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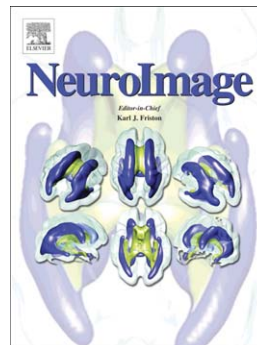Susanne Knake, ChunMao Wang, Istvan Ulbert, Donald L. Schomer, Eric Halgren

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Specific Increase of Human Entorhinal Population Synaptic and Neuronal Activity

During Retrieval

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Abstract

Population transmembrane currents and neuronal firing in different layers of the human entorhinal cortex (ER)were recorded during semantic and episodic memory processes using a linear array of 24 laminar microelectrodes . Both measures, as well as local broadband spectral power, increased during retrieval of newly-learned characteristics, especially in superficial layers. No differences were observed in the activity evoked by remembering people as compared to places. Semantic retrieval evoked similar activity. In contrast, intentional encoding of declarative memory evoked relatively little activity. A double-dissociation of these responses with simultaneously recorded lateral inferotemporal recordings suggests that entorhinal cortex may be specifically engaged during retrieval, across multiple memory types and materials.

Introduction

Lesions of the medial temporal lobe (MTL) produce a profound and specific amnesia (Squire et al., 2004), and conversely, MTL electrical hyper-activation can evoke intense memories (Bartolomei et al., 2004; Halgren et al., 1978b), implying that the MTL contributes to memory retrieval. However, temporary MTL disruption produces a temporary inability to lay down new traces, implying that it is also necessary for encoding (Halgren, 1984). Direct recordings of MTL neurons in humans have found increased firing during both input and output phases of memory tasks (Cameron et al., 2001; Halgren et al., 1978a).

Rat hippocampal (HC) neurons fire in particular spatial locations, leading to theories that the MTL is particularly involved in spatial navigation (O'Keefe and Nadel, 1978). Consistent data were found in recent hemodynamic and unit studies in humans (Ekstrom et al., 2003; Maguire et al., 1998). Other data, however, suggest that the involvement of the HC in spatial processing is secondary to a more general role whenever novel configurations of elements are processed (Eichenbaum, 2000).

While many studies find that amnesics with bilateral hippocampal damage are unable to learn new semantic facts even when divorced from their context (Squire et al., 2004), studies of patients whose HC had been lesioned in early childhood found relatively preserved semantic knowledge, suggesting that the HC may only be necessary for episodic memory (Vargha-Khadem et al., 1997). In summary, although the critical role of the MTL for human episodic memory is one of the key findings of cognitive neuroscience, crucial aspects of this role remain in doubt: is the MTL involved in both encoding and retrieval? in spatial processing or in configurational learning? in semantic as well as episodic memory?

In order to address these issues, we recorded multiunit activity (MUA) and current source density (CSD) at 150μ intervals across different cortical layers from the left ER of

a patient suffering from medically refractory epilepsy. Time- and frequency-domain ER responses were compared to those simultaneously recorded in the inferotemporal cortex (IT) and nearby MTL locations. ER responses were largest during episodic retrieval, but were not selective for spatial information.

Patient and Methods

Patient

A 37-y old right handed male suffering from medically intractable temporal lobe epilepsy since early childhood was investigated with bilateral stereotactic invasive EEG depth recordings within the clinical presurgical evaluation for the localization of the seizure onset zone. The subject had normal neuropsychological and psychiatric function and left hemispheric language dominance. Invasive EEG recordings found the seizure onset zone in the right amygdala. A right sided selective amygdalohippocampectomy was performed and the patient has now been seizure free for over 3 years (Engel Ia). Histopathology revealed right medial temporal sclerosis. The position of the electrodes, and the duration of the invasive recordings were based entirely on clinical considerations. Before taking part in the study, the participant gave fully informed consent according to the guidelines of the Declaration of Helsinki, monitored and approved by the Institutional Review Boards of Beth Israel/Deaconness Medical Center and Massachusetts General Hospital, Boston.

Task

The paradigm was visually presented on a 19" computer monitor as white capital letters in Geneva font on a black background in the central ~5° of visual angle. The patient performed 60 trials of each of 6 conditions: EPISODIC ENCODING. EPISODIC RETRIEVAL, and SEMANTIC RETRIEVAL, crossed with PERSON and LOCATION.

Each trial regardless of condition was comprised of four frames presenting successively a cue, a name, a category and a characteristic. EPISODIC ENCODING trials began with a CUE to 'LEARN,' followed by a NAME of a previously unknown person or location, then a CATEGORY of attribute (e.g., 'HOBBY' for a person, 'LANGUAGE' for location), and finally the CHARACTERISTIC itself (e.g., 'PAINTING' or 'SPANISH'). Each NAME-CATEGORY-CHARACTERISTIC association was presented twice during learning. EPISODIC RETRIEVAL trials began with a CUE to 'ANSWER' followed by a NAME-CATEGORY-CHARACTERISTIC, and the patient indicated if they were correct. SEMANTIC RETRIEVAL trials had an identical format, but probed public knowledge (e.g. 'RONALD REAGAN-JOB-PRESIDENT' or 'AUSTRIA-LANGUAGE-GERMAN'). Half of the retrieval trials were correct, i.e. the presented characteristic matched that which had been presented previously in association with the same name and category. Thus both encoding and retrieval trials included both novel and repeated characteristics, roughly balancing for repetition effects.

Probes and recording details:

Details of electrode construction, recordings and analysis techniques can be found elsewhere (Ulbert et al., 2001). Briefly, clinical electrodes were modified to be smaller in diameter (350 µm) in a 5 mm segment at their tips, containing 24 Platinum-Iridium contacts (each 40 µm diameter, 110 µm interelectrode distance). The tip of electrode was in the left ER (see Figure 1). Differential recordings were obtained from 23 pairs of successive contacts. Population trans-synaptic current flows were estimated using Current Source Density (CSD) analysis (Nicholson and Freeman, 1975; Ulbert et al., 2001). CSD approximates the depth distribution of the current sources in laminated structures such as the cerebral neocortex (Mitzforf, 1985). Excitatory post synaptic currents (EPSCs) produce current sinks at the active synapses, with passive sources as

current returns (Nicholson and Freeman, 1975). Conversely, at the membrane potentials typical of waking and active human neocortex, inhibitory post synaptic currents (IPSCs) should produce current sources at the active synapses, that would be accompanied by passive sinks as current returns. Simultaneously recorded multi unit activity (MUA) as a continuous estimate of the population neuronal firing can help distinguish if a sink reflects an active excitation or passive current return (Ulbert et al., 2001). In contrast to local field potentials, which do not distinguish between excitatory and inhibitory events, CSD current sinks with increased MUA are interpreted as representing local population excitatory postsynaptic currents (EPSCs). Due to the small size of the recording contacts (40μ), the close spacing of the contacts (150μ center-to-center), and the particular analytic methods, CSD and MUA decline steeply with distance, estimating activity of neurons in a volume roughly corresponding to that of a cortical column (Grover and Buchwald, 1970; Wang et al., 2005)

The temporal evolution of task modulation was examined by calculating on every trial the spectral power for each latency, frequency and cortical depth. For these measures, the single trial signal for each channel was convolved with complex Morlet's wavelets (Kronland-Martinet et al., 1987). Each Morlet's wavelet used here has a Gaussian shape both in the time domain (SD σ_t) and in the frequency domain (SD σ_f) around its central frequency f_0: $w(t, f_0) = A \exp(-t^2/2\sigma_t^2) \exp(2i\pi f_0 t)$, with $\sigma_f = 1/(2\pi\sigma_t)$. Relatively constant temporal and spectral resolution across target frequencies was obtained by adjusting the wavelet widths, according to the target frequency (Wang et al., 2005). Wavelet widths were kept at 1 for frequencies 1, 2, and 3 Hz, resulting in σ_t of 159, 80, 53ms and σ_f of 1, 2, and 3Hz. Wavelet widths increased from 1 to 15 as the frequency went from 4 to 60Hz, resulting in a constant σ_t of 40 ms and a constant σ_f of 4 Hz. Tests with simulated data confirmed that the methods used here are accurate as low as 1 Hz (Wang et al., 2005). Phase-locking was calculated between microelectrode recordings in

different layers of entorhinal cortex, and macroelectrode recordings in inferotemporal, entorhinal and temporal polar cortices (Lachaux et al., 1999). The resulting time-frequency and phase-locking plots were averaged across trials and normalized with respect to the pre-stimulus baseline for each frequency and channel (Halgren et al., 2002). To test the difference between conditions, two-tailed student t-tests were applied to baseline corrected spectral powers with the standard deviation from individual trials. All comparisons noted in the figures or text were significant at $p<10^{-5}$.

Results

Behavioral Performance

The hit rate was slightly similar for the episodic condition (97%) and for the semantic condition (95%), and both hit rates differed significantly from chance ($p < 0.001$, two-sided binomial test, n = 320). The reaction times (RT) were similar between episodic retrieval (1228ms) and semantic retrieval (1243ms), and for correct (1235ms) and incorrect (1236ms) trials.

Laminar recordings

EPSCs were evoked in both superficial and deep ER layers during episodic encoding and retrieval, as well as semantic retrieval (Figure 1). These responses were largest during episodic retrieval and significantly smaller during episodic encoding. CSD sinks and especially MUA increases were prolonged (~1s long). The responses mainly occurred following presentation of the characteristic when the subject was retrieving the recently-learned association rather than in earlier parts of the same trial when the context was being established. These excitatory currents were largest in the superficial ER layers. In the same layers, spectral analysis of the CSD from individual trials found that power in both lower frequency (delta/theta) and higher frequency (beta/gamma)

bands again increased more strongly during retrieval than during encoding (Figure 1c). Thus, both time-domain and frequency-domain measures were elevated during retrieval as compared to encoding trials, during the part of the trial when active retrieval took place.

Macro-depth electrodes

In order to compare ER responses to those in different parts of the temporal lobe, we recorded local field potentials from macro-electrodes in white matter 5mm lateral to the ER laminar microelectrode array ('ER-lat'), in left lateral inferotemporal cortex (IT), and in rhinal cortex (RH) in the collateral fissure of the anteroventral temporal lobe (Figure 2). ER-lat macrorecordings replicated ER CSD recordings in demonstrating increased theta power during episodic retrieval as compared to encoding, but high frequency changes were absent suggesting that they are highly focal. In IT, local field potentials and low frequency spectral power increased sharply to all categories of visual stimuli, consistent with its known role in visual information processing. Similar to ER, the rhinal cortex (RH) showed the largest increase in delta, theta, alpha and beta frequencies during retrieval, and especially during episodic retrieval. The ER extends a variable amount into the collateral sulcus at this anterior level (Insausti and Amaral, 2004), so it is possible that this recording reflects ER activity. Increased event-related phase-locking was observed between both superficial and deep layers of ER, and IT (see Figure 2d), consistent with sustained event-related communication between ER and this neocortical area. This increased phase-locking was confined to lower frequencies (theta and delta), and was less regular between ER and the other macroelectrode contacts (see Supplemental figure 1). No difference was observed in either laminar or macro-recordings between items presenting or probing memory for places *versus* people (see Supplemental figure 2).

Discussion

Entorhinal cortex population EPSCs, neuronal firing, and spectral power across multiple bands were strongest during the retrieval of memories, especially of episodic memories, as compared to memory encoding. This difference was not seen in simultaneous recordings from inferotemporal cortex, supporting previous suggestions that different parts of the MTL may contribute primarily to different phases of memory (Brown and Aggleton, 2001). For example, in monkeys, while lateral inferotemporal (IT) firing strongly decreases when stimuli are repeated, this effect may not be present in ER, suggesting that IT may support priming whereas medial areas including ER are more involved in retrieval (Suzuki and Eichenbaum, 2000; Xiang and Brown, 1998). A similar dissociation has been noted in humans, when population firing and excitatory currents are suppressed by word repetition in IT and perirhinal sites, but not in ER (Halgren et al., 2006). Further support for a role of ER in conscious retrieval is the fact that hyperactivation of this area may evoke vivid recollections (Bartolomei et al., 2004; Halgren et al., 1978b).

The elevated response during retrieval of different characteristics appeared equal regardless of whether those characteristics referred to people *versus* locations. This is consistent with views of the MTL as related to declarative memory in general rather than being restricted to spatial information (Eichenbaum, 2000). Similarly, although as with fMRI, the ER response was larger during episodic as compared to semantic retrieval (Steinvorth et al., 2005), it was present during both. This is consistent with the notion that the MTL may continue to be engaged by retrieval processes in general, even after the trace becomes either sufficiently consolidated (Squire et al., 2004) or interlinked with semantic knowledge (Nadel and Moscovitch, 1997).

Superficial ER layers are the main source of input from IT and other neocortical

areas to HC, and deep ER layers relay HC activity back to neocortex (Insausti and Amaral, 2004). This HC-ER-neocortical interaction may be modulated and synchronized by theta and gamma oscillations (Chrobak and Buzsaki, 1998). Similarly, we found increased delta and theta phase-locking between ER and IT during our task. Human ER firing and theta and gamma coherence between rhinal and HC areas help predict subsequent memory, suggesting that the ER may be involved in encoding (Cameron et al., 2001; Fell et al., 2003). Our results are consistent with these previous studies in showing that the encoding and retrieval conditions evoked similar patterns of activity, and differed only in the intensity of activation.

Previous studies have found the onset latency of activity in IT and PR evoked by visual words to be at about 120ms, consistent with the IT recordings here (Halgren et al., 1994; Halgren et al., 2006). ER activity in these recordings began at about 180ms, and continued for over a second with the maximal response at about 500ms. Since IT and HC activity is also long-lasting, all three structures in this circuit are simultaneously active. The HC-EC and EC-IT relationships are bidirectional, and the conduction delays are about 2 orders of magnitude shorter than the period of co-activation, suggesting that this period is also one of cyclic interaction. This interaction is central to models that posit MTL participation in encoding during the creation of a neural network representing an event, and again in retrieval as the previous network is re-created (Alvarez and Squire, 1994; Halgren, 1984). In this view, the activation of superficial ER neocortex-recipient layers during retrieval is to be expected, because they are a key link in the cyclic interaction of MTL and neocortical structures as they progressively refine the re-created network.

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Alvarez P, Squire LR. Memory consolidation and the medial temporal lobe: A simple network model. Proceedings of the National Academy of Sciences of the United States of America 1994; 91: 7041-7045.

Bartolomei F, Barbeau E, Gavaret M, Guye M, McGonigal A, Regis J, et al. Cortical stimulation study of the role of rhinal cortex in deja vu and reminiscence of memories. Neurology 2004; 63: 858-64.

Brown MW, Aggleton JP. Recognition memory: what are the roles of the perirhinal cortex and hippocampus? Nat Rev Neurosci 2001; 2: 51-61.

Cameron KA, Yashar S, Wilson CL, Fried I. Human hippocampal neurons predict how well word pairs will be remembered. Neuron 2001; 30: 289-298.

Chrobak JJ, Buzsaki G. Operational dynamics in the hippocampal-entorhinal axis. Neurosci Biobehav Rev 1998; 22: 303-10.

Eichenbaum H. A cortical-hippocampal system for declarative memory. Nat Rev Neurosci 2000; 1: 41-50.

Ekstrom AD, Kahana MJ, Caplan JB, Fields TA, Isham EA, Newman EL, et al. Cellular networks underlying human spatial navigation. Nature 2003; 425: 184-8.

Fell J, Klaver P, Elfadil H, Schaller C, Elger CE, Fernandez G. Rhinal-hippocampal theta coherence during declarative memory formation: interaction with gamma synchronization? Eur J Neurosci 2003; 17: 1082-8.

Grover FS, Buchwald JS. Correlation of cell size with amplitude of background fast activity in specific brain nuclei. J. Neurophysiol. 1970; 33: 160-171.

