

Power of theta waves in the EEG of human subjects increases during recall of haptic information

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Abstract

Several studies have reported a functional relationship between spectral power within the theta-band of the EEG (theta-power) and memory load while processing visual or semantic information. We investigated theta power during the processing of different complex haptic stimuli using a delayed recall design. The haptic explorations consisted of palpating the structure of twelve sunken reliefs with closed eyes. Subjects had to reproduce each relief by drawing it 10 s after the end of the exploration. The relationship between mean theta power and mean exploration time was analysed using a regression model. A linear relationship was found between the exploration time and theta power over fronto-central regions (Fp1, Fp2, F3, F7, F8, Fz, C3) directly before the recall of the relief. This result is interpreted in favour of the hypothesis that fronto-central theta power of the EEG correlates with the load of working memory independent of stimulus modality. © 1999 Elsevier Science Ireland Ltd. All rights reserved.

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Different studies reported a functional relationship between spectral power density within the theta band of the EEG (theta power) and working memory load during perceptive-cognitive processing. Results from Daniel [2], Gale et al. [3] and Schacter [16] showed that theta power changes depending on the stimulus complexity. It was observed that theta power increased linearly over parieto-central regions depending on working memory load for visual stimuli. Bösel [1], Mecklinger [10] and Pennekamp et al. [11] reported on systematic linear trends over fronto-central regions during visual memory tasks. These working memory dependent changes have been interpreted as psychophysiological correlates of working memory processing [1,10]. Cortical theta activity was assumed to assist working memory processing during current action planning and action realization.

Such changes in theta power were mainly described dur-

ing semantic-visual processing (words, pictures, letters). Results on systematic theta-power changes during spatial tasks without visual information have not yet been reported. However we assume theta-changes related to working memory load to be independent on stimulus modality.

Taking into account the serial manner of haptic exploration [14], we followed the assumption of Rösler et al. [14] that the exploration time does not reflect a reaction time but rather varies depending on the stimulus size or complexity.

Therefore, the aim of this study was to test this hypothesis using a haptic task. We investigated theta power during the processing of different complex haptic stimuli in a delayed recall design. Six subjects (three females, three men, 18–23 years old, all unfamiliar with the aim of the study) volunteered for this study. The study was approved by the local Ethic Commission.

The haptic explorations with closed eyes consisted of palpating the structure of twelve sunken reliefs which were presented in a pseudorandom order (13 × 13 cm, for a typical example see Fig. 1). The structure of the reliefs consisted of

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milled traces with a depth of 3 mm and a width of 7 mm. Schematic graph of the reliefs are shown in the first line of Table 1. Ten seconds after the end of exploration, subjects were asked to reproduce each relief by drawing it on a sheet of paper with their eyes open. Exploration time per stimulus (see Table 1) was not limited but was registered by means of pressure sensors and PC time-keeping (in seconds). Subjects were prevented from gathering visual information on the stimuli. They received no feedback on the quality of their reproduction or on the stimulus structure.

A 19-channel digital EEG (Walter Graphtek, Bad Oldesloe, Germany) was continuously recorded during rest, haptic explorations, and delay (retention) conditions. In accordance with the International 10–20 system [7], Ag-AgCl electrodes were attached to the scalp in the standard electrode positions (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, O1, O2; reference: linked earlobes, sampling rate: 333 Hz, time constant: 0.3 s, low pass filter: 70 Hz). Horizontal and vertical eye movements were recorded from bipolar montages with the same sampling parameters. During data acquisition, the EEG was displayed on a monitor and stored on hard disk. Segmentation of EEG data and subsequent calculations of the mean spectral power density was performed with an EEG analytical software package [13]. Artifact-free segments of 1.53 s (512 samples/channel) from rest condition, haptic explorations, and retention intervals were chosen by visual inspection and substantiated by cross correlation analysis between relevant frontal EEG and EOG electrodes ($r_{\text{crit}} < 0.5$). The remaining segments were submitted to a Fast Fourier Transform (FFT) analysis and smoothed with a seven-point low-pass filter (weights 1/64, 3/32, 15/64, 5/16, 15/64, 3/32, 1/64) in order to balance out between resolution of the power spectra and its variance. Mean spectral power density was calculated as the mean amplitude of the spectral lines of each EEG band (theta: 4–8 Hz, alpha: 8–13 Hz, alpha1: 8–10 Hz, alpha2: 10–13 Hz). The timing sequence of a typical trial is given in Fig. 1. The relationship between exploration

