_{(3,67)}$=3.54, p<.02), and TP10 ($F_{(2,45)}$=3.47, p<.04).

Table III. Pearson correlations between theta, beta-1 and beta-2 power for all electrodes.

	Theta						
Beta-1	Fp1	Fp2	Fz	FCz	FT9	FT10	C3
Fp1	-0,55**						
Fp2		-0,48					
Fz			-0,55**				
FCz				-0,43*			
FT9					-0,42*		
FT10						-0,5*	
C3							-0,72**

	Theta						
Beta-1	C4	Cz	Pz	TP9	TP10	O1	O2
C4	-0,73**						
Cz		-0,65**					
Pz			-0,71**				
TP9				-0,58**			
TP10					-0,69**		
O1						-0,75**	
O2							-0,77**

	Theta						
Beta-2	Fp1	Fp2	Fz	FCz	FT9	FT10	C3
Fp1	-0,8**						
Fp2		-0,64**					
Fz			-0,71**				
FCz				-0,64**			
FT9					-0,73**		
FT10						-0,76**	
C3							-0,77**

	Theta						
Beta-2	C4	Cz	pz	TP9	TP10	O1	O2
C4	-0,76**						
Cz		-0,77**					
Pz			-0,74**				
TP9				-0,74**			
TP10					-0,77**		
O1						-0,79**	
O2							-0,77**

* – p<0.05; ** – p<0.01; *** – p<0.001; ns – non-significant.

Beta-2 (20-30Hz)

Beta-2 power increased under high load compared with both baseline and low load condition at C3 ($F_{(2,55)}$=9.21, p<.001), C4 ($F_{(2,53)}$=8.75, p<.001), Fz ($F_{(2,57)}$=5.96, p<.002), Cz ($F_{(2,52)}$=8.24, p<.001), Pz ($F_{(2,48)}$=11.26, p<.001), TP9 ($F_{(2,52)}$=4.36, p<.02), TP10 ($F_{(2,45)}$=9.51, p<.001), O1 ($F_{(2,55)}$=7.94, p<.001), and O2 ($F_{(2,57)}$=7.43, p<.002). In contrast, beta-2 power decreased under low load relative to the baseline at C3 ($F_{(2,55)}$=9.21, p<.001), C4 ($F_{(2,53)}$=8.75, p<.001), Cz ($F_{(2,52)}$=8.24, p<.001), TP9 ($F_{(2, 52)}$=4.36, p<.02), and TP10 ($F_{(2,45)}$=9.51, p<.001). In addition, beta-2 power was larger at higher loads than in the recovery at C3 ($F_{(2,55)}$=9.21, p<.001), C4 ($F_{(2,53)}$=8.75, p<.001), Fz ($F_{(2,57)}$=5.96, p<.002), FCz ($F_{(2,53)}$=6.32, p<.002), Cz ($F_{(2,52)}$=8.24, p<.001), Pz ($F_{(2,48)}$=11.26, p<.001), TP10 ($F_{(2,45)}$=9.51, p<.001), O1 ($F_{(2,55)}$=7.94, p<.001), and O2 ($F_{(2,57)}$=7.43, p<.002). Finally, beta-2 power increased under high load compared with the low load condition at Fz ($F_{(2,57)}$=5.96, p<.002), FCz ($F_{(2,53)}$=6.32, p<.002), and TP9 ($F_{(2,52)}$=4.36, p<.02).

Correlations

Significant correlations between EEG power, performance and perceived cognitive load were found in the high load condition but not in the low load condition. Alpha power did not correlate with performance at all but positively correlated with the perceived cognitive load. The correlation was significant at FP1 (r=.42, p<.04), FP2 (r=.42, p<.04), FT10 (r =.52, p<.001), Fz (r =.49, p<.01), and TP10 (r =.43, p<.04). Delta power correlated neither with performance nor with the perceived cognitive load. A clear-cut tendency for negative correlations between theta power and RT under high load at all electrodes was seen. The correlations reached significance at FT9 (r=–.48, p<.02), FT10 (r=–.44, p<.03), and O1 (r=–.53, p<.01). In contrast, EEG power in the beta frequency range revealed a tendency for positive correlation with RT at all electrodes. The correlations for beta-1 reached significance at Pz (r=.45, p<.03) and O1 (r=.47, p<.02), while for beta-2 at O1 (r=.47, p<.02). The oppositely directed correlations of theta and beta bands with RT appeared interesting, so that correlations between theta and beta power were computed (Table III). The correlations between theta and both beta bands were significant at all electrodes ranging from r=–.42 (p<.05) to r=–.80 (p<.01) with greater effects for beta-2 power.