Halgren E. Human hippocampal and amygdala recording and stimulation: Evidence for a neural model of recent memory. In: Butters N and Squire L, editors. The Neuropsychology of Memory. New York: Guilford, 1984: 165-181.

Halgren E, Babb TL, Crandall PH. Activity of human hippocampal formation and amygdala neurons during memory testing. Electroencephalography and Clinical Neurophysiology 1978a; 45: 585-601.

Halgren E, Baudena P, Heit G, Clarke JM, Marinkovic K. Spatio-temporal stages in face and word processing. 1. Depth-recorded potentials in the human occipital, temporal and parietal lobes. Journal of Physiology (Paris) 1994; 88: 1-50.

Halgren E, Boujon C, Clarke J, Wang C, Chauvel P. Rapid distributed fronto-parieto-occipital processing stages during working memory in humans. Cerebral Cortex 2002; 12: 710-728.

Halgren E, Walter RD, Cherlow DG, Crandall PH. Mental phenomena evoked by electrical stimulation of the human hippocampal formation and amygdala. Brain 1978b; 101: 83-117.

Halgren E, Wang C, Schomer DL, Knake S, Marinkovic K, Wu J, et al. Processing stages underlying word recognition in the anteroventral temporal lobe. Neuroimage 2006; 30: 1401-13.

Insausti AM, Amaral DG. Hippocampal Formation. In: Paxinos G and Mai JK, editors. The Human Nervous System. San Diego: Elsevier Academic, 2004: 871-914.

Kronland-Martinet R, Morlet J, Grossmann A. Analysis of sound patterns through wavelet transforms. International Journal of Pattern Recognition and Artificial Intelligence 1987; 1: 273-302.

Lachaux JP, Rodriguez E, Martinerie J, Varela FJ. Measuring phase synchrony in brain signals. Hum Brain Mapp 1999; 8: 194-208.

Maguire EA, Burgess N, Donnett JG, Frackowiak RS, Frith CD, O'Keefe J. Knowing where and getting there: a human navigation network. Science 1998; 280: 921-924.

Mitzforf U. Current source density method and application in cat cerebral cortex: Investigation of evoked-potentials and EEG-phenomena. Physiological Reviews 1985; 65: 37-100.

Nadel L, Moscovitch M. Memory consolidation, retrograde amnesia and the hippocampal complex. Current Opinion in Neurobiology 1997; 7: 217-227.

Nicholson C, Freeman JA. Theory of current source density analysis and determination of the conductivity tensor for anuran cerebellum. Journal of Neurophysiology 1975; 38: 356-368.

O'Keefe J, Nadel L. The Hippocampus as a Cognitive Map. Clarendon: Oxford, 1978.

Squire LR, Stark CE, Clark RE. The medial temporal lobe. Annu Rev Neurosci 2004; 27: 279-306.

Steinvorth S, Corkin S, Halgren E. Ecphory of autobiographical memories: an fMRI study. NeuroImage 2005; in press.

Suzuki WA, Eichenbaum H. The neurophysiology of memory. Ann N Y Acad Sci 2000; 911: 175-91.

Ulbert I, Halgren E, Heit G, Karmos G. Multiple microelectrode - recording system for human intracortical applications. Journal of Neuroscience Methods 2001; 106: 69-79.

Vargha-Khadem F, Gadian DG, Watkins KE, Connelly A, Van Paesschen W, Mishkin M. Differential effects of early hippocampal pathology on episodic and semantic memory [see comments] [published erratum appears in Science 1997 Aug 22; 277(5329):1117]. Science 1997; 277: 376-80.

Wang C, Ulbert I, Schomer DL, Marinkovic K, Halgren E. Responses of human anterior cingulate cortex microdomains to error detection, conflict monitoring, stimulus-response mapping, familiarity, and orienting. J Neurosci 2005; 25: 604-13.

Xiang JZ, Brown MW. Differential neuronal encoding of novelty, familiarity and recency in regions of the anterior temporal lobe. Neuropharmacology 1998; 37: 657-76.

