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Journal

Brain research, 558(2)

ISSN

0006-8993

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Publication Date

1991-09-01

DOI

10.1016/0006-8993(91)90767-p

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Peer reviewed

BRES 16904

Research Reports

Localization of brain activity during auditory verbal short-term memory derived from magnetic recordings

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(Accepted 2 April 1991)

Key words: Magnetic evoked field; Auditory verbal short-term memory

We have studied magnetic and electrical fields of the brain in normal subjects during the performance of an auditory verbal short-term memory task. On each trial 3 digits, selected from the numbers 'one' through 'nine', were presented for memorization followed by a probe number which could or could not be a member of the preceding memory set. The subject pressed an appropriate response button and accuracy and reaction time were measured. Magnetic fields recorded from up to 63 sites over both hemispheres revealed a transient field at 110 ms to both the memory item and the probe consistent with a dipole source in Heschl's gyrus; a sustained magnetic field between 300 and 800 ms to just the memory items localized to the temporal lobe slightly deeper and posterior to Heschl's gyri; and a sustained magnetic field between 300 and 800 ms to just the probes localized bilaterally to the medio-basal temporal lobes. These results are related to clinical disorders of short-term memory in man.

INTRODUCTION

Studies of short-term memory in man reveal that the time required for scanning the contents of the short-term store increases linearly as the number of items memorized increases and that the entire memory store is scanned before a response is made^{25,26}. There is consensus that, in man, verbal short-term memory for auditory items is superior to that for visual items and that lesions in the left parietotemporal region severely impair auditory verbal short-term memory²⁸. These behavioral and clinical findings have been complemented by the definition of brain electrical events accompanying memory scanning in normal adults^{18,19,20} and in patients with disordered auditory verbal short-term memory²⁴. A sustained potential shift appears frontally during the memorization of a list of items with a polarity that is positive for visually presented digits and negative for acoustically presented digits²⁰. In contrast, during the scanning of the short-term memory store, a positive potential appears over the midline, maximal in the parietal region, which is independent of the modality or type (verbal or non-verbal) of stimulus¹⁸. These results suggest that different areas of the brain are active during memorization versus scanning.

The ability to localize the generators of these electrical events from the distribution of the potentials over the scalp is complicated by distortions of the fields induced by changing conductivities of the brain, skull, and overlying tissues¹¹.

In contrast, source localization using the distribution of magnetic fields that accompanies electrical potentials has many advantages^{4,23,30}. Those electrical events that are generated by a dipole source tangentially oriented to the skull surface will be accompanied by a magnetic field whose lines of strength can be detected over the scalp without distortion by the underlying bone and subcutaneous tissues. This technique has been used to localize the generators of cerebral cortical activity evoked by sensory input in the somatosensory^{5,9} visual^{12,27} and auditory^{14,15} systems as well as the pre-movement related activity emanating from motor cortex^{1,2,3}. While studies of brain magnetic fields accompanying cognitive activities are few^{9,13,29} this method should also provide insights into neural events accompanying cognition.

The present study was undertaken to measure brain magnetic fields accompanying auditory verbal short-term memory processes in man. The magnetic events associated with sensory reception, memorization, and retrieval were sampled across the scalp allowing the topographic

identification of the sites of brain that were active during these periods. The data are related to both brain electrical events and behavioral indices (accuracy and reaction times) of short-term memory performance. The results bear on our understanding of clinical disorders of memory in man.

MATERIALS AND METHODS

Brain activity during auditory verbal short-term memory functions was measured in 3 normal right-handed male subjects (ages 24, 27 and 30) who were scientists in the laboratory. The test procedure, modified from that of Sternberg²⁵, consisted of presenting a 3 item memory set followed by a probe item which the subject identified as being or not being a member of the preceding memory list. The items used in these experiments were the digits 'one' through '9' which were presented in the auditory modality. The probability that the probe would be the same digit as one of the 3 memory items ('in-set' probe) was 0.5 and its occurrence was randomly intermixed with trials in which the probe was not a member of the preceding set ('out-of-set' probe). The subject responded by pressing a reaction time button when the probe was identified as 'in-set' (right hand) or 'out-of-set' (left hand). The subject initiated each trial by pressing both reaction time buttons causing the first memory set item to appear after a 2 s delay. The interval between each subsequent item in the memory set was 1.2 s followed by a 2 s period between the last item and the probe.