DISCUSSION

The aim of the present study was to examine EEG correlates of cognitive load in tasks differed in motor requirements and the number of S-R mappings, which should be maintained in WM. As expected, accuracy was lower and RT was longer at higher WM loads than at lower loads. Performance data well agree with studies used various WM tasks (Gevins et al., 1997, 2000; Smith et al., 1999; McEvoy et al., 2001; Jensen et al., 2002; Johnson et al., 2011; Itthipuripat et al., 2013; Gärtner et al., 2014).

In the present study we examined two effects of experimental conditions on EEG, i.e. the responsivity to cognitive load and the after-effects of cognitive load. Analyzing the after-effects, we found a lower delta activity at centro-parietal electrodes and an enhanced alpha activity at all electrodes in the recovery compared with the baseline. The increase in delta power has usually been observed in drowsiness state indicating a diminished arousal level of the brain (see e.g. Knyazev 2012, for review). The effect has usually been found in prolonged driving tasks (Hoedlmoser et al., 2011) and interpreted as an index of fatigue associated with decline in top-down executive control governed by the prefrontal cortex (Lorist, 2008). In contrast, a delta power decrease in the recovery condition may be seen as an increase in the brain arousal level probably due to practice or adaptation of participants to the test situation. Interestingly, this effect paralleled increases in alpha activity in the baseline compared with the recovery in the same brain areas where decreases in delta activity were observed. This coincidence suggests that both EEG effects are associated rather with practice than with fatigue. Other studies also reported practice-related increases in alpha activity (Gevins et al., 1997; Smith et al., 1999). The effect is probably due to that less cortical regions are involved into the task and therefore are progressively deactivated in the course of practice (Raichle et al., 1994). To summarize, the reduction in delta power and the increase in alpha power as after-effects of cognitive load may reflect practice-related inhibition of non-relevant brain networks and a moderate increase of brain arousal level.

The most sensitive indicators of WM load were changes in theta and alpha power showed both an increase in theta and a reduction in alpha activity with increasing task difficulty. After cognitive load theta activity returned to baseline values while alpha activity enhanced above the baseline. The effects are consistent with other data showed a hightened theta activity with increasing WM demands (Gevins et al., 1997, 2000; McEvoy et al., 2001; Deiber et al., 2007; Gärtner et al., 2014; Ozdemir et al., 2016). The cited studies used the n-back task, which is of similar characteristics with the multiple choice reaction task used in the present study. Both task types required running inhibition of irrelevant information and updating of WM content on every trial. Increases in theta power were also found in tasks required focused attention (Gundel and Wilson, 1992; Sauseng et al., 2007) or inhibition of irrelevant information (Barwick et al., 2012). Decreases in theta activity in older relative to younger adults to targets in the 2-back task were accompanied by a reduction in the frontal P3a component of the event-related potential indicating that age-related deficits in WM may partly be accounted for by deficits in attentional control (Gajewski et al., 2014). Hence, theta oscillations appear to be unspecific to working memory and may also be related to other higher-order cognitive processes which sub-serve efficient WM functioning. Finally, theta increases can be observed in multiple, functionally distinct regions and may depend on the particular neural sources that generate theta oscillations during task performance (Kahana et al., 2001). This finding receives support from source localization studies suggesting the medial prefrontal cortex (mPFC) and the anterior cingulate cortex (ACC) as possible sources for fronto-medial theta activity in WM tasks (Gevins et al., 1997). These brain structures are also critical for attentional control, action selection, performance monitoring, and response inhibition (for review see Ridderinkhof et al., 2004). Together, theta activity may reflect putative communication mechanism between WM and other higher-order cognitive processes. This mechanism is assumed to act at an "item level", where multi-item WM information needs to be organized into sequential memory representations, and also at a higher-order "process level" relating to the integration and control of a variety of cognitive functions involved in WM (Sauseng et al., 2010). The enhancement in theta power at higher loads in the present study may also be mediated by motivation. Gärtner et al. (2014) reported a theta increase with moderate WM load (2-back condition) while theta decreased with further increasing WM load (3-back condition). Authors concluded that theta activity increased with WM load as long as participants had feeling of control over task demands; the cognitive overload was accompanied by loss of control and therefore by the theta decrease. In a similar way, the demands in our high load condition can be characterized as controllable. This is also confirmed by participant's ratings of perceived cognitive loads as the subjective exertion was rated by participants between "high" and "very high". The negative correlation between theta power and RT we obtained suggests that theta activity may be associated with facilitation of information processing in WM, which results in performance improvement.