Figure legends

Figure 1. Estimates of population synaptic activity (CSD) and neuronal firing (MUA) in ER during memory. **a**. CSD responses from representative superficial and deep channels show a sustained sink beginning about 200ms after the name of the object or location is presented, and continuing for over 2 s, through the presentation of the Category and peaking about 500 ms after presentation of the individual characteristic to be learned or retrieved (↑). This sink is larger during episodic retrieval (blue line) than during episodic encoding (green line). Significant intervals indicated by red bars in the baseline. **b**. MUA increases during the retrieval period during the retrieval tasks (↓), suggesting that the sink in a represents an excitatory post-synaptic current. **c**. Time-depth maps of current sinks (red) and sources (blue). Current sinks in superficial layers are greatest during the matching of a presented characteristic to that retrieved from recent episodic memory (*****). **d**. Individual trial event-related spectral power (iERSP), plotted as z-scores relative to pre-stimulus baseline. Power in the delta/theta (↓) and beta/gamma (↑) bands significantly increases in the superficial channels for sustained periods during retrieval trials.

Figure 2. Local field potentials simultaneously recorded in different left MTL areas during memory. **a**. MRI taken with the electrodes *in situ*, showing the microelectrode array in entorhinal cortex (ER) whose recordings are in figure 1, as well as macroelectrode contacts in the anterior collateral sulcus (RH, rhinal cortex), inferotemporal cortex (IT), and in the temporal white matter 5 mm lateral of the entorhinal cortex,(ER-lat). Please note that the sizes of the artifacts on the MRI images are larger than that of the probes themselves. **b**. Event-related potential gradients in IT show a sharp initial response peaking at ~170ms (↓), as well as later components peaking at ~540ms (⇓). The

responses to each stimulus in the sequence was similar, and did not change between conditions, consistent with these responses representing visual processing. In contrast, ER-lat and RH contacts record mainly late and small responses (Δ). **c**. Spectral power maps showing activity in IT, ER-lat and RH during episodic encoding, episodic retrieval and semantic retrieval. Frequency spectra from 1 to 60 Hz are displayed. Spectral power in IT initially increases across delta, theta, alpha, and beta bands (*), followed by a sustained increase in delta activity (**^**), and does not change between conditions. ER-lat also shows a late delta increase (Δ), but it is greater during retrieval. RH shows a large broadband response, specifically to retrieval, and especially episodic retrieval (⇑). **d**. Phase locking between IT and ER-lat in the delta/theta band increases relative to baseline during the memory task (↑). Shown here are all trials; increases were seen during both encoding and retrieval (see Supplementary Figure 1).

Supplementary Figure 1: Phase-locking. Individual trial event-related phase locking was calculated between CSD in entorhinal cortex, and macroscopic field potentials recording in inferotemporal cortex (IT), what matter lateral to entorhinal cortex (ER-lat) and temporal polar cortex (TP), presented as z-scores relative to baseline. Phase-locking was calculated separately for superficial and deep layers of entorhinal cortex (odd and even rows, respectively), and for episodic encoding (top two rows), episodic retrieval (rows 3 and 4), semantic retrieval (rows 5 and 6), and all trials combined (rows 7 and 8). Relative to baseline, phase-locking in delta/theta band increases in all three conditions, and for an extended period (see phase-locking between superficial entorhinal cortex and IT, for example, indicated with **^**). Phase-locking also occurs between deep entorhinal layers and IT (*), and between laminar recordings in entorhinal cortex and ER-lat (Δ) and TP (↑) macroelectrode recordings.

Supplementary Figure 2. Lack of significant differences between trials probing memory for characteristics of locations as compared to characteristics of persons. Legend as for Figure 1. All trials including encoding, episodic and semantic retrieval, were included in these averages.

a. Transmembrane currents (CSD)

b. Population firing (MUA)

episodic encoding
episodic retrieval
semantic retrieval

c. CSD time-depth maps

d. Spectral power time-frequency maps

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a. Recording locations (in situ MRI)

b. Local field potentials

c. Spectral power time-frequency maps

d. Phase locking of IT with ER CSD