time and theta activity was analyzed with a linear regression model. Exploration time has previously been shown to reflect aspects of stimulus complexity rather than reaction time [14]. Thus, in order to account for individual differences in the subjective complexity of the stimulus given, the theta power for individual retention intervals was sorted in the order of mean exploration times. The regression analysis used z-transformed (mean = 0, SD = 1) mean theta-power data for retention interval.

When testing the central hypothesis, we focus on systematic linear trends between fronto-central theta-power and mean exploration time in nine single tests (Fp1, Fp2, F3, F4, Fz, F7, F8; $\alpha = 0.05$, Bonferoni corrected $\alpha' = 0.007$). However in order to justify this approach, we also examined the linear regression model for all individual comparisons between 19 channels and mean exploration time. The model estimates (r^2) for the linear model were highest for Fp1, Fp2, F3, F7, F8, Fz, and C3. Table 2 shows the F statistics for testing of the null hypothesis. It was found that seven single tests of the regression coefficient (b_1) showed significant differences from zero. For these tests a significant linear relationship between theta power and mean exploration time can be assumed. The regression plots with significant coefficients are shown in Fig. 2. The tests of the linear model for F4, C4, Cz, T3, T4, P3, P4, Pz, T3, T4, T5, T6, O1, and O2 showed smaller model estimations ($r^2 < 0.30$) and no significant differences in regression coefficients. The regression estimations for Alpha, Alpha1, Alpha2, Beta1 and Beta2 showed no significant results with the exception of a significant trend for two tests: for electrode F8 in the beta2 range ($r^2 = 0.476$, $b_0 = -0.3025$, $b_1 = 0.0027$) and for electrode Cz in the beta1 range ($r^2 = 0.368$, $b_0 = 0.3783$, $b_1 = -0.0022$). A significant power decrease within all frequency bands similar to previous results [12] was found during the exploration period in comparison to the rest [5].

Our data show a linear trend of the mean theta power related to the exploration time for different complex haptic

