Integrative Visuomotor Behavior Is Associated With Interregionally Coherent Oscillations in the Human Brain

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Classen, Joseph, Christian Gerloff, Manabu Honda, and Mark Hallett. Integrative visuomotor behavior is associated with interregionally coherent oscillations in the human brain. J. Neurophysiol. 79: 1567–1573, 1998. Coherent electrical brain activity has been demonstrated to be associated with perceptual events in mammals. It is unclear whether or not it is also a mechanism instrumental in the performance of sensorimotor tasks requiring the continuous processing of information between primarily executive and receptive brain areas. In particular it is unknown whether or not interregional coherent activity detectable in electroencephalographic (EEG) recordings on the scalp reflects interareal functional cooperativity in humans. We studied patterns of changes in EEG coherence associated with a visuomotor force-tracking task in seven subjects. Intergroup coherence of EEG signals recorded from scalp regions overlying the visual and the motor cortex increased in comparison to a resting condition when subjects tracked a visual target by producing an isometric force with their right index finger. Coherence between visual and motor cortex decreased when the subjects produced a similar motor output in the presence of a visual distractor and was unchanged in a purely visual and purely motor task. Increases and decreases of coherence were best differentiated in the low beta frequency range (13–21 Hz). This observation suggests a special functional significance of low frequency oscillations in information processing in large-scale networks. These findings substantiate the view that coherent brain activity underlies integrative sensorimotor behavior.

METHODS

We studied seven right-handed normal subjects (3 male, 4 female; mean age 47 ± 14 yr, mean ± SD). The protocol was approved by the Institutional Review Board and all subjects gave their written consent.

Tasks

Subjects were tested in four tasks (Fig. 1A). They were asked to fixate on a stationary dot in the middle of the oscilloscope or the computer screen, to maintain central fixation, and to avoid blinking throughout each individual recording trial. In task VM (visuomotor), subjects tracked a target signal by exerting force isometrically against a strain gauge with their right index finger. The target signal consisted of a horizontal bar that moved sinusoidally up and down on an oscilloscope screen at 0.2 Hz. The visual signal about force production was presented as a second horizontal bar on the oscilloscope screen. The extreme vertical positions of the target beam subtended a visual angle of 4°. In task V + M (visual plus motor) subjects were instructed to produce the same sinusoidal isometric force activation as in VM but were not provided with a target signal nor with visual feedback about their force production. During the production of isometric force, a randomly reversing (mean presentation time 180 ± 10 ms) checkerboard pattern was presented on a computer screen (diagonal distance 0.49 m) ~1.2 m in front of the subject. In task V (visual), the subject watched the sinusoidally moving oscilloscope signal while relaxed. V always preceded VM to avoid motor system activation secondary to imagination of movement primed by the visual stimulus. In task M (motor), the subject was to produce the same sinusoidal isometric force activation as in VM and V + M, but was not provided with any visual input used in these tasks.

Experiments were performed in one or two sessions, depending on the subjects’ compliance. Tasks VM and V + M were performed in one session in all seven subjects. In two of these subjects, V
A: Input

B: 2048 ms

C: 2048 ms

and M were also tested in the same session. In the other five subjects, V and M were tested in a separate session and VM was retested. For each subject, 25–50 trials of ~12 s rest followed by 12 s continuous activity (VM, V + M, V, or M) were sampled for each task (Fig. 1B). The signal to produce a force was given after the rest period by the onset of the vertical movement of the horizontal target bar in VM and by the appearance of the checkerboard pattern on the computer screen in V + M. In M, the start signal was a verbal command, to avoid any interference with processing visual information.

Recording

EEG recordings were obtained from 28 channels with linked-earlobe reference with scalp tin electrodes mounted on an elastic cap (Electrocap International, Eaton, OH) according to the 10–20 international system of electrode placement, with additional electrodes placed along the longitudinal axis (Fig. 1C). EEG signals were amplified (Synamps amplifiers, Neuroscan, Herndon, VA) between DC and 50 Hz, and digitized with a sampling frequency of 250 Hz. Electrode impedances were kept below 5 kΩ. Bipolar electromyogram (EMG) from the first dorsal interosseous muscle (FDI) was recorded using tin cup electrodes to monitor unwanted muscle activity during resting periods. Bipolar recordings of the electrooculogram were registered to aid in detecting eye movements or blinks. Force was measured by a force transducer (model 31, Sensolec, Columbus, OH).

