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Oscillatory brain activity during a motor task

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CHANGES in spectral power in neuromagnetic fields associated with a manual task requiring a high level of sensorimotor integration (SMI) were investigated by analysing spontaneous, non-invasively recorded activity during motor preparation (WAIT), task performance (SMI), and control (REST) conditions in four healthy, right-handed human subjects. Neuromagnetic fields were recorded over the left sensorimotor cortex using a 37-channel instrument. In all subjects, a prominent narrow-band motor preparation rhythm centred near 19 Hz was consistently observed during the WAIT state. During SMI, mean relative increases in 26–30 Hz activity appeared in two of the subjects, paralleling gamma band enhancement recently observed during SMI in monkeys.

Key words: Magnetoencephalography (MEG); Oscillatory activity; Sensorimotor integration; Gamma band; Motor cortex; Rhythmic; EEG

Introduction

Gamma band (above 15–20 Hz) oscillatory electromagnetic brain activity induced by sensory stimulation has been proposed to represent integration of distributed neuronal activity underlying conscious perception (particularly olfactory and visual) and sensorimotor integration.[1–5] This study investigates whether or not replicable high-frequency oscillatory activity can be recorded non-invasively from sensorimotor areas in humans performing a fine motor control task demanding a high level of sensorimotor integration (SMI) and focused attention. The paradigm used was derived from that employed in a recent study on monkeys by Murthy and Fetz.[1] The results suggest that non-invasive electromagnetic measurements can be used to study global oscillatory brain dynamics associated with human performance of complex tasks, and that coherent oscillatory activity in at least three narrow frequency ranges accompanies human sensorimotor processing.

Materials and Methods

Four healthy, right-handed subjects (1 female, 3 males, ages 26–38) performed a task consisting of finding quickly, by touch, with eyes closed, small plastic figurines named by the experimenter from among four similar figurines (trolls, about 10 cm^3 in size) placed in a cup near their right hand. Subjects were positioned on a non-magnetic bed inside a magnetically shielded room, with their head and right hand stabilized by vacuum casts. Prior to the experiment, subjects were given as much practice as they needed to learn to perform the task reliably.

During the first part of each trial, the subject waited (about 8 s) for the next instruction from the investigator (WAIT condition) with their right hand relaxed. Then the investigator announced, via a loudspeaker, the figurine the subject was to find next. This cued the subject to begin the next SMI period, which lasted in different trials from 5–15 s. As soon as the subject found the required figurine, he/she lifted it out of the cup using a sharp wrist extension, in order to create an EMG record of the end of the SMI period. The subject then opened his/her eyes briefly to verify that the correct object had been found, and then closed them again to enter the next WAIT period. The same protocol was repeated in a second experimental session on another day, each session lasting approximately 1 h. In both sessions, subjects searched for each figurine an equal number of times in the same pseudo-random order. As a control condition, data was collected during 6 min periods of relaxed wakefulness (REST), first with eyes closed, then with eyes open.

Neuromagnetic fields (bandpass 0–50 Hz, sampling rate 208.3 Hz) were recorded over the left sensorimotor cortex using a 37-channel first-order gradiometer. Electromyographic (EMG) activity was recorded from surface electrodes overlying the flexor and extensor digitorum communis muscles of the right forearm. Mean power spectra were calculated by averaging power spectral estimations derived from Fourier transforms on 0.3 s (64 data points), Welch-windowed segments with 50% overlap. For each subject, a total of 60 to 100 artifact-free periods (of 3–10 s each) were averaged for each condition (WAIT, SMI, REST/open, REST/closed).

Results

Figure 1 shows spontaneous neuromagnetic activity during a typical trial. Mean power spectra at representative channels for each of the subjects are shown in Figure 2, which shows that spectral power was higher, across the entire frequency range, in the WAIT

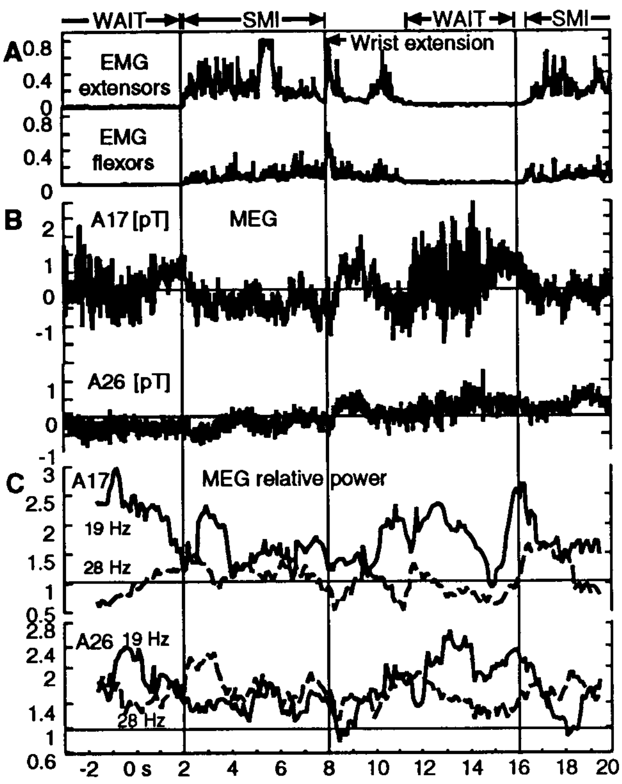

FIG. 1. (A) Typical single trial for one subject. Top panels (A) show rectified EMG from the flexors and extensors of the forearm. EMG signals served as criteria to segment WAIT and SMI conditions in each trial. Middle panels (B) show neuromagnetic field activity from two selected channels. Note the increased level of oscillatory activity in the WAIT periods. Bottom panels (C) show power within two narrow frequency bands (3.2 Hz width, centres at 19 and 28 Hz) relative to the average power over all frequencies at the respective channel and time point. Note the relative increase in 19 Hz power during both WAIT periods, and the relative increase at 28 Hz in the lower channel at the beginning of SMI.

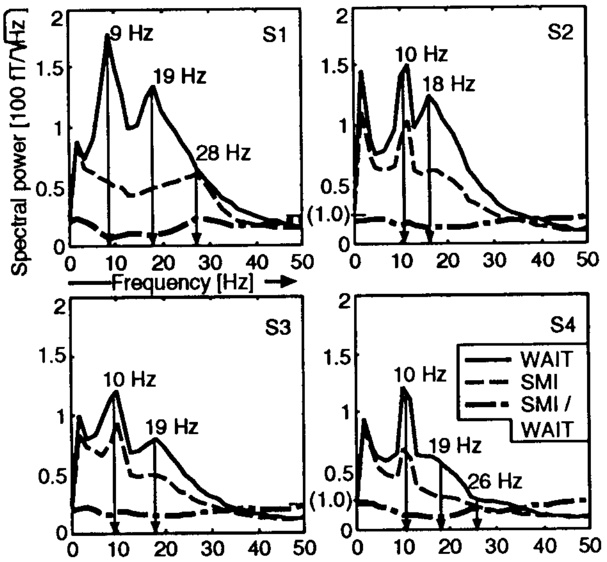

FIG. 2. Power spectra of mean spontaneous neuromagnetic activity in the second session for each of the four subjects at representative channels. In the WAIT (solid line) state, two power peaks can be seen in all subjects: one at 9–10 Hz and the other at approximately 19 Hz. Note that during SMI (dashed line) power at all frequencies is lower than during WAIT periods. The lower (dashed-dotted) line in each plot shows the ratio SMI/WAIT for the same channel (1/4 scaling). Note the relative peaks near 28 Hz in two subjects (S1 and S4).

condition than in the SMI condition. In addition, for both sessions and in all four subjects the WAIT condition spectra contain two peaks, near 10 Hz and 19 Hz, which had consistent differences in spatial distribution and reactivity to experimental conditions. In all subjects, isocontour maps of power at the 10 Hz peak appeared to have a single posterior maximum, and showed larger changes between eyes open and closed (REST) than between WAIT and SMI conditions. In contrast, the 19 Hz peak appeared only during the WAIT condition (i.e. during preparation for sensorimotor activity), and had a double-peaked spatial distribution which was in each case different from the 10 Hz pattern. Since no circa 19 Hz spectral peak appeared during REST condition (compare Fig. 3C), this rhythm cannot be associated with relaxation *per se*.

To investigate frequency domain changes related to the transition from WAIT to SMI more closely, the mean SMI spectrum for each subject was divided by the mean WAIT spectrum. Results for subject S1 contained a relative peak in oscillatory activity between 26 and 30 Hz (Fig. 2, S1). Figure 3A shows isocontour field maps of spectral power at 10, 19 and 28 Hz in this subject. Note the different spatial patterns at the three frequencies: the characteristic spatial pattern of 28 Hz power during SMI (in both sessions) consisted of two nearby spatial foci (Fig. 3A), while the 28 Hz spatial pattern during the WAIT condition was more diffuse. The 28 Hz SMI pattern for this subject was also stable within sessions: as an example, Figure 3B maps power in three successive averages of forty SMI segments. However, the relative increase near 28 Hz was not consistent across subjects. Subject S4 displayed a weaker relative increase near 26 Hz (Fig. 2), but no such increases could be detected in the remaining two subjects. Figure 3C plots the spatial patterns of 18 Hz power during WAIT and REST for subject S2: the bipolar pattern appearing during WAIT does not occur during REST. This was the case for the near 19 Hz patterns of the other three subjects as well.

Discussion

Modulation of ongoing processing through interaction with external events is an important aspect of brain function. Event-related spectral response averaging can reveal modulatory event-related brain dynamics that do not appear in time-domain event-related response averages.[6] Our results reveal that MEG spectral changes accompanying SMI involve a decrease in power over the entire spectrum (2–50 Hz), with most pronounced changes near 10, 19 and for some subjects,

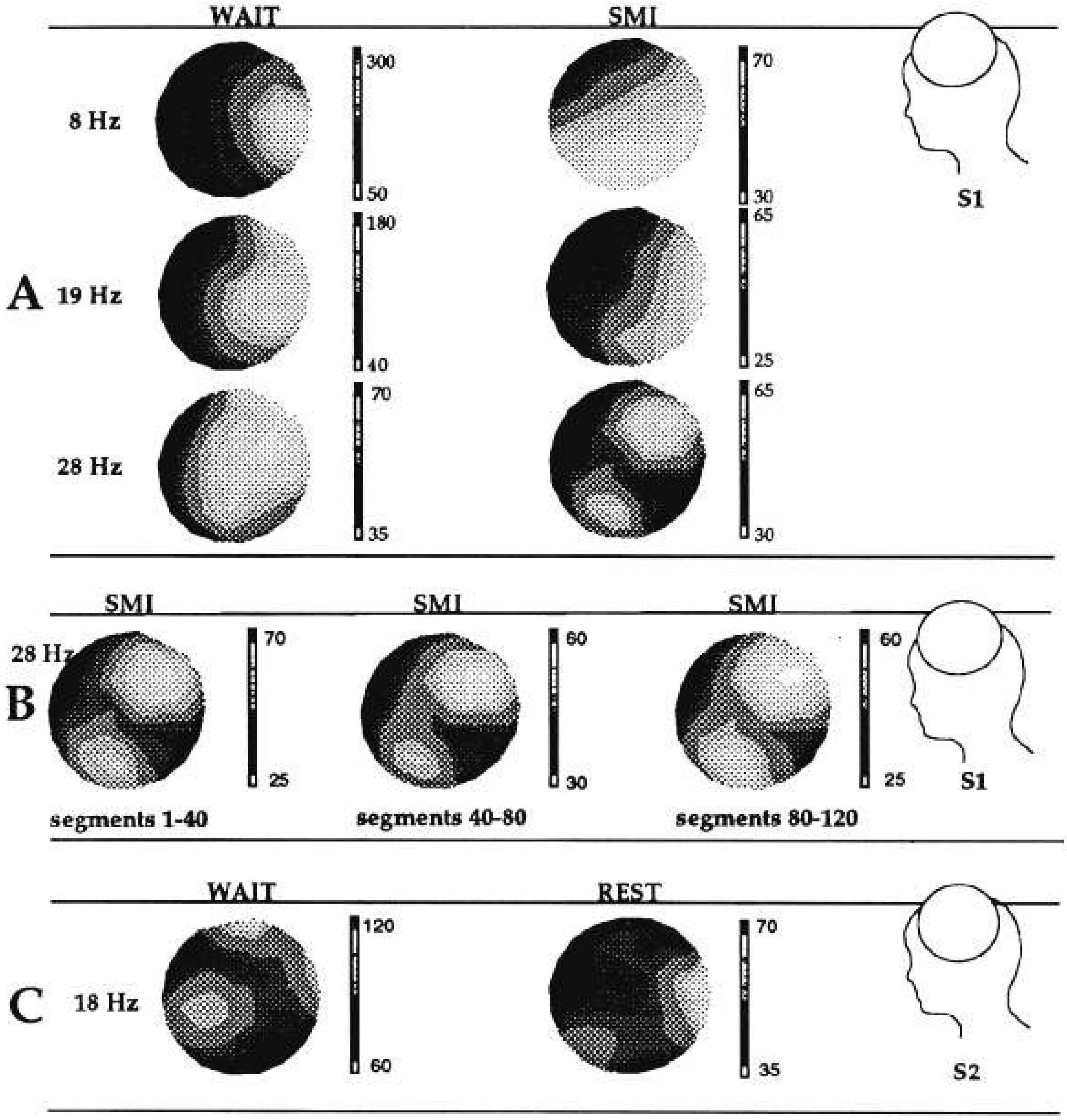

FIG. 3. (**A**) Isocontour field maps for the second session of subject S1 at the three frequencies of interest (10, 19 and 28 Hz) during WAIT and SMI conditions. Dewar position as shown in the upper right corner. Note scale differences. (**B**) Isocontour field maps showing the spatial stability of S1's 28 Hz rhythm during the second session. (**C**) Isocontour field maps at 18 Hz during WAIT and eyes closed REST conditions for subject S2. Note differences in scale (Units $\text{fT}/\sqrt{\text{Hz}}$).

near 28 Hz (Fig. 1). Prominent spontaneous activity near 10 Hz was present during both motor preparation (WAIT) and, as expected, during eyes-closed REST, but not during SMI or eyes open REST.[7]

Since in previous studies of time-domain movement-related response averages 19 Hz activity has not been noted, it appears that the motor preparation rhythm may not be phase-locked to onset of motor activity. The 19 Hz motor preparation rhythm also appears not to be a harmonic of the 10 Hz activity, because: (1) in none of the subjects is its frequency exactly twice that of the 10 Hz rhythm (Fig. 2); (2) the spatial patterns of the 10 and 19 Hz rhythms differ distinctly (Fig. 3A), and (3) the two rhythms have different patterns of appearance across conditions (Fig. 3A). Apparently the condition under which the circa 19 Hz activity appears can best be described as preparing or waiting in readiness to move.[7] A similar phenomenon has been described as a motor preparation rhythm of the brain,[8] a term properly differentiating this oscillatory state from unfocused resting states associated with synchronized alpha rhythms. As yet, few details of the dynamics and function of the motor preparation rhythm are available.[6] One can speculate that the circa 19 Hz rhythm reflects thalamocortical oscillations facilitating processing of information in the sensorimotor system, possibly arising in or priming a regulatory loop comprising sensory cortices, basal ganglia, thalamus and motor cortex. Rhythmic activity in this loop during the wait states might prepare the human or animal to react more quickly or forcefully to anticipated events. However, such rhythmic activity might also arise from cortico-cortical oscillations.

A still higher-frequency, gamma band oscillatory activity near 28 Hz was reliably observed, during SMI only, in one of the subjects (S1), and a relative increase near 26 Hz appeared, more weakly, in a second (Fig. 2, S4). While narrow-band gamma activity may, therefore, accompany SMI in humans, possibly it may not play an essential role in sensorimotor processing analogous to that currently hypothesized for visual system gamma band oscillations in sensory integration.[3,9,10] However, between-subjects differences, (1) in motivation or task strategies, (2) in physical orientations of the cortical generator regions and/or, (3) in degree of narrow-band frequency focus of sensorimotor gamma band activity may have contributed to the observed subject differences in the SMI/WAIT relative power spectra (Fig. 2). It may be noted that subject S1, who exhibited the strongest gamma band activity during SMI, also performed the best of the four subjects on the task in terms of both speed and accuracy, suggesting that enhanced gamma band activity during SMI might relate more to arousal and motivation than to SMI *per se*.[11]

If one assumes that the two spatial maxima in spectral power at 28 Hz (Figs. 3A and 3B), as well as the 19 Hz spatial maximum during motor preparation (WAIT) (Fig. 3C), are generated by single oscillating equivalent current dipoles, then the relative positions of the spatial maxima in Figure 3 suggest that the generator regions could be located within the sensorimotor cortex, with expected antero-posterior orientation. This would be compatible with the observations of Bouyer *et al*,[11] who reported a focal generator region for a similar 'rhythm of quiet vigilance', located within the dominant paw region in cats waiting patiently for a mouse to appear. However, since SMI requires simultaneous processing of sensory cues, motor outflow, and reafferent perception, multiple sources for these rhythms would not be unexpected. Nonetheless, the bipolar patterns in Figure 3 suggest the possibility that the observed narrow-band motor preparation and SMI gamma band rhythms are generated in relatively small cortical generator regions.

Conclusions

Wide band spectral averaging methods can be usefully applied to non-invasively-acquired electromagnetic data to study oscillatory human brain dynamics during performance of complex motor tasks. Since narrow-band activity at about 19 Hz was prominent over sensorimotor cortex during the WAIT state in all subjects, but did not appear during sensorimotor integration (SMI) or during eyes open or closed REST conditions, apparently a 19 Hz 'motor preparation rhythm' is a regular feature of the human motor system. Enhanced narrow-band, spatially focused gamma-band activity in the 26–30 Hz range, appearing during sensorimotor integration in two of the four subjects, may be a human correlate of activity at similar frequencies reported recently in monkeys during sensorimotor integration.[1]

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