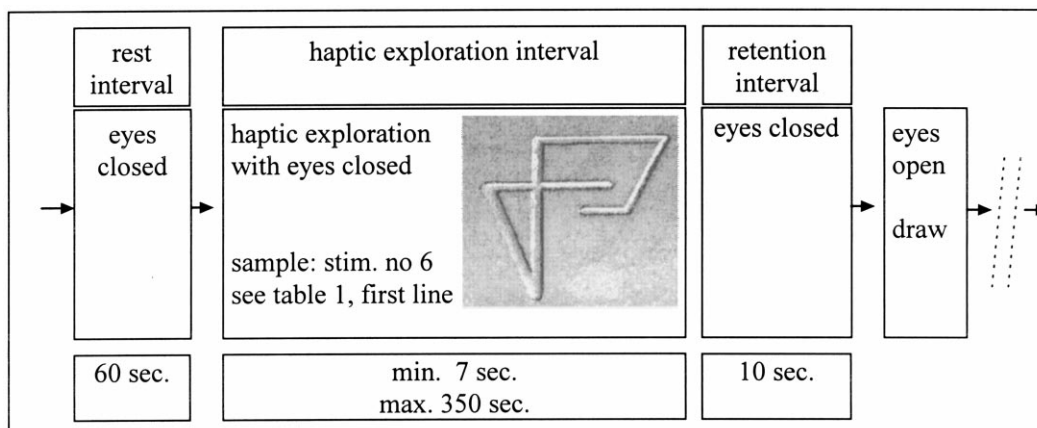








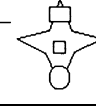





Fig. 1. Schematic time course of a single trial. The upper part shows the trial intervals (rest, exploration, retention), while the middle part shows the task to be performed by the subject in the respective trial intervals. The lower part gives the data recorded during each interval. EEG data were recorded during rest, haptic exploration, and retention interval. The inset shows a relief used as haptic stimuli (No. 6).

Table 1
Exploration time per stimulus (s) and subjects

Subjects	Stimulus											
	1	3	4	5	6	7	9	10	11	12	13	19
												
B	51.81	237.74	183.39	39.47	232.40	231.88	262.30	53.43	397.92	57.33	420.27	261.80
H	18.49	154.41	109.89	24.20	221.86	187.88	153.51	35.90	186.66	16.97	87.79	129.57
S	29.27	120.14	96.25	30.02	120.46	245.95	152.52	29.74	387.67	40.71	101.13	150.00
T	46.25	101.56	71.84	23.05	146.48	175.67	124.60	50.94	267.09	37.23	145.10	181.12
Z	42.21	121.20	99.52	10.70	143.24	217.17	217.73	17.19	343.09	7.37	238.75	215.23
L	55.66	214.90	170.05	66.24	237.29	270.23	289.78	74.90	278.36	31.97	73.68	149.81

Schematic graph of the reliefs are shown in the first line.

stimuli. This trend was observed over fronto-central regions during the retention intervals. While neither active exploration movements were performed nor were visual or haptic informations processed during this interval. Therefore the observed linear relationship cannot be attributed to such processes. On the other hand, S's were required to retain the results of the haptic exploration in the retention interval for reproduction 10 s after the end of exploration. The expenditure of haptic processing increases with stimulus complexity. Furthermore, one can assume that the higher the stimulus complexity is the higher the active load of working memory during retention interval will be. Theta activity during the retention interval for simple haptic stimuli (e.g. triangle) was close to baseline and lower than theta activity during complex stimuli. This result is in accordance with data from Bösel [1] and Klimesch [8] demonstrating only minimal involvement of working memory capacity and minimal changes in theta power during automatic stimulus discrimination. With increasing complexity of the haptic stimulus we found higher

values of theta power. Therefore we conclude that the linear trend between theta power and exploration time reflects a functional relationship between complexity of the haptic stimulus and the load of working memory for these stimuli. The topographic allocation of the linear trends for theta power over fronto-central regions corresponds with previous results from neuropsychological studies. Thus, memory processing for imminent action planning is organized predominantly in fronto-central brain regions [4,9]. The fronto-central cortex is also activated during working memory processing of visual stimuli [10]. Likewise, MEG-EEG-studies documented increased theta power over fronto-central regions during perceptive-cognitive processing [6,15]. The inverse effect, linear decrease of theta-activity was observed over parieto-occipital cortex during isometric contraction with maximal voluntary effort [17,18]. The authors showed a linear correlation between theta power and the examined force level. It was assumed that the decrease of theta power in parieto-occipital regions during isometric muscle contraction was