The members of the stimulus sequence were generated by a native English or native German speaker whose enunciations of the digits were transduced by a microphone, amplified, and digitized by a computer at an 18 kHz rate. The computer was programmed with two separate lists of 200 digit sequences of 3 memory items followed by a probe. Each digit occurred with equal probability at each position of the memory list and the probe position. These lists could be presented in the forward or reverse direction. The onset of the voltages comprising each of the digits was the trigger to commence the analysis of brain activity. These digitized signals were transduced into sounds and presented binaurally to the ears via a 4 m length of tubing, resulting in a transmission delay of approximately 13 ms. The tubing minimized magnetic field artifacts from electrical and metal components of the transducers. The digits were presented either in English or German depending on the 'mother tongue' of the subject at an intensity of approximately 70 dB nHL.

Magnetic recordings were taken from 36 to 49 positions over the left hemisphere encompassing the posterior frontal, temporal, and anterior parietal areas. In two of the subjects, additional magnetic recordings were made from 14 positions over the right hemisphere restricted to only the anterior and posterior temporal regions but corresponding to these same locations studied over the left hemisphere. The recordings were made using one of the two dewars of the dual recording dewar system that contained 6 second-order gradiometers arranged concentrically on a circle, 5 cm in diameter, centered on a 7th gradiometer. The system was housed in a magnetically shielded room with an overall noise level of 15 fT/Hz^{1,2}. The position and orientation of each of the 7 gradiometers was located within a 3 dimensional head coordinate system defined by the nasion and preauricular points and having an accuracy of ± 2 mm.

Event-related potentials (ERPs) were derived from a single scalp site with electrodes placed at Pz referenced to a mastoid to minimize interference with the magnetic fields that might result from their motion. The Pz-mastoid recording derivation provides a reasonable estimate of the electrical activity occurring during short-term memory¹⁷. The electro-oculogram (EOG) was derived from electrodes placed medially just above the eye and laterally just below the eye for detecting both vertical and horizontal eye movements. A ground electrode was placed on the forehead. The placement of the reference, ground, and EOG electrodes was opposite

to the side of the head over which the dewar was located to reduce distortions in the magnetic fields.

The band pass of the recording system for magnetic fields was from 0.1 to 50 Hz and 0.3 to 50 Hz for electrical fields. The sample rate for digitizing both the magnetic and electrical events was 200 Hz.

The subject was positioned on a wooden recording platform in a magnetically shielded room, the acoustic transmission tubes inserted in the ears, the head stabilized using a vacuum pillow, and the dewar positioned over the appropriate scalp region. The instructions to the subjects were to push the appropriate response button as soon as they could distinguish the category of the probe. They were also told not to move the head and to inhibit blinking and respirations during the trial until 1 s after their response. Two hundred trials were made for each dewar position. Up to 4 different dewar locations were assessed each day and each subject was studied over 4 days. Measures of accuracy, reaction time (RT), and ERP provided assurances that the subjects performed in a consistent manner over these repeated trials.

Several control experiments were done to evaluate the contribution of different factors to the results. These included (1) having the subject keep a mental tally of the in-set probes instead of making a button press; (2) having the subject switch which hand was used for responding to the in-set and out-of-set probes; and (3) having the subject 'ignore' the stimuli with the onset of the trials being controlled by the experimenter.

The data from the magnetic and electrical brain recordings were averaged for the activity evoked by the third memory item and for the probe separating the averages into two categories: those accompanying the in-set condition and those accompanying the out-of-set conditions. Thus, for both the third memory item and for the probe there were two separate averages made for the in-set and out-of-set conditions. The analysis time was 1700 ms, 200 ms of which were prior to the memory item or the probe onset. Those trials containing large eye movements or artifacts in the magnetic field, defined as changes of greater than 1000 fT during the 1700 ms analysis period, were excluded from the average. The averaged activity was digitally low-pass filtered at 15 Hz (24 dB/octave slope, zero phase shift).