In contrast to the effects of WM load on theta power, alpha activity was attenuated already at lower loads and dramatically decreased at higher loads. The finding well agrees with studies used attention tasks (Gundel and Wilson, 1992; Ergenoglu et al., 2004) and visual n-back WM tasks (Gevins et al., 1997; McEvoy et al., 2001). However, other studies reported an increase in alpha power with increased WM load (Jensen et al., 2002; Herrmann et al., 2004; Johnson et al., 2011, Ozdemir et al., 2016). The discrepancy between the results may be accounted for by differences in WM tasks, experimental conditions and, in some cases, individual differences of participants. The tasks applied by Jensen et al. (2002), Herrmann et al. (2004) and Johnson et al. (2011) were modifications of the Sternberg task (Sternberg 1966) when participants had to retain a memory set for a short time (3 to 4 s) and give "match/non-match" responses thereafter. In these tasks encoding, retention, and recognition were separated in time as compared with the n-back task or with the multiple choice reaction task used in the present study in which all the processes closely overlapped in time to provide continuous information updating. Thereby "updating" tasks were more demanding for participants than the Sternberg's task. Ozdemir et al. (2016) reported increases in alpha power in a dual task (posture task plus n-back task) relative to a single task (posture task only). However, they reported data averaged across older and younger adults, while the effect on alpha is clearly seen in younger but not in older participants. Moreover, in their semantic n-back task, spoken words were presented acoustically every 3 s. This task appears to be easier to perform than the typical n-back task with rapid visual presentation of abstract stimuli. Taken together, studies reported increases in alpha power under WM load cannot be directly compared with our experiment. Nevertheless, our results are quite consistent with data from studies used tasks with comparable WM demands (Gevins et al., 1997; McEvoy et al., 2001).

The functional role of alpha activity has been a matter of debate. The model proposed by Klimesch (1999) assumes that alpha activity reflects inhibition of irrelevant information during task performance. Indeed, in studies on spatial attention the alpha amplitude in response to an attentional cue is generally higher on sites that are not involved in target processing (Sauseng et al., 2005; Freunberger et al., 2008). It is thought that a decreased alpha activity indicates an enhanced efficiency of information transfer within thalamo-cortical pathways resulting in an increase of attention or memory performance (Klimesch 1999; Deiber et al., 2007). An enhanced alpha power is also interpreted as inhibition or disengagement of extended networks or brain areas not involved in performance of the current task (Klimesch 1999; Haegens et al., 2010). In our task the alpha reduction was generalized across all brain areas suggesting that widespread cortical areas were recruited for task performance at higher WM loads.

We found that alpha power positively correlated with perceived cognitive load. This result is hard to explain in context of cognitive performance. It is possible that the correlation may be of motivational nature. The participants, who perceived the multiple choice reaction task as very demanding, perceived it as less controllable and thereby were less motivated to perform the task. In contrast, participants who rated the task as less demanding, perceived more control over the task and tried to actively cope with task demands. These differences in motivation may account for a lower brain arousal (i.e. higher alpha power) in low motivated participants and for a higher brain arousal (i.e. lower alpha power) in high motivated ones.