Analysis

EEG signals were digitally filtered off-line (0.1–50 Hz, slope 24 dB/octave). Each 12 s period was segmented into nonoverlapping epochs of 2,048 ms (thus allowing a frequency resolution of ~0.5 Hz) (Fig. 1B). After removal of slow drifts by linear trend correction (linear detrend module of the Neuroscan Software, NeuroScan) and baseline correction, the single sweeps were visually inspected and trials with artifacts were rejected. Approximately 100 artifact-free epochs of rest and 100 artifact-free epochs of activation per subject were obtained for each task. Each data segment of 2,048 ms was Hamming windowed to reduce spectral leakage. For coherence and power analysis, a discrete Fourier transform was computed for each 2,048-ms epoch and all electrodes. Spectral power and coherence were calculated in four different frequency bands: alpha (8–13 Hz), beta 1 (13–21 Hz), beta 2 (21–31 Hz), and gamma (31–50 Hz). The coherence values were calculated for each frequency bin (f_i; width: 0.49 Hz) according to Eq. 1, implemented in commercial software (NeuroScan)

\[
\text{Coh}_{xy}(f_i) = \left( \frac{\sum_{n=1}^{\infty} (X_n - \overline{X})(Y_n - \overline{Y})^*}{\sum_{n=1}^{\infty} (X_n - \overline{X})^2 \sum_{n=1}^{\infty} (Y_n - \overline{Y})^2} \right)^{1/2} (1)
\]

which is the extension of the Pearson’s correlation coefficient to complex number pairs (Bronstein and Semendjajew 1987; Papoulis 1984). In this equation, X_i and Y_i are complex values of frequency spectra at a given frequency f_i for two signals from electrodes x and y, calculated for n single epochs i. n is determined by the number of all artifact-free epochs in either the rest or activation condition. The coherence value \( \text{Coh}_{xy} \) is obtained by squaring the magnitude of the complex correlation coefficient and is a real number between 0 and 1. To obtain broadband coherence values, \( \text{Coh}_{xy}(f_i) \), \( \text{Coh}_{xy}(f_i) \) was summed over frequency bins j = f_min to f_max (with f_min and f_max corresponding to the lower and upper frequency bins in the chosen frequency band) and divided by the number of frequency bins. Absolute coherence differs between electrode pairs and between subjects. To reduce the effect of intersubject and interelectrode pair variability of absolute coherence, task-related relative coherence (TRCoh) was obtained by subtracting rest from corresponding active conditions for each pair of electrodes and in each subject according to Eq. 2 (Andrew and Pfurtscheller 1996)

\[
\text{TRCoh} = \text{Coh}_{\text{act}} - \text{Coh}_{\text{rest}} (2)
\]

Group averages of coherence differences of all subjects were then calculated. For topographic mapping, TRCoh values were displayed as color-coded lines between pairs of electrodes, separately for TRCoh increases and decreases. The band-averaged power was calculated as the average of the power calculated for the discrete frequencies within one frequency band. Task-related power change was expressed as \( (\text{power}_{\text{act}} - \text{power}_{\text{rest}})/\text{power}_{\text{rest}} \). Topographical power maps were constructed with a linear four-nearest-neighbors interpolation (Neuroscan).
Statistical analyses

We tested the hypothesis that TRCoh increases in electrode pairs overlying central and occipital regions in VM. Four electrode pairs (C3-O1, C3-O2, FC3-O1, FC3-O2) were selected considering O1 and O2 as electrode pairs representing activity from the visual cortices (Buchner et al. 1994) and C3 and FC3 activity from the contralateral primary motor regions (Gerloff et al. 1996; Steinmetz et al. 1989). The statistical analysis was performed on the complete data set of all subjects. Centro-occipital coherence changes were analyzed statistically with factorial analyses of variance (ANOVA, TASK × FREQ, 4 × 4). Statistical testing for power changes was done using factorial ANOVAs (TASK × FREQ, 4 × 4) for each of central (electrodes C3 and FC3) or occipital (O1 and O2) regions. Post hoc testing was done with t-tests with Bonferroni-Dunn correction for multiple comparisons. The significance level was set to $P < 0.05$.

RESULTS

Spatial patterns of task-related coherence changes

Group averages of TRCoh are shown in Fig. 2A for the beta1 band (13–21 Hz) in VM and V + M. In VM, increases of TRCoh were maximal in electrode pairs overlying any two of central, parietal, or occipital brain regions (Fig. 2A). TRCoh decreased in electrode pairs over frontal regions. A similar, but less pronounced pattern was observed in the other frequency bands with predominantly symmetrical changes in beta2 and gamma. Slightly asymmetric changes were observed in the alpha band showing increases with a preponderance in the right hemisphere and decreases in the left hemisphere (not illustrated). In V + M, the pattern was different from VM in that TRCoh decreases in pairs of electrodes overlying any two of central, parietal, or occipital regions (Fig. 2A). TRCoh was compared between VM and V + M using statistical mapping (paired t-tests, transformed into z-scores) (Fig. 2B). These maps revealed a pattern of predominant differences of TRCoh in electrode pairs overlying central, right parietal, and occipital regions. The differences were most pronounced in beta1, but also visible in the alpha and beta2 frequency bands. VM was also compared with V and M in the same subjects. No increases of TRCoh in electrode pairs overlying occipital and contralateral cen-
FIG. 3. Spatial pattern of task-related spectral power changes. A: alpha frequency band. B: beta1 frequency band. In alpha, power decreases were located over occipital region in V and over bilateral homologous central regions in M. Tasks VM and V + M led to an extended power decrease involving central, parietal, and occipital regions. In beta1, power decrease over occipital region in VM was less pronounced than in alpha and occipital power changes occurred in no consistent direction in V + M. Statistical comparison of regional power changes associated with different tasks. C: alpha frequency band. D: beta1 frequency band. VM and V + M were compared with V (M) for central, (occipital) region, respectively. ∗ Significant differences on post hoc testing (P < 0.05, Bonferroni-correction for multiple comparisons).

tral regions emerged with either of the controls V or M (not illustrated). Because TRCoh was similar for VM in experiments 1 and 2 for those subjects in whom the study was carried out on two different days, in these cases the mean of TRCoh of the two experiments was taken for subsequent analyses of VM.

Spatial pattern of task-related power changes

The most prominent spectral power changes were seen in the alpha frequency band (Fig. 3A). Cortical activation related to the purely motor, or visual task led to a decrease in the spectral power of oscillatory signals from electrodes overlying the contralateral and ipsilateral motor cortex, or visual cortex confirming previous findings by other investigators (Pfurtscheller and Aranibar 1977; Pfurtscheller and Berghold 1989; Pfurtscheller et al. 1994) and our group (Leocani et al. 1997). Our results extend these findings in that both VM and V + M led to a more widespread relative power decrease involving both the occipital and the central regions. Similar topographic patterns of power were seen in all frequency bands; however, no consistent power change over occipital regions was found in the beta1 frequency band in V + M (Fig. 3B).

Task-related changes of centro-occipital coherence and central and occipital power

The hypothesis was tested that the task properties were reflected in centro-occipital coherence of EEG signals. With the use of ANOVA, significant effects were found for TASK ($F = 16.96; P < 0.001$) and TASK × FREQ interaction ($F = 3.08; P < 0.01$; Fig. 4). On post hoc testing TRCoh in VM was significantly higher than in all other tasks ($P < 0.02$) and TRCoh in V + M was significantly lower than M ($P < 0.01$), differences between the other tasks were not
statistically significant. A one-factorial ANOVA (TASK) was then performed for each frequency band separately, to characterize the TASK x FREQ interaction further. Significant task effects were found in the alpha (F = 3.80; P < 0.05), beta1 (F = 20.35; P < 0.001) and in the beta2 (F = 4.77; P < 0.01) frequency bands. Posthoc t-testing between individual pairs of tasks is summarized in Table 1 for all three frequency bands that showed a significant task effect. Changes of TRCoh with tasks were similar in individual subjects. In beta1, TRCoh increased in VM in all four electrode-pairs in six subjects; in the seventh subject, TRCoh increased in C3-O2 only. In V + M TRCoh decreased in all four electrode-pairs in five subjects; in one subject TRCoh decreased in C3-O1 and C3-O2 and in one subject no TRCoh decreases in V + M were noted in beta1.