Data analysis consisted of deriving behavioral measures of accuracy and reaction times by a computer program. Those trials in which the incorrect response button was pressed or in which a response did not occur within 1500 ms were considered errors. The averaged event-related brain activity was analyzed for the latency and amplitude of the evoked components, with the average amplitude in the prestimulus 200 ms period serving as the baseline level from which component amplitude measures were taken. The components which were measured occurred at approximately 100 ms, 200 ms, and 300–700 ms corresponding to the periods of maximal activity in both the electrical and magnetic recordings. The averaged magnetic event-related activity was processed with isocontour maps of the distribution of the magnetic fields to identify dipolar field patterns for each subject based on the appropriate latencies of the respective components. For the components occurring close to 100 and 200 ms the maps comprised 4 sequential 5 ms samples (a 20 ms epoch) around the peak of the component. For sustained fields accompanying the memory item and the probes in the time period of 300–700 ms, the maps comprised 20 sequential 5 ms samples (a 100 ms epoch) that varied in its starting position between 350 and 500 ms based on visual inspection of the brain activity in this time domain. Source localization was achieved by the fitting of the theoretical magnetic fields produced by one or more tangential current dipole sources to the observed data using a least-squares minimization procedure¹. The fitting algorithm took into account both the 3-dimensional position and tilt of the gradiometers in the head coordinate system and the proportion of the variance in the observed data accounted for by the theoretical field (goodness of fit). The actual 3-dimensional locations of the sources were then projected onto a coronal magnetic resonance image of the brain constructed at the same angle as the head coordinate system used

TABLE I

Behavioral data

S.D. = standard deviation; ND = no data.

Subjects	Accuracy % correct (S.D.)		Reaction times ms (S.D.)	
	In-set	Out-of-set	In-set	Out-of-set
1	96 (2)	98 (2)	573 (34)	618 (29)
2	97 (2)	98 (2)	616 (37)	614 (32)
3	ND	ND	889 (137)	1022 (132)

in the data collection. Statistical treatment of the amplitudes and latencies of the brain potentials utilized paired *t*-test with values < 0.05 considered to be significant.

RESULTS

Behavioral measures

Two of the subjects performed with high accuracy (Table I) throughout the study. The determination of accuracy in the third subject was not possible because approximately 1/2 of the responses were too slow, occurring after the 1500 ms window. This subject chose to be very certain and responded slowly. The mean RTs to

the in-set and out-of-set probes were within 2 ms of each other in one subject, while in the other two subjects RTs were slightly faster (mean difference of 132 ms and 45 ms) to in-set than to out-of-set probes. These differences in RT to in-set and out-of-set probes were not statistically significant.

EEG data; event-related potentials

The components elicited to the digits included an N100 and P200 to both the memory item and to the probe, a sustained negativity (N250–500) beginning at approximately 200 ms for the memory item, and an N200 and a late sustained positivity (P450) beginning at approximately 300 ms to only the probe. The definition of the early positive component, labelled P3a, which is maximal frontally could not be made as the recording electrode was located over the parietal scalp (Pz). Only the N100 and P450 components were consistently present in the Pz-mastoid derivation employed and their latency and amplitude for each subject based on a minimum of 6 separate averages are contained in Table II. Fig. 1 depicts superimposed averages and a grand average from one of the subjects. From both the tabulated data and

TABLE II

Latency and amplitude of the event-related components

Item measures were taken from the third item; probe measures were taken from the in-set probe. S.E. is given in brackets. $\bar{x}$ = mean; ND = not defined.

Component	Ss	(a) Latency (ms)				(b) Peak amplitudes	
		Electrical		Magnetic		Electrical (μ V)	Magnetic (fT)
		Peak	Duration	Peak	Duration		
N 100							
	Item						
	1	114		135		-3.2	192
	2	110		140		-4.2	57
	3	111		115		-3.1	86
	$\bar{x}$	111 (6)		130 (10)		-3.5 (0.4)	111 (58)
	Probe						
	1	112		120		-6.2	299
	2	123		130		-4.4	120
	3	116		105		-5.3	220
	$\bar{x}$	117 (5)		118 (10)		-5.3 (0.7)	213 (73)
SF							
	Item						
	1	ND	160-550	ND	370-765	1	119
	2	ND	250-520	ND	280-845	1	70
	3	ND	ND	ND	280-710	ND	106
	$\bar{x}$					ND	98 (21)
	Probe						
	1	535	250-950	465	285-800	5.7	256
	2	515	300-1500	465	240-870	15.2	220
	3	708	480-1500	505	275-845	2.4	130
	$\bar{x}$	586 (75)		478 (13)		7.8	202 (53)

Fig. 1. Averaged evoked potentials (recorded between Pz and the right mastoid) to in-set and out-of-set probe items (left side of figure), the third memory item (middle panel) and their differences (traces on the bottom and the far-right). Several averages are superimposed along with their grand average just below. Positivity at the Pz electrode is plotted upwards. The components N100 and P450 are labelled. Stimulus onset is at the time of the short vertical lines. The analysis duration was 1700 ms and includes a prestimulus period of 200 ms.

from the figure, several differences between the potentials to the memory items and to the probes can be distinguished. First, the amplitude of the N100 is larger to the probes than to the memory item but the difference did not reach statistical significance ($P = 0.18$). Secondly, an N200 and a sustained positivity, the P450, occur to the probes. Thirdly, the P450 to the in-set and out-of-set probes differed.

The peak amplitudes of the sustained positivity, P450, associated with the probe were 2.4, 5.7, and 15.2 μV in the 3 subjects. It was initiated at approximately 300 ms, peaked between 500 and 700 ms and decayed slowly

reaching baseline by 1000 ms in two of the subjects. The grand average from each of the subjects showed a consistent difference between in-set and out-of-set probes, and the data from one of the subjects are in Fig. 1. The positivity associated with the in-set probes began approximately 50 ms earlier than to the out-of-set probes with the difference between the two potentials being maximal at approximately 450 ms.

The memory items in two subjects were associated with a low amplitude (approx. 1 μV) sustained negative field beginning at approximately 200 ms. This negative potential shift during memorization of auditory verbal

Fig. 2A: MEG waveforms of left side of the head to the third memory item (interrupted traces) and the in-set probe (solid traces) are shown for 14 different scalp positions. B: MEG waveforms to in-set (solid traces) and out-of-set (interrupted traces) probes are compared. The analysis time was 1700 ms and includes a 200 ms prestimulus period. An upward deflection of the trace indicates an outward magnetic field. The time of stimulus onset is indicated by the small vertical lines.

material is typically maximum in the frontal region and is usually absent in the parietal region^{16,17}.

MEG data; event-related magnetic fields (Fig. 2)

100–200 ms. The magnetic fields contained a distinct component peaking at approx. 110 ms after stimulus onset (termed AEF100, for auditory evoked field at approx. 100 ms latency) which corresponded in time to the peak of the N100 in the evoked potentials (Table II). The amplitude of this component was large and ranged up to 300 fT. The spatial distribution of the fields were quite similar in the 3 subjects: over the left hemisphere there was an outward magnetic flux posteriorly and an inward flux anteriorly (Fig. 3, left display). The direction of the flux was exactly opposite when recorded from comparable sites over the right hemisphere. The location and strength of a dipole source for the AEF100 was localized to the primary auditory projection area, Heschl's gyrus, and accounted for from 79 to 93% of the variance of the data (Table III, Fig. 5). The strength of the AEF100 dipole associated with the third memory item was reduced compared to the probe (means were 9.01 ± 0.94 nA·m vs 14.12 ± 6.3 nA·m, respectively). This reduction in source strength was also associated with a relatively greater reduction in the outward magnetic fields posteriorly in the left hemisphere than in the inward magnetic fields anteriorly suggestive of a slight change in orientation of the dipole source in addition to its change in net strength. The latency of the peak of this field was shorter for the probes than for the third memory item (mean of 118 ms vs 130 ms, $P = 0.04$). Thus the latency and strength of the AEF100 dipole for the memory items differed from that of the probes (Table III) corresponding to the differences in the N100 in the evoked potentials. The amplitude disparity at approx. 100 ms between the probe and the third memory item most likely reflects sensory adaptation rather than cognitive processes since the disparity persisted when the subject was not engaged in the short-term memory task.

