

Research report

Theta power in the EEG of humans during ongoing processing in a haptic object recognition task

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Abstract

Dynamic changes in spectral theta power (TP) in the EEG over frontal regions were reported previously during the processing of visually presented spatial and verbal tasks [Cereb. Cortex, 7 (1997) 374–385]. Lower TP was found at the beginning compared to the end of processing. In order to test another modality, we examined theta power during the exploration of haptic stimuli with different complexity. A linear correlation between theta power and mean exploration time (as a measure of stimulus complexity) was found at the end of exploration but not at its beginning. These data are in line with our hypothesis since one could expect minimal load of working memory independent of stimulus complexity at the beginning of exploration whereas working memory would have integrated the stimuli of differing complexity into a perceptual model at the end of exploration.   2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Gevins and coworkers [4] found for visually presented spatial and verbal tasks a significant increase in theta power (TP) over frontal regions at the end of processing compared to the beginning. Thus, it has been shown by these authors that dynamic changes of TP occur during the processing of visually presented stimuli. However, it remains unclear whether or not similar dynamic changes exist during the processing of stimuli in other modalities. Therefore, we investigated changes of TP during haptic perception tasks.

Haptic object recognition tasks usually are realized by successive hand explorations [14]. The exploration strate-

gies seem to follow the schema that information of details of the object will be assessed successively [9,10]. In different studies it was assumed that cognitive processing of haptic object recognition is a serial process that involves working memory [12,16]. Thus, it was demonstrated that the velocity of processing a haptic stimulus depends on the amount of information inherent to the stimulus (i.e. of the haptic object). Additionally, we showed that exploration time for haptic object recognition increases with subjective stimulus complexity ($r=0.634$, $P<0.001$) [5]. In these studies as well as in some others a functional relationship was hypothesized between spectral power density within the theta band of the EEG (theta power) and working memory load during the processing of the stimulus material [1–3,6,7,11,13,15,18]. If this hypothesis is correct one should expect that theta power is a suitable parameter to detect different stages within the serial processing of haptic object recognition. One might postulate that at the begin-

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ning of the exploration no knowledge about the structure or complexity of the stimulus exists, i.e. one would expect theta power to be independent of the stimulus material during the initial part of exploratory processing. However, a percept of the object will be built up in the course of exploration. Thereby, information about the object will be processed successively leading to a working memory load depending on the complexity of the given stimulus. In accordance with the hypothesis of a functional relationship between theta power and working memory load, these different loads should be accompanied by different levels of theta power. Thus, we hypothesize that theta-power at the beginning of a haptic exploration is not related to the complexity of the stimuli whereas a clear linear relationship is expected at the end of exploration. The aim of the present study was to test this hypothesis using a haptic exploration task.

2. Materials and methods

A total of six subjects (three females, three men, 18–23 years old, all unfamiliar with the aim of the study) volunteered for this study which was approved by the local ethics committee. We investigated theta power during the

processing of haptic stimuli differing in complexity in a delayed recall design. The haptic exploration task consisted of palpating the structure of 12 sunken reliefs of 13×13 cm which were presented in a pseudorandom order with eyes closed. The structure of the reliefs consisted of milled traces with a depth of 3 mm and a width of 7 mm. Then 10 s after the end of exploration (retention), subjects were asked to reproduce each relief by drawing it on a sheet of paper with their eyes open. Exploration time per stimulus 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. The timing sequence of a typical trial and two examples of haptic stimuli are shown in Fig. 1.

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 [8], Ag-AgCl electrodes were attached to the scalp at 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