A similar type of analysis was applied to evaluate statistically task-related power changes in the central and occipital regions. For the central (C3 and FC3) region, significant effects were seen for TASK (F = 12.02; P < 0.001) and FREQ (F = 51.256; P < 0.001), as well as for TASK x FREQ interaction (F = 4.32; P < 0.001). This allowed us to perform a one-factorial ANOVA (TASK) for each frequency band separately, to characterize the TASK x FREQ interaction further. These analyses revealed significant task effects for alpha (F = 10.24; P < 0.001), beta1 (F = 10.79; P < 0.001), and gamma (F = 5.94; P < 0.001). On post hoc testing, power in VM as well as V + M decreased significantly more than in V in alpha (Fig. 3B) and beta1 (Fig. 3D); power in M decreased significantly more than in V in beta1 only (P < 0.01). For the occipital (O1 and O2) region, power data were more variable. Significant effects were found for TASK (F = 9.67; P < 0.001) and FREQ (F = 15.08; P < 0.001); however, there was no statistically significant TASK x FREQ interaction (P = 0.095). We explored the TASK-effect further by performing post hoc t-testing of power changes over all frequencies combined. Power was decreased significantly more in VM and V than in M (P < 0.005), but the difference between V + M and M was not significant.

**DISCUSSION**

A number of observations lead us to suggest that an interregional increase of coherent activity in our visuomotor task is causally related to a cooperativity between regions involved in the processing of the task. First, centro-occipital coherence increase was specific to the visuomotor task and did not occur in tasks activating the visual or motor system only. Second, a task activating the visual and motor areas simultaneously, but in a functionally unrelated fashion, led to a decrease of centro-occipital coherent activity as compared with the rest condition. Third, the pattern of coherence changes associated with the visuomotor task produced in all recorded electrode-pairs was spatially specific and corresponded well with the pattern of active network components derived from multiple sources of evidence (Grafton et al. 1992; Ungerleider and Haxby 1994). Fourth, changes of interregional coherence were not simply related to changes in regional spectral power of the EEG oscillations as demonstrated, for example, by the dissimilarity of TRCoh in VM and V + M in the alpha band in the presence of similar regional power changes.

In animal studies, coherent oscillatory activity has previously been suggested to reflect functional cooperativity in the visual cortex over short distances (Engel et al. 1991a; Fries et al. 1996) and interhemispherically, via the corpus callosum (Engel et al. 1991b). In addition to visual percepts, coherent activity has been associated with the generation of auditory (deCharms and Merzenich 1996), and olfactory (Laurent et al. 1996) percepts, as well as motor behavior (Murthy and Fetz 1992; Sanes and Donoghue 1993), in a
number of studies on intraregional cortical physiology. A phasic interregional increase of coherence between striate and motor areas related to a visually triggered movement has been found in the monkey (Bressler et al. 1993, 1995). In this situation, the interpretation of coherence in relation to behavior is less clear. Both the GO and the NO-GO condition would appear to require an instantaneous interaction between the brain areas evaluating the visual command and the brain areas executing, or withholding, the motor action. Therefore, the degree of functional cooperativity between striate and motor cortex was presumably not fundamentally different in the GO and in the NO-GO condition, which were, however, differentiated by the presence, or absence, of an interregional coherence increase. More recently, Chiang et al. (1996) presented preliminary data in the cat indicating an increase of synchronous activity between striate and sensorimotor association cortex in a visuomotor stimulus-response task.

We found that the beta1 (13–21 Hz) frequency band differentiated best the differences between the four tested conditions. A less pronounced response was also observed in the alpha and in the beta2 band, but the gamma band coherence could not differentiate between the tasks. Because gamma power showed a significant modulation with task, both in the central, and in the occipital regions, a purely biophysical reason for the lack of task-specificity of gamma coherence is unlikely. This suggests a special role for lower frequency oscillations, particular for those between 13 and 21 Hz which could be to mediate coherent activity in large neuronal networks. Slowly oscillating cell assemblies are believed to comprise more neurons (Singer 1993) and are likely to be spatially more extended than rapidly oscillating cell assemblies. That oscillations in large neuronal ensembles occur at lower frequencies than in small ensembles has also been the result of modeling studies (Kottmann and Eckhorn 1996; Lopes da Silva 1991, 1996; Traub et al. 1996).

Although coherence changes were most pronounced in the beta1 frequency band, changes in alpha and beta2 also reflected some task properties. The finding of multiple-band elevated coherence during the motor response differs from those of studies reporting narrowband synchronization in relation to motor activity, but confirms previous findings in monkeys (Bressler et al. 1993) and recent findings in the cat (Chiang et al. 1996). The increase of coherence over a broad frequency range during task processing may either reflect interregional cortical coupling on multiple timescales, as has been suggested by other investigators (Bressler 1995) or multiple intricately and hierarchically interconnected networks of a different spatial extension.

The concept of assembly coding requires that the binding together of elements constituting an assembly is an emergent property of reciprocal connections between the elements of an assembly and not achieved by common input (Singer 1993; Singer and Gray 1995). Such reciprocal connections can involve cortico-cortical, as well as subcortical routes (Sillito et al. 1994). We have no direct evidence that the network of coherent oscillatory activity associated with visuomotor tracking is self-organizing. However, it is important to note that there is no known candidate brain structure acting as a single common driving pacemaker on the visual and motor areas. Because there are no direct anatomic connections between primary visual and motor areas, a network comprising the two areas will necessarily have at least one intermediate synapse. Possible intermediate nodes in a purely cortico-cortical network are the dorsal parietal cortex and the premotor and prefrontal cortices, which are interconnected by a long association track (Fuster 1989; Wise et al. 1997).

The spatial resolution of EEG signals does not allow making detailed inferences about the anatomic origin of the recorded oscillations, beyond the resolution of regions, without the use of spatial decomposition algorithms. With VM, the pattern of coherence increases comprised central, parietal, and occipital regions; temporal regions exhibited a decrease. This spatial distribution of coherence changes is in agreement with what is known about the organization of visual information flow (Ungerleider 1995; Ungerleider and Haxby 1994). Visuomotor force tracking would likely utilize the dorsal, “where,” rather than the ventral, “what” pathway. In a positron emission tomography (PET) study, tracking a moving target with the index finger defined a spatially distributed pattern of focal responses of relative cerebral blood flow including the contralateral and ipsilateral primary motor cortex, dorsal parietal cortex, and precuneate cortex (Grafton et al. 1992).

We found a specific depression (vs. rest) of coherence in the visual plus motor task. In this task the subject had to minimize the influence of a distracting stimulus to maintain the quality of the motor performance. A suppression of activity in sensory areas not involved in the processing of a task has been observed in PET studies (Corbetta et al. 1990; Weeks et al. 1996). Attentional aspects have been described to have an impact on the distribution of regional activation of blood flow evoked by the same stimulus (Drevets et al. 1995; Orban et al. 1996) and also to regional spectral power changes (Klimesch et al. 1990). Our results suggest that modulation of coherent activity might be another powerful mechanism to control the relative weight of a source of information in conscious behavior, or, to focus attention. An alternative view would be that coherence is a physiological substrate of focused attention.

Our findings are in excellent agreement with recent results reporting interareal synchronicity with zero time-lag related to motor behavior in cats trained to act in a visual discrimination task (Roelfsema et al. 1997). Strongest synchronization was observed between parietal and striate cortex similar to our reported pattern of coherence changes (Fig. 2A) and in the beta band (20–25 Hz), which is a little higher than the optimal frequency band for differentiation between tasks in our paradigm. The difference in optimal frequency bands can probably be best explained by the different conduction times necessary to establish synchronicity between areas that are a factor of two longer in humans. One important difference between our results and the Roelfsema et al. (1997) results is that in their study no synchronicity was observed between the primary motor region and the visual cortex (see their Fig. 2c). One might speculate that this difference is due to the difference in the tasks, requiring a phasic response
in the paradigm of Roelfsema and coworkers and a continuous visuomotor integration in ours.

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