Both beta bands revealed similarities in reaction to WM load as they decreased in the low load condition and increased in the high load condition relative to the baseline. Notably, these changes were more pronounced for beta-2 than for beta-1 activity. In addition, increases in beta-1 were restricted to occipital areas, while the effect for beta-2 power was generalized also across central, parietal, and parieto-temporal sites. The result partly agrees with data by Deiber et al. (2007) who reported an increase of EEG activity in the 15-25 Hz range in the n-back task with enhancing task difficulty. Analyses at the stimulus level in a visual attention task demonstrated that an increase in beta-1 power (17-19 Hz) preceded correct responses (Cola et al., 2011). Low task demands are usually accompanied by diminishing of beta activity, e.g. during prolonged driving tasks (Lal and Craig 2002; Zhao et al., 2012). We also observed a reduction of beta power in the low load condition that is probably due to lowering of effort or reduction of brain arousal or both. Interestingly, that increases in beta activity, especially in the beta-2 range paralleled the changes in theta activity under high load suggesting that beta oscillations may also be related to processes that are involved in coping with task demands.

Similar to theta, beta activity correlated with RT at higher WM loads, but in an opposite direction. The effect is in agreement with literature considering beta activity in context of motor functioning. Kuo et al. (2014) showed that movement-related beta activity was consistently localized in the hand region of the primary motor cortex. The relation of beta activity (or at least a part of it) to the motor processes is supported by the fact that beta power positively correlated with RTs under high but not under low load; that is probably due to difficulties in preparation and execution of motor responses in a task with high motor requirements. In contrast, negative correlations between theta power and RT suggest that theta activity may be associated with facilitating of motor processes. Keeping in mind negative correlations between beta and theta power, it is intuitive to think that these two frequency bands reflect processes, which can reciprocally mediate motor activity. Increases in theta power may indicate efficient information processing in WM resulting in improvements of a higher-order executive control over all the sub-processes including motor preparation and execution. This may reduce a compensatory over-activation of motor system (lowering of beta activity), and facilitate motor responses (shortening of RT). Conversely, an enhanced beta activity may be an index of impairments in WM and lowering of executive control, resulting in compensatory over-activation of motor system and lengthening of RT.

Delta activity was enhanced under cognitive load as compared to the baseline irrespective of task difficulty. The result is well in line with other studies reported increases in delta power associated with WM retention (Fernández et al., 2002), response inhibition in a go/no-go task (Harmony et al., 2009), during mental arithmetic task (Dimitriadis et al., 2010) and in a dual task (Ozdemir et al., 2016). Gajewski et al. (2014) found that delta power increased to target versus non-target trials in the simple oddball task (0-back task in their study) indicating that delta oscillations may be related to control over selective attention at the stimulus level.

CONCLUSIONS

In the present study an increase of EEG power in delta, theta, and beta frequency bands as well as a decrease in the alpha band with increasing WM demands was found. Moreover, the effect on alpha power was generalized across all the electrodes. Theta and alpha changes were larger and more widespread across brain areas as compared to other frequency bands, so that these changes can be considered as the most sensitive indicators of cognitive load.

Taken together, a negative correlation between theta and RT, a positive correlation between beta and RT, and a negative correlation between theta and beta power indicate that theta and beta activity may reflect mechanisms that reciprocally mediate motor system. In sum, the data converge on the conclusion that improvements in WM processing and in executive control facilitate motor processes and result in better motor performance.

An increase in alpha power and a reduction in delta power in the recovery relative to the baseline may be associated with inhibition of non-relevant brain networks due to practice and quick recovery from cognitive load.

To our knowledge, this is the first study showed that maintenance and inhibition of multiple S-R mappings in WM may also be investigated in a multiple choice reaction task. Particularly, selective inhibition of currently irrelevant S-R mappings has not sufficiently been examined until now. The time course of this process at the stimulus level using event-related EEG methods should be analyzed in the future studies. The findings from the present study may be applied to an EEG assessment of cognitive load at modern work places requiring continuous attention switching, multitasking, time pressure or using of mobile assistance systems.

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