300–700 ms. During the 300–700 ms period following the onset of the stimulus, the magnetic fields to the last memory item and to the probe differed. To the memory item there was a low amplitude sustained magnetic field of up to 120 fT (labelled AESF for auditory evoked sustained field) that reversed direction between the anterior and posterior portions of the brain, approximately over the sylvian fissure (Fig. 2, Fig. 3, middle panel). The calculations for a dipole source accounted for 71–76% of the variance and localized the generator to the region of the temporal lobe close to the AEF100 source. (Table III, Fig. 5). In the two subjects in whom the dewar had been placed over the right hemisphere, the directions of the sustained fields were reversed.

TABLE III

Parameters for least-squares estimated dipole sources

Q = dipole strength in nanoAmpere·meters (nA·m); Intracranial positions (left hemisphere, unless otherwise noted) are given in right-handed coordinate system with +x-axis through nasion and +y-axis through left pre-auricular point; Radius = distance from origin; % fit = percent of observed variance accounted for by the theoretical field. S 1, 2, 3 = subject designations.

	Q (nA·m)	X (cm)	Y (cm)	Z (cm)	Radius (cm)	% fit
AEF100						
<i>(items)</i>						
Out-of-set						
S1	9.2	0.49	4.66	6.09	7.7	87%
S2	9.9	-0.99	4.55	7.03	8.4	81%
S3	8.6	1.16	5.99	6.62	9.0	93%
In-set						
S1	8.4	0.40	4.91	6.02	7.8	84%
S2	8.1	-0.88	4.89	8.19	9.6	79%
S3	10.7	0.50	5.58	6.04	8.2	93%
<i>(probes)</i>						
Out-of-set						
S1	9.8	0.89	4.89	6.01	7.8	76%
S2	11.8	0.24	4.69	6.45	8.0	87%
S3	15.6	1.20	5.50	5.86	8.1	87%
In-set						
S1	11.6	1.05	4.82	5.70	7.6	81%
S2	8.5	-0.29	5.16	5.49	7.5	77%
S3	27.4	1.38	4.54	6.19	6.2	89%
'Sustained field'						
<i>(items)</i>						
Out-of-set						
S1	12.5	-1.14	3.04	6.71	7.5	73%
S2	6.3	-0.50	4.89	5.34	7.3	84%
S3	3.4	0.29	6.65	6.33	9.1	72%
In-set						
S1	6.3	-0.20	3.14	9.40	9.9	73%
S2	3.7	-1.95	4.32	9.23	10.4	57%
S3	8.4	0.34	5.66	5.03	7.6	80%
<i>(probes)</i>						
In-set						
S1 left	10.0	0.03	4.49	4.87	6.6	76%
right	11.7	0.56	-5.67	4.62	7.4	
S2 left	50.8	-1.42	3.58	2.75	4.7	93%
right	37.4	0.65	-4.92	1.59	5.2	

Magnetic fields to the probes in the period from 300 to 700 ms were characterized by their large amplitude (up to 250 fT) and uniformity of direction: the fields were always outward over the left hemisphere and inward over the right hemisphere (Fig. 3, right panel, Fig. 4 from another subject). We did not separately analyze for the distribution of fields during the initial (300–400 ms) and later (400–700 ms) portions of this period and are therefore unable to address the issue of the separate generation of the two subcomponents, P3a and P3b, that have been identified in this period using electrical recordings¹⁷. The finding of a uniform direction of the magnetic flux over each of the hemispheres is incompat-

Fig. 3.

Fig. 4.

←

Fig. 3. Averaged MEG waveforms (A) to in-set probes (left and right panels) and to the third memory items (middle panel) from one subject. There are two waveforms in each panel selected from the left scalp recordings: the solid trace is from a posterior recording site and the interrupted trace from a more anterior site. The colored maps of the head in B show the topography of field strength and direction (see scale, red for inward flux and blue for outward flux). In the left panel, a 20 ms time domain of the short latency AEF at approx. 110 ms latency is depicted. Note the boundary between the direction of flux in the region of T3 over the left temporal lobe and a corresponding but opposite topography over the right hemisphere. In the middle panel the MEG map is the 300–400 ms epoch of the response to the third memory item. Note that the boundary at which the direction of the magnetic fields changes over the left hemisphere is slightly different to that of the AEF100 in the left panel. The direction of the magnetic fields are reversed in the right hemisphere. The waveforms in the right panel contain the MEG data to in-set probes and the corresponding map depicts the magnetic fields for a 100 ms epoch beginning 300 ms after the probes' presentation. Note that the direction of magnetic flux is unidirectional over each hemisphere, outward over the left hemisphere and inward over the right hemisphere.

Fig. 4. MEG waveforms (left column) and maps showing scalp distributions of magnetic fields after the presentation of in-set (solid traces in MEG waveforms) and out-of-set (interrupted traces in MEG waveforms) probes. The difference MEG waveforms (waveforms in the middle column) and maps are also presented. The time base of the waveforms is 1700 ms and the vertical line indicates the stimulus onset at 200 ms. Note that the fields have a uniform and opposite direction over each hemisphere and that the amplitude of the magnetic fields is greater to in-set than to out-of-set probes in this time period.

ible with dipole sources near the lateral surfaces of each hemisphere. Rather, medial dipolar sources oriented in the anterior-posterior direction could produce a scalp distribution as found in the present experiment. Candidate medial structures for such a field pattern could be the cingulate cortex or the medio-basal temporal lobes.

The amplitude and time course of the magnetic fields differed according to whether the probes were in-set or out-of-set (see Fig. 4). In-set probes were associated with sustained fields that deviated from baseline earlier than the sustained fields to out-of-set probes. Fig. 4 from one subject contains waveforms and maps of the magnetic fields to in-set and out-of-set probes as well as their differences during the 300–400 ms periods. This is the time period when the P450 event-related potentials also were different to the in-set and out-of-set probes (Fig. 1).

The sustained high amplitude magnetic fields to the probes sampled at one dewar placement site were found to be essentially unchanged in two subjects who carried out the short-term memory task by keeping a mental count of the occurrence of the in-set probes rather than by making a button press. Changing the hand used for in-set and out-of-set responses in two subjects slightly prolonged the RTs but had essentially no effect on the scalp distribution of the fields. Moreover when the instructions were changed so that the subjects ignored the stimuli, the sustained magnetic fields to both the memory items and the probes were not observed.

DISCUSSION

The results of this study, using measures of both electrical and magnetic fields, show a sequence of brain activity extending over approx. one second during the memorization and recall of digits presented acoustically in a paradigm that engages short-term memory pro-

cesses²⁶. The electrical events, sampled from the midline parietal region, provided measures of the time course of these changes while the magnetic field measures, sampled from up to 63 sites over both hemispheres, provided details of the location of the active brain sites.

At about 100 ms after the presentation of a digit, there is evidence of sensory registration of both the items being memorized and recalled localized to the vicinity of primary auditory cortex, Heschl's gyri. From 300 to 700 ms both the location and type of activity differed depending on whether the digit was being memorized or whether it was being compared to the contents of the short-term store. With memorization, activity is localized to a region of the temporal lobe close to that active during sensory processing. In contrast, during scanning of the contents of the short-term memory store activity appears in deep medial structures, the medial temporal lobes. The results of prior studies of brain magnetic fields during the processing of auditory signals are consistent with many of the current results. The early magnetic fields, occurring at approx. 100 ms after stimulus onset, originate in the primary auditory cortex, Heschl's gyrus^{4,16} even though the type of auditory stimuli used differed between these studies: tones, and phonemes in these prior studies, or words in the present study. Hari and colleagues⁴ recently reported a sustained field from 200 to 700 ms accompanying 'attention' to words compatible with a dipole source localized to the supratemporal auditory cortex. In the present experiment, the sustained fields accompanying the presentation of items to be memorized (AESF) had a similar latency range and were also localized somewhat deeper and posterior to the source of the AEF100 in the temporal lobe. This portion of auditory cortex is active both during instructions to pay 'attention' to auditory signals⁴ as well as during the 'memorization' of a list of digits (the present experiments). The finding that the strength of the sus-

Fig. 5. MRI of a coronal section through the mid temporal region from one of the subjects showing the position of the generators of brain activity at different time epochs during the performance of a short-term auditory verbal memory task. The positions of the dipoles generating the short latency AEF100 (○) and the sustained field during memorization [AESF, (item)] as well as the sustained fields during memory scanning [AESF (probe)] are localized using the data collected from up to 49 recording sites over the left hemisphere. There are comparably located generators in the right hemisphere for the AEF100 and the AESF (item) which are not mapped because of the limited number of recording sites sampled over the right scalp (14 positions). The location of the generator sites for the AEF100 and the sustained field to the memory items (AESF item) is in the region of the auditory cortex whereas the generators of the fields accompanying the scanning of the short-term memory store, AESF (probe), are in the medial-basal portions of both temporal lobes. The asymmetry of the medio-basal temporal sources is most likely due to the reduction in precision accompanying localization of deep compared to superficial sources.

tained magnetic fields in both experiments was larger over the right than the left hemisphere merits further study as, perhaps, reflecting hemispheric asymmetry during certain types of cognitive processing of acoustic signals.

Some of the highest amplitude magnetic fields accompanied the comparison of the probe with the contents of the short-term memory store in the time domain of 350–700 ms. The scalp distribution of the fields showed an outward flux over the left hemisphere and an inward flux over the right hemisphere, a pattern quite different from the bidirectional magnetic fields over each hemisphere accompanying sensory registration (AEF100) and memorization (AESF). Four alternative dipolar models could account for the unidirectionality of the hemispheric fields during memory scanning. First, a single anteriorly directed dipole placed superiorly between the hemispheres of high current density. Second, a single deep midline source directed in a posterior direction. Third, two symmetrical anteriorly directed sources located in the superior aspect of each hemisphere with their medial fields of opposite direction cancelling, leaving flux patterns

over the two hemispheres of opposite direction. Fourth, a mirror image of the immediately prior model with the sources located deep and directed posteriorly. We tested all of the above models separately and found that the best goodness of fit was for the last model (94 and 76% for the two subjects, Table III) with the localization of the sources to the medio-basal temporal lobes (Fig. 5). The accuracy of localizing a deep source as in medio-basal temporal lobe vs a superficial source as in lateral temporal lobe differs because of noise constraints⁶. Thus for a relatively weak dipole, localization accuracy to a superficial site is 2–3 mm whereas for a deep site it can be as much as 1 cm. This constraint probably accounts for the asymmetrical position of the medio-temporal dipolar sources depicted in Fig. 5. Thus, during the scanning of the auditory short-term memory store there is evidence from magnetic field measures that the medio-basal portions of the temporal lobes are active. This conclusion corresponds to the observations of McCarthy and coworkers¹⁰ who recorded from the temporal lobe of epileptic patients at the time of surgery while the patients were engaged in a slightly different memory task requiring the detection of infrequently occurring signals (the so-called 'odd-ball' or target detection task). They found high amplitude electrical fields in the hippocampus during the performance of the target detection task. With scalp recordings, a parietal positivity is recorded to target stimuli with features similar to the parietal positivity accompanying the short-term memory task used in the present experiments²⁰. Our data are not sufficient to localize the activity occurring during memory scanning to a particular portion of the medio-basal temporal lobe, i.e., cortex, hippocampus, or amygdala.

The clinical evidence from lesions of parietal cortex of its importance in auditory short-term memory was not supported by the results from the present study. The distribution of the magnetic field was not compatible with a focal dipole source in the parietal lobe during the short-term memory task. Instead, activity was clearly evident in the superior and posterior portion of the temporal lobes during memorization of digits presented acoustically as well as in the medial temporal lobes during the scanning of the contents of the short-term store. We did not systematically scan the superior frontal, inferior temporal, posterior parietal, or occipital scalp areas and cannot exclude the presence of additional focal dipolar sources active in these regions during memory scanning. However, in preliminary studies in one subject we did sample one region over the occiput and one region over the midline frontal areas without defining prominent magnetic fields. The failure to detect evidence of focal parietal lobe activity may be due to a limitation of magnetic field recordings of being sensitive to dipole

sources oriented tangentially. A dipole source within parietal cortex oriented radially to the scalp, as would occur at the tip of a gyrus, would not be detected whereas a tangentially oriented source within the sulcus would have been detected. An alternate possibility is that a parietal lobe lesion interrupts connections of the auditory cortex to other portions of the brain involved in auditory verbal short-term memory processes and thereby causes deficits of auditory verbal short-term memory as in a 'disconnection' syndrome. The definition that the medial temporal lobes are active during the scanning of the short-term memory store poses an additional paradox since bilateral lesions of this region are not associated with a disturbance of auditory verbal short-term memory but rather impairments of long-term memory functions³¹. The significance of medial temporal lobe activity during memory scanning will require further study.

There are only a few published studies of magnetic fields accompanying cognitive activity. Okada and colleagues¹³ and more recently Lewine, et al.⁹ measured magnetic fields accompanying the detection of infrequent target stimuli and concluded that in the time domain of 300 to 400 ms there was evidence of activity in symmetrical deep limbic structures in the temporal lobe. The conclusions from the present study using a cognitive task specific for auditory verbal short-term memory, are somewhat similar. Differences between the scalp distributions of the magnetic fields in the Okada et al.¹³ and present papers could be due to slight differences in the depth and/or orientation of the dipole sources attributable perhaps to differences in the modality of the stimuli being processed (visual for Okada et al.¹³ vs auditory in the present paper) or the task demands (target detection in Okada et al.¹³ and memory scanning in the present paper).

The combination of magnetic recordings, electrical recordings, and behavioral measures on the same subjects provide complementary images of brain activity during short-term memory. One notable finding was that both the electrical and magnetic recordings clearly distinguished different patterns of brain activity accompan-

ing the classification of the probes into two types, in-set and out-of-set: the positivity associated with in-set probes began approx. 50 ms earlier than the positivity associated with out-of-set probes. This finding is of interest as it is counter to Sternberg's original proposal²⁶, based on RT measures, that the brain processes in-set and out-of-set probes similarly. He suggested that the contents of the short-term store must be scanned in a serial and exhaustive manner regardless of the probe type before a response was made. The findings of differences between the potentials to in-set and out-of-set probes indicates that these two classes of probes are processed differently lending support to alternative models that scanning of short-term memory is not necessarily serial and exhaustive but may be parallel and self-terminating²². The definition of brain activity using event-related potentials or magnetic fields appear to be a more sensitive indicator of probe processing differences than does reaction time. The detection of differences in potentials to in-set and out-of-set probes defined in the present paper may be related to the large number of trials employed (approx. 3000 trials for each subject) since such differences were not noted in earlier studies employing only several hundred trials^{18,24}.

Electrical recordings are relatively simple to perform and provide evidence of the microstructure of sensory and cognitive processes. Magnetic field measurements are relatively complex but have the capability of localizing activity to specific areas of the brain. The combination of these methods to a specific cognitive task, auditory verbal short-term memory, has provided evidence as to the locus and timing of brain activity during different aspects of the task.

Acknowledgements. Supported in part by Grant 11876, National Institutes of Health. Development of the MEG system at the University Clinic of Neurology, Vienna (Bti Systems, San Diego, CA, U.S.A.) and the magnetically shielded room (Vacuumschmelze, Hanau, F.R.G.) was supported in part by grants from the FWF (Fonds zur Förderung der Wissenschaftlichen Forschung) of Austria, The Austrian National Bank and Ministry of Science and Research of Austria.

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