Coherent EEG Indicators of Cognitive Binding during Ambiguous Figure Tasks

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We tested the hypothesis that perception of an alternative image in ambiguous figures would be manifest as high-frequency (gamma) components that become synchronized over multiple scalp sites as a ''cognitive binding'' process occurs. For 171 combinations of data from 19 electrodes, obtained from 17 subjects and 10 replicate stimuli, we calculated the difference in correlation between the response to first seeing an ambiguous figure and when the alternative percept for that figure became consciously realized (cognitively bound). Numerous statistically significant correlation differences occurred in all frequency bands tested with ambiguous-figure stimulation, but not in two kinds of control data (a reaction-time test to sound stimuli and a no-task, mind-wandering test). Statistically significant correlation changes were widespread, involving frontal, parietal, central, and occipital regions of both hemispheres. Correlation changes were evident at each of five frequency bands, ranging up to 62.5 Hz. Most of the statistically significant correlation changes were not between adjacent sites but between sites relatively distant, both ipsilateral and contralateral. Typically, these correlation changes occurred in more than one frequency band. These results suggest that cognitive binding is a distinct mental state that is reliably induced by ambiguous-figure perception tasks. Coherent oscillations at multiple frequencies may reflect the mechanism by which such binding occurs. Moreover, different coherent frequencies may mediate different components of the total cognitive-binding process.   © 2000 Academic Press

Key Words: ambiguous figures; cognition; binding; EEG; EEG coherence.

INTRODUCTION

This research focuses on possible neural mechanisms by which humans recognize spatially distributed elements of a stimulus or endogenous thought pattern, detect salient relationships, and bind them into a meaningful and coherent whole. For convenience, we refer to this process as cognitive binding. Admittedly, this notion of cognitive binding is underspecified, and indeed this way of thinking about certain mental states only becomes compelling when viewed in the light of recent discoveries about *sensory* binding (see below). At the moment, we can only say that cognitive binding consists of a set of functions involving *registration* of sensory information or endogenous thought pattern, *interpretation* of alternative meanings or solutions (some of

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which reside in memory), *decision* or problem solution, and *recalling* the task result long enough to consciously realize and report it.

Although cognitive binding is commonly experienced, to our knowledge no one has developed any hypotheses for its neural mechanisms nor conducted any associated experiments. However, in recent years, a new theory for *sensory* binding has been advanced. In cats, visual-stimulus elements were reported to drive local neuronal populations (multiple-unit activity, MUA) into high-frequency (near 50 Hz) oscillation. Multiple oscillating populations became phase locked, which supposedly was the means by which sensory binding was achieved (Singer, 1993a, 1993b).

Several workers have suggested that it would be useful to extend the binding idea to include cognition (Bressler, 1990; Llinas & Pare, 1991; Llinas & Ribrary, 1993). Cognitive binding necessarily includes sensory binding, but extends it to interpretation of sensory input. In this present study, we tested the hypothesis that the brain accomplishes cognitive binding by coherent oscillation in the cortical areas that mediate mental performance.

RATIONALE FOR EEG METRICS OF BINDING

Cognition is least equivocally studied in humans, and MUA recording from humans is not ordinarily feasible. However, we might reasonably expect that the electroencephalogram (EEG) could be related to MUA and be a useful metric for cognitive binding, because

> Clear relations are evident between unit activity and EEG of some phenomena, such as with epileptiform discharges and population spikes in hippocampus.
> Simultaneous microelectrode recording of action potentials and field potentials in the same regions shows that when multiple units are stimulus driven, the EEG in that area can be a slow-frequency field potential that is highly correlated with the action potentials. (Gray & Singer, 1989)

Neurons that generate high-frequency oscillations involve the cortical neurons that contribute extracellular voltages to the EEG, which in turn are influenced by corticothalamic projections and reentrant thalamocortical projections (Steriade et al., 1998).

EVIDENCE THAT COGNITIVE TASKS DO INDUCE HIGH-FREQUENCY EEG OSCILLATION IN HUMANS

Evidence has accumulated for several decades that indicates that the EEG contains high-frequency oscillations (gamma activity, >30 Hz). Gamma activity has been associated with (1) arousal and attention (Kristeva-Feige et al., 1993; Murthy & Fetz, 1992; Sheer, 1989, Spydell et al., 1979; Steriade et al., 1996a, 1996b); (2) stimulus-feature integration (Eckhorn et al., 1988; Engel et al., 1992); (3) spatio-temporal reasoning (Sarnthein et al., 1996); (4) learning and memory (Mittner et al., 1997; Andres et al., 1999; Klopp et al., 1998); (5) music and language sound patterns (Cunic et al., 1998); and (6) language interpretation (Weiