Neural networks engaged in short-term memory rehearsal are disrupted by irrelevant speech in human subjects

Franziska Kopp, Erich Schröger, Sigrid Lipka

Institut für Allgemeine Psychologie, Universität Leipzig, Seeburgstrasse 14-20, D-04103 Leipzig, Germany
Institute of Behavioural Sciences, University of Derby, Mickleover, Derby, DE3 9GX, UK

Received 22 August 2003; accepted 23 September 2003

Published in:
Neuroscience Letters, 354 (1), 42-45. DOI: 10.1016/j.neulet/2003.09.065

Abstract
Rehearsal mechanisms in human short-term memory are increasingly understood in the light of both behavioural and neuroanatomical findings. However, little is known about the cooperation of participating brain structures and how such co-operations are affected when memory performance is disrupted. In this paper we use EEG coherence as a measure of synchronization to investigate rehearsal processes and their disruption by irrelevant speech in a delayed serial recall paradigm. Fronto-central and fronto-parietal theta (4–7.5 Hz), beta (13–20 Hz), and gamma (35–47 Hz) synchronizations are shown to be involved in our short-term memory task. Moreover, the impairment in serial recall due to irrelevant speech was preceded by a reduction of gamma band coherence. Results suggest that the irrelevant speech effect has its neural basis in the disruption of left-lateralized fronto-central networks. This stresses the importance of gamma band activity for short-term memory operations.

Keywords: EEG coherence; Short-term memory; Rehearsal; Irrelevant speech effect; Gamma

Every-day experience shows that any ongoing mental activity like a telephone conversation can easily be disrupted by background speech or speech-like stimuli. Especially the storage of new information in short-term memory [1] seems to be susceptible to external interference. Interestingly, simultaneous presentation of a tone or of white noise does not yield a corresponding disrupting effect. Numerous findings have been reported showing which materials disrupt phonological rehearsal processes that are necessary to transfer information into memory and keep it online for further processing [6,11,12].

One major principle of the human brain system is the synchronization of neural activity [17] underlying the execution of cognitive processes such as object perception, speech comprehension or memory. Coherence, defined as the degree of similarity with respect to frequency, is mostly interpreted as a level of functional cooperation between different brain regions [8,16]. In this study we used the coherence measure in a special way: a model-based or parametric approach to spectral analysis developed by Schack was chosen. It provides an estimate of the spectral density matrix by fitting an autoregressive moving average(ARMA) model to the observed time data [14,15]. This method provides coherence values for every single sample point of an EEG recording and may therefore be suitable for tracking the high dynamics of cognitive processes. It was applied to investigate the neural dynamics – especially synchronization effects – underlying the classic irrelevant speech effect which has been well investigated in behavioural research [6,12].

In the current experiment 12 participants (ten female, aged 19–29 years, students and professionals) were tested in a delayed serial recall paradigm. In every trial a list of five bisyllabic concrete German nouns (balanced for frequency and semantic relatedness) [20] was presented sequentially on a PC screen with a presentation rate of 1 s per item and an ISI of 250 ms. After the presentation of the last noun, a fixation cross appeared for 10 s during which the items had to be retained in short-term memory. At the end of this interval three question-marks prompted the participants to recall the items aloud. To investigate rehearsal processes and their disruption, there were three experimental conditions (with 30 trials each): condition quiet enabled participants to subvocally rehearse the items, in condition noise participants were exposed to auditory stimulation (white noise) which was assumed not to disrupt rehearsal, and in condition speech participants were prevented from rehearsing by the presentation of irrelevant speech (digitalized radio recordings of speech without background noise or music). Both auditory stimulations were presented via headphones during the 10 s retention interval. Additionally, participants were tested in a simple detection paradigm as a control task intended to make demands on attention but not on memory. In the control tasks a fixation cross was presented for 10 s. During this time in some trials a small dot appeared for 100 ms in a region within a few millimetres around the fixation cross. Upon the presentation of the three question-marks at the end of the 10 s, participants had to indicate whether the dot had been there or not. Only 'no'-trials (30 out of 45 trials per condition) were analyzed. Exactly as in the memory paradigm, there were also three conditions (quiet, noise, speech) in the control task.

EEGs were recorded with the Neuroscan system at a rate of 250 Hz according to the 10/20 system with 19 scalp electrodes (Ag-AgCl). Artefact-free trials were analyzed for the 10 s retention interval. EEG coherence was computed for a 2 s period (the period between 2 and 4 s after the onset of the retention interval) using ARMA-based SpecTrial and SpecPara programs [15] in three frequency bands: theta (4–7.5 Hz), beta (13–20 Hz) and gamma (35–47 Hz). Inspection of coherence histograms led to the determination of 0.7 as the threshold for computing coherence duration.

The behavioural data indicated that our participants fell into two groups (Fig. 1). The first group showed the classic irrelevant speech effect, i.e. noise and quiet did not differ in the percentages of correctly recalled word lists whereas speech differed significantly both from quiet and from noise. The second group of participants, however, did not show this disrupting effect of irrelevant speech. As the dependent variable in the EEG analysis we computed the duration of high coherence, i.e. the sum of all periods of coherence levels above a given threshold (0.7) during the retention intervals. This measure reflects the long-lasting strong communication between associated brain structures and might therefore be considered as an indicator of distinct mental processes performed by these structures.

Fig. 2 shows the contribution of memory demands in performing the tasks. Comparing each memory condition to its respective control condition gives a picture of the underlying network co-operations. It is obvious that the theta band (4–7.5 Hz) seems to contribute more to the memory demands than the other frequency bands. The theta band shows synchronization changes especially at fronto-parietal and fronto-central electrode pairs which partially confirms previous findings of working-memory experiments showing enhanced frontal-posterior co-operations in the theta frequency range [13]. Common to gamma (35–47 Hz) and theta bands are co-operations between central electrodes suggesting the involvement of motor or premotor activations in the performance of rehearsal. Furthermore, the finding of synchronizations in the beta band (13–20 Hz) at left lateral sites confirms the assumption that language-specific areas are involved in rehearsal [20].

Comparisons within the memory conditions should reveal mechanisms of the nature of the irrelevant speech effect. Based on the behavioural data, a comparison of the two participant groups (disrupting speech effect vs. no irrelevant speech effect) was performed on the corresponding EEG data. Significant patterns in the gamma frequency range were found at central and left frontal electrode combinations (Fig. 3). Coherence duration within and between these two regions does not differ between quiet and noise in either group but decreases significantly when storage of verbal material is disrupted by irrelevant speech according to the behavioural data. Interestingly, the group of participants that does not show the speech effect does not reveal this decrease of coherence either. Thus, the pronounced reduction of long-lasting synchronization of gamma activity in the underlying phonological rehearsal network might reveal the neural basis of the irrelevant speech effect.

EEG coherence can only partially be attributed to subjacent cortical areas [8]. It is more likely that deep structures of the human brain such as the hippocampus also contribute to gamma responses and to memory performance [3,10]. Nevertheless, the topographic findings in our study strongly correspond to findings of neuroimaging studies, especially to those that reported that frontal, premotor and supplementary motor areas are involved in rehearsal processes of working memory [2,5,9]. Importantly, however, with gamma activity the brain has an optimal frequency to create a durable memory trace from a temporary representation [4,18] and synchronization of this gamma activity is reduced when rehearsal processes are impaired. Further research needs to clarify the cross-talk between different frequencies [7,14,19].

Acknowledgements
We thank E. Sommerfeld and B. Schack for helpful comments on EEG coherence and E. Herrmann and F.-M. Schleif for assistance in data acquisition and analysis. This work was supported by DFG.

References
[1] A.D. Baddeley, Is working memory still working?, Am. Psychol. 56 (2001) 851–864.
[2] J.M. Chein, J.A. Fiez, Dissociation of verbal working memory system components using a delayed serial recall task, Cereb. Cortex 11 (2001) 1003–1014.
[3] J. Fell, P. Klaver, K. Lehnertz, T. Grunwald, C. Schaller, C.E. Elger, G. Ferna´ndez, Human memory formation is accompanied by rhinalhippocampal coupling and decoupling, Nat. Neurosci. 4 (2001) 1259–1264.
[4] G. Ferna´ndez, J. Fell, P. Fries, Response: the birth of a memory, Trends Neurosci. 25 (2002) 281–282.
[5] O. Gruber, Effects of domain-specific interference on brain activation associated with verbal working memory task performance, Cereb. Cortex 11 (2001) 1047–1055.
[6] D. LeCompte, C.B. Neely, J.R. Wilson, Irrelevant speech and irrelevant tones: the relative importance of speech to the irrelevant speech effect, J. Exp. Psychol. Learn. Mem. Cogn. 23 (1997) 472–483.
[7] J.E. Lisman, M.A.P. Idiart, Storage of 7 / 2 short-term memories in oscillatory subcycles, Science 267 (1995) 1512–1515.
[8] P.L. Nunez, R. Srinivasan, A.F. Westdorp, R.S. Wijesinghe, D.M. Tucker, R.B. Silberstein, P.J. Cadusch, EEG coherency I: statistics, reference electrode, volume conduction, Laplacians, cortical imaging, and interpretation at multiple scales, Electroenceph. clin. Neurophysiol. 103 (1997) 499–515.
[9] E. Paulesu, C.D. Frith, R.S.J. Frackowiak, The neural correlates of the verbal component of working memory, Nature 362 (1993) 342–344.
[10] C. Ranganath, M. D'Esposito, Medial temporal lobe activity associated with active maintenance of novel information, Neuron 31 (2001) 865–873.
[11] P. Salame´, A. Baddeley, Effects of background music on phonological short-term memory, Q. J. Exp. Psychol. 41A (1989) 107–122.
[12] P. Salame´, A. Baddeley, Disruption of short-term memory by unattended speech: implications for the structure of working memory, J. Verb. Learn. Verb. Behav. 21 (1982) 150–164.
[13] J. Sarnthein, H. Petsche, P. Rappelsberger, G.L. Shaw, A. von Stein, Synchronization between prefrontal and posterior association cortex during human working memory, Proc. Natl. Acad. Sci. USA 95 (1998) 7092–7096.
[14] B. Schack, N. Vath, H. Petsche, H.-G. Geissler, E. Mo¨ller, Phasecoupling of theta-gamma EEG rhythms during short-term memory processing, Int. J. Psychophysiol. 44 (2002) 143–163.
[15] B. Schack, P. Rappelsberger, S. Weiss, E. Mo¨ ller, Adaptive phase estimation and its application in EEG analysis of word processing, J. Neurosci. Methods 93 (1999) 49–59.
[16] W. Singer, Striving for coherence, Nature 397 (1999) 391–393.
[17] W. Singer, The role of synchrony in neocortical processing and synaptic plasticity, in: E. Domany, J.L. van Hemmen, K. Schulten (Eds.), Models of Neural Networks, II, Springer, Berlin, 1994, pp. 141–173.
[18] C. Tallon-Baudry, A. Kreiter, O. Bertrand, Sustained and transient oscillatory responses in the gamma and beta bands in a visual short-term memory task, Vis. Neurosci. 16 (1999) 449–459.
[19] F. Varela, J.-P. Lachaux, E. Rodriguez, J. Martinerie, The brainweb: phase synchronization and large-scale integration, Nat. Rev. Neurosci. 2 (2001) 229–239.
[20] S. Weiss, P. Rappelsberger, Left frontal EEG coherence reflects modality independent language processes, Brain Topogr. 11 (1998) 33–42.