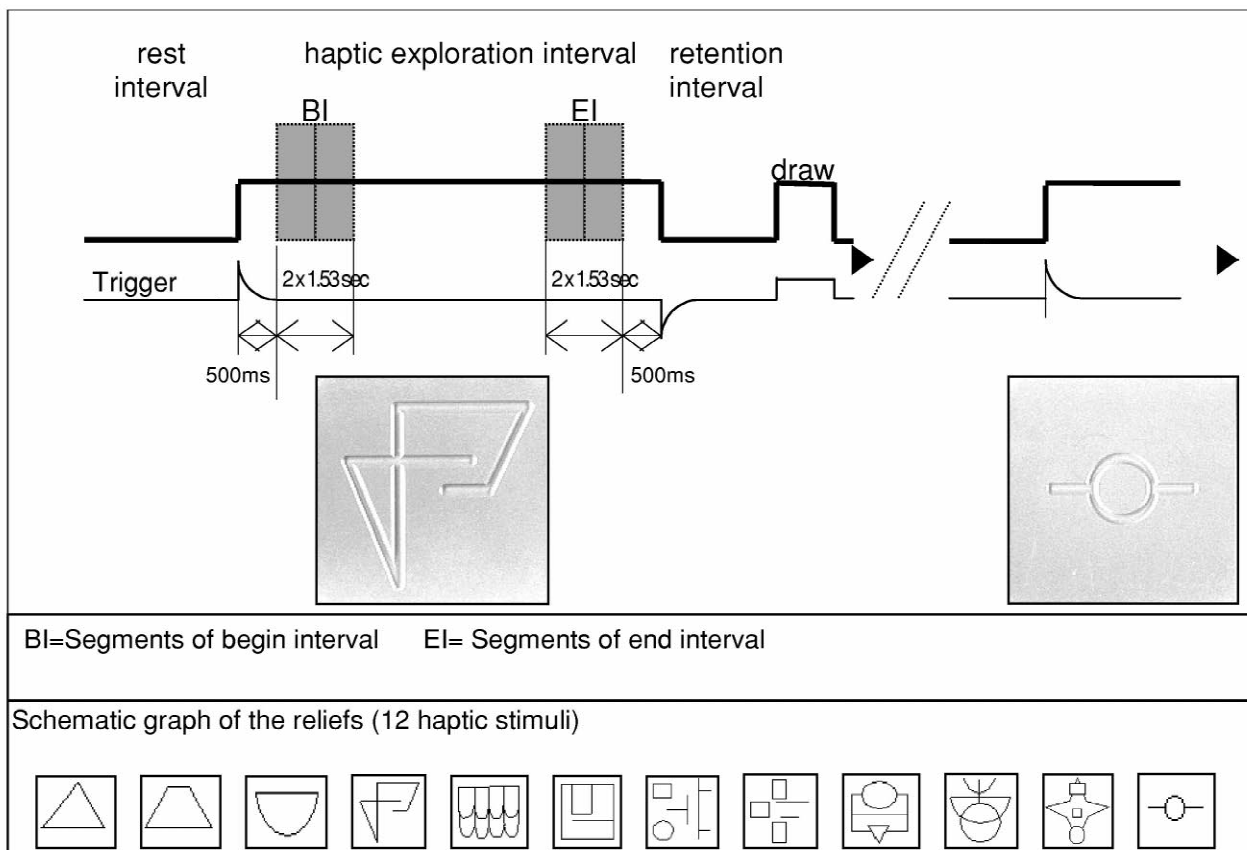


Fig. 1. Schematic time course of a single trial. The upper part illustrates the different intervals (rest, exploration, retention, drawing) and the examined beginning and end intervals. The lower part shows two examples of the stimulus material, a more complex one (left) and a less complex one (right).

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 were performed with an EEG analytical software package [17]. Artefact-free segments of 1.53 s (512 samples/channel) from the rest period (R), from the beginning (BI) and from the end of haptic exploration (EI) were used. Artefact contaminated segments were detected using visual inspection and cross correlation analysis between frontal EEG and EOG electrodes ($r_{crit.} < 0.5$) and subsequently removed. Two artefact-free successive segments were chosen for each stimulus located 500 ms after the onset of exploration (BI) and 500 ms before its end (EI), respec-

tively. The 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 their 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).

3. Results

The relationship between exploration time and theta activity was analysed with a linear regression model. In a

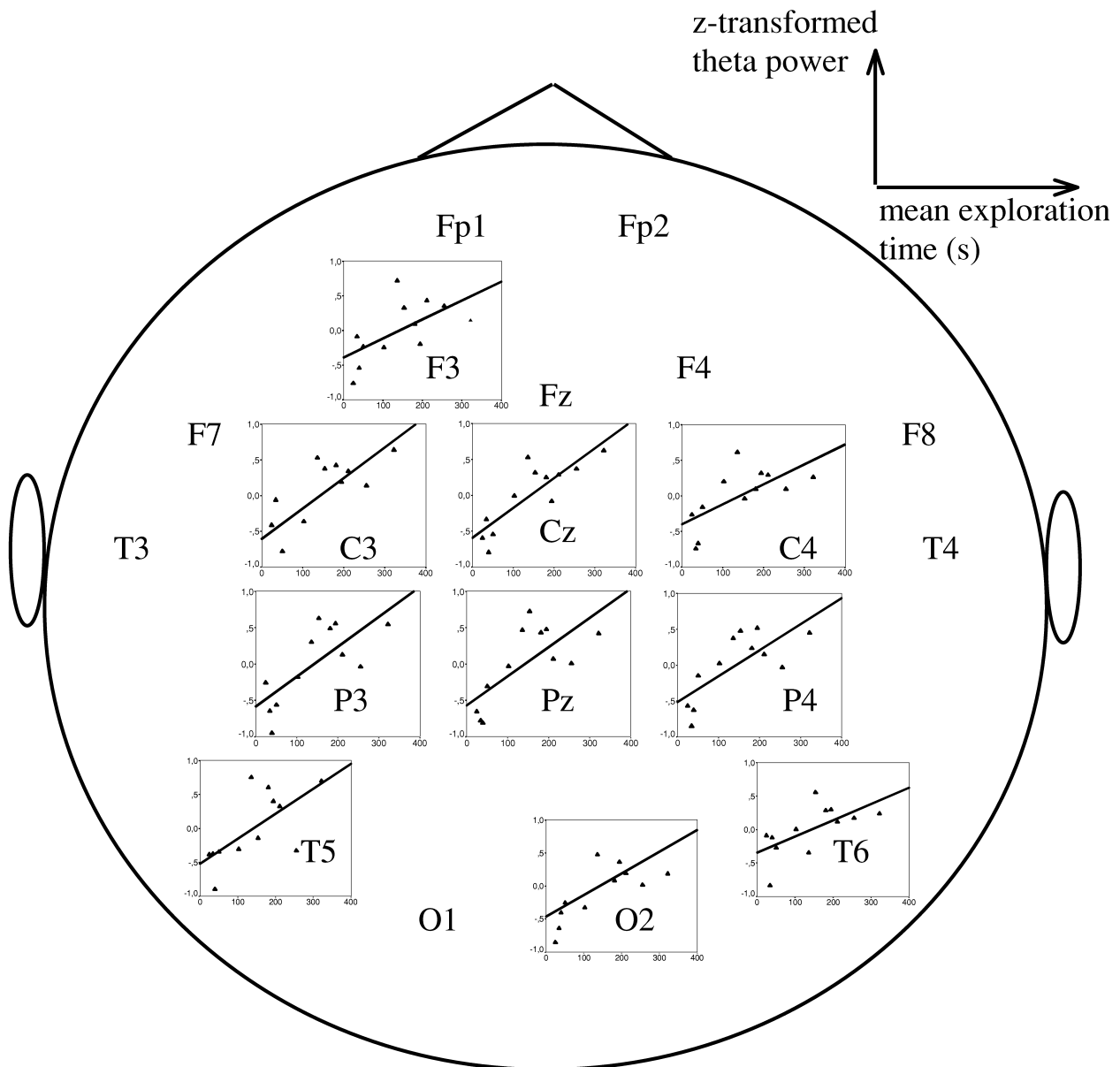


Fig. 2. Regression plots for significant ($P < 0.05$, $r^2 > 0.3$) individual tests of the linear regression model between mean z -transformed theta power from the end interval and mean exploration time.

previous experiment we have shown that subjective complexity of the stimuli correlates with exploration time [5,6]. Thus, stimuli were arranged in order of increasing exploration time for each subject to account for individual differences in perceived stimulus complexity and to normalize for complexity.

The regression analysis used z -transformed (mean=0, S.D.=1) mean theta power for BI and EI segments. When testing the central hypothesis, we focused on systematic linear trends between theta power and mean exploration time in 19 single tests for BI and 19 single test for EI ($\alpha=0.05$, Bonferoni corrected $\alpha'=0.002$). Furthermore, we also examined the linear regression model for all individual comparisons between 19 channels and mean exploration time in order to justify this approach.

No significant changes were found estimating the linear model (r^2) for the BI interval, i.e. none of the P -values reached the critical $\alpha'=0.002$. For the EI interval, significant linear trends were found between z -transformed theta power and mean exploration time. The estimates (r^2) for the linear model were highest for F3, C3, C4, P3, P4, O2, T5, T6, Cz, and Pz. Regression plots with significant coefficients for EI are shown in Fig. 2. Table 1 shows the F -statistics for testing the null hypothesis for BI and EI. As can be seen from Table 1, the regression coefficient (b1) was found to be significantly different from zero in ten out of 19 tests. During EI the value was below the critical $\alpha'=0.002$ for electrode Cz. Therefore, a significant linear relationship between theta power and mean exploration time can be assumed. The tests of the linear model for Fp1, Fp2, F4, O1, F7, F8, T3, T4, and Fz showed smaller model

estimates ($r^2<0.3$) and no significant differences in regression coefficients.

The regression estimates for alpha, alpha1, alpha2, beta1, and beta2 power in the EEG showed no significant differences either for BI or for EI.

4. Discussion

We observed a lack of correlation between theta power and exploration time (as a measure of stimulus complexity) at the beginning of haptic exploration (i.e. during BI). In contrast, theta power and exploration time were found to correlate at the end of haptic exploration (EI). The correlation was observed for ten out of 18 electrodes including central, parietal, and parieto-temporal regions bilaterally. This is in line with our hypothesis postulating minimal working memory load at the beginning of exploration. At that time, working memory load should be independent of stimulus complexity since no a priori knowledge exists concerning the given haptic stimulus, as can be seen from the lack of correlation between theta power and stimulus complexity during BI. In contrast, at the end of exploration nearly all features of the stimulus should be integrated into a perceptual model of the object, since the subjects could explore the haptic object as long as they considered necessary. It seems plausible that working memory load during this period depends primarily on the complexity of the stimulus material. This is in line with the observed linear trend between theta power as a postulated measure of working memory load and explora-

Table 1

Results of the linear regression analysis between z -transformed theta-power during the beginning (BI) and ending intervals (EI) and mean exploration time^a

Elect.	BI						EI					
	r^2	df	F	Sig. F	b0	b1	r^2	df	F	Sig. F	b0	b1
Fp1	0.016	10	0.17	0.692	-0.1021	0.0007	0.086	10	0.94	0.355	-0.1703	0.0012
Fp2	0.026	10	0.27	0.617	-0.1216	0.0009	0.056	10	0.59	0.460	-0.1344	0.0009
F3	0.172	10	2.08	0.180	-0.2417	0.0017	0.374	10	5.96	0.035	-0.3881	0.0027
F4	0.308	10	4.45	0.061	-0.2905	0.0020	0.102	10	1.14	0.311	-0.1699	0.0012
C3	0.068	10	0.73	0.414	-0.1517	0.0011	0.579	10	13.77	0.004	-0.6069	0.0043
C4	0.114	10	1.29	0.283	-0.1609	0.0011	0.440	10	7.87	0.019	-0.3973	0.0028
P3	0.070	10	0.75	0.407	-0.1605	0.0011	0.549	10	12.20	0.006	-0.5840	0.0041
P4	0.047	10	0.49	0.500	-0.1146	0.0008	0.551	10	12.26	0.006	-0.5135	0.0036
O1	0.022	10	0.22	0.647	0.0732	-0.0005	0.266	10	3.62	0.086	-0.3711	0.0026
O2	0.000	10	0.01	0.959	-0.0087	0.0001	0.328	10	4.89	0.052	-0.4648	0.0033
F7	0.176	10	2.13	0.175	-0.2935	0.0021	0.095	10	1.05	0.330	-0.1463	0.0010
F8	0.144	10	1.68	0.224	-0.2467	0.0017	0.015	10	0.15	0.708	-0.0457	0.0003
T3	0.004	10	0.04	0.846	-0.0378	0.0003	0.134	10	1.55	0.242	-0.2199	0.0015
T4	0.079	10	0.86	0.376	-0.1872	0.0013	0.124	10	1.41	0.262	-0.2123	0.0015
T5	0.015	10	0.15	0.703	0.0883	-0.0006	0.440	10	7.86	0.019	-0.5247	0.0037
T6	0.180	10	2.19	0.169	-0.3415	0.0024	0.397	10	6.58	0.028	-0.3458	0.0024
Fz	0.356	10	5.53	0.040	-0.3305	0.0023	0.253	10	3.39	0.095	-0.3183	0.0022
Cz	0.037	10	0.39	0.549	-0.1285	0.0009	0.709	10	24.36	0.001	-0.5907	0.0042
Pz	0.164	10	1.97	0.191	-0.2544	0.0018	0.517	10	10.70	0.008	-0.5710	0.0040

^a Significant coefficients are in bold. Elect., electrode; r^2 , model estimates; df, degrees of freedom; F , F -statistic; Sig. F , significance level; b0 and b1, model coefficients.

tion time as a postulated measure of stimulus complexity. However, our data can only spotlight the continuous processing of haptic stimuli. Special paradigms are necessary to allow the examination of the proposed serial processing of such stimuli in more detail.