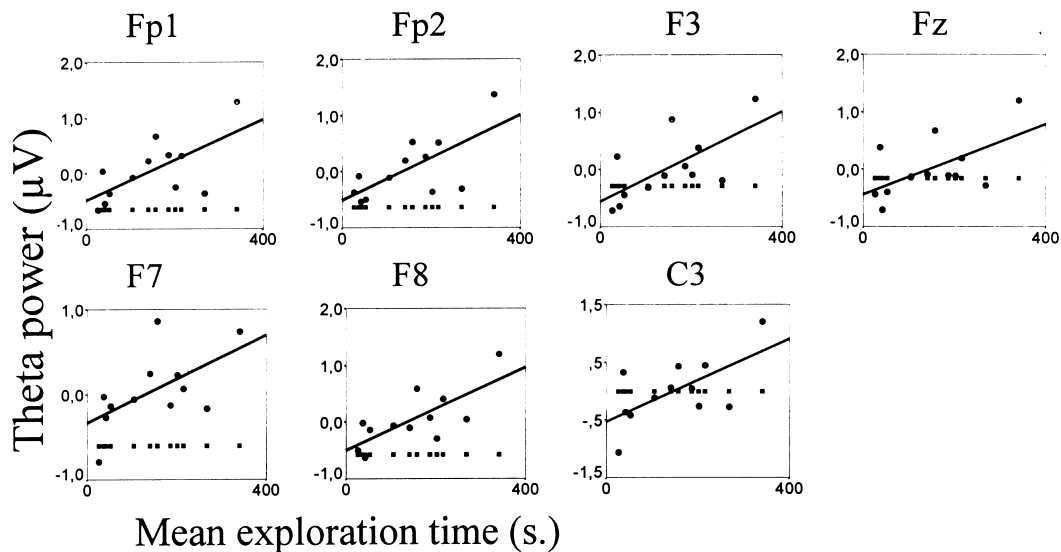


Fig. 2. Regression plots for significant ($P < 0.05$, $r^2 > 0.3$) individual test of the linear regression model between mean z-transformed theta-power from retention interval and mean exploration time. Regression plots lacking significant results are not shown.

Table 2

Results of linear regression per channel between z-transformed mean theta-power of retention interval and mean exploration time

Channel	r^2	d.f.	F	Sig. F	b0	b1
Fp1	0.432	10	7.61	0.020	-0.4865	0.0037
Fp2	0.467	10	8.77	0.014	-0.5121	0.0038
F3	0.453	10	8.27	0.017	-0.5598	0.0039
F4	0.257	10	3.45	0.093	-0.3339	0.0023
C3	0.404	10	6.77	0.026	-0.5321	0.0036
C4	0.031	10	0.32	0.582	-0.1245	0.0007
P3	0.269	10	3.67	0.084	-0.5137	0.0033
P4	0.028	10	0.28	0.606	-0.1235	0.0007
O1	0.041	10	0.42	0.530	-0.2535	0.0016
O2	0.035	10	0.36	0.559	-0.1930	0.0011
F7	0.341	10	5.19	0.046	-0.3321	0.0026
F8	0.546	10	12.04	0.006	-0.4937	0.0037
T3	0.186	10	2.29	0.162	-0.1847	0.0013
T4	0.130	10	1.50	0.249	-0.2481	0.0017
T5	0.156	10	1.85	0.204	-0.2677	0.0017
T6	0.019	10	0.19	0.672	-0.1286	0.0007
Fz	0.337	10	5.09	0.048	-0.4395	0.0031
Cz	0.168	10	2.02	0.185	-0.3290	0.0021
Pz	0.207	10	0.60	0.138	-0.3659	0.0023

Significant coefficients are accentuate. r^2 , model estimates; d.f., degrees of freedom; F -statistic; $p(b1)$ = significance level, b0 and b1 model coefficients.

due to a down-regulation of the posterior attention system in order to minimize the influence of external stimuli during movement preparation.

Different functional relationships were observed between theta-activity and attention/planning as well as memory processes. Processing of new and previously unknown information leads to an increase the theta-activity over fronto-central regions. Processing of well known or simple information was accompanied by decreases of theta activity. The linear relationship between the theta activity over fronto-central cortex during retention interval and the mean exploration time for complex haptic stimuli observed in this study indicates a functional connection between working memory processing and brain electrical activity in theta band. Thus, our data are in keeping with our main hypothesis that this functional relationship is independent from the stimulus modality.

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