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References

- [1] R.S. Daniel, Alpha and theta EEG in vigilance, *Percept. Motor Skills* 25 (1967) 697–703.
- [2] A. Gale, B. Christie, V. Penfold, Stimulus complexity and the occipital EEG, *Br. J. Psychol.* 62 (1971) 527–531.
- [3] P.S. Goldman-Rakic, Cortical localization of working memory, in: J.L. McGaugh, N.M. Weinberger, G. Lynch (Eds.), *Brain Organization and Memory*, Oxford University Press, New York, 1990.
- [4] A. Gevins, M.E. Smith, L. McEvoy, D. Yu, High-resolution EEG mapping of cortical activation related to working memory: effects of task difficulty, type of processing, and practice, *Cereb. Cortex* 7 (1997) 374–385.
- [5] M. Grunwald, *Haptische Reizverarbeitung und EEG-Veränderungen*, unpublished thesis, Jena, 1998.
- [6] M. Grunwald, T. Weiss, W. Krause, L. Beyer, R. Rost, I. Gutberlet, H.J. Gertz, Power of theta waves in the EEG of human subjects increases during recall of haptic information, *Neurosci. Lett.* 260 (1999) 189–192.
- [7] K. Iramina, S. Ueno, S. Matsuoka, MEG and EEG topography of frontal midline theta rhythm and source localization, *Brain Topogr.* 8 (1996) 329–331.
- [8] H.H. Jasper, The Ten Twenty Electrode System of the International Federation, *Electroenceph. Clin. Neurophysiol.* 10 (1958) 371–375.
- [9] R.L. Klatzky, S.J. Lederman, D.E. Matula, Haptic exploration in the presence of vision, *J. Exp. Psychol. Hum. Percept. Perform.* 19 (1993) 726–743.
- [10] R.L. Klatzky, J.M. Loomis, S.J. Lederman, H. Wake, N. Fujita, Haptic identification of objects and their depictions, *Percept. Psychophys.* 54 (1993) 170–178.
- [11] W. Klimesch, M. Doppelmayr, H. Schimke, B. Ripper, Theta synchronization and alpha desynchronization in a memory task, *Psychophysiology* 34 (1997) 169–176.
- [12] S. Knecht, E. Kunesch, A. Schnitzler, Parallel and serial processing of haptic information in man: effects of parietal lesions on sensorimotor hand function, *Neuropsychologia* 34 (1996) 669–687.
- [13] A. Mecklinger, *Gedächtnissuchprozesse-eine Analyse ereigniskorrelierter Potentiale und der EEG-Spontanaktivität*, Psychologie Verlags-Union, Weinheim, 1992.
- [14] B.A. Morrongiello, G.K. Humphrey, B. Timney, J. Choi, P.T. Rocca, Tactual object exploration and recognition in blind and sighted children, *Perception* 23 (1994) 833–848.
- [15] P. Pennekamp, R. Bösel, A. Mecklinger, H. Ott, Differences in EEG-theta for responded and omitted targets in a sustained attention task, *J. Psychophysiol.* 8 (1994) 131–141.
- [16] B. Roeder, F. Rosler, E. Hennighausen, Different cortical activation patterns in blind and sighted humans during encoding and transformation of haptic images, *Psychophysiology* 34 (1997) 292–307.
- [17] R. Rost, E. Hansen, L. Beyer, T. Weiss, EEG topography software for description of central nervous activation, in: W. Haschke, E.J. Speckmann, A.I. Roitbak (Eds.), *Slow Brain Potentials and Magnetic Fields*, Friedrich Schiller Universität Jena, Jena, 1992, pp. 137–145.
- [18] D.L. Schacter, EEG theta waves and psychological phenomena: a review and analysis, *Biol. Psychol.* 5 (1977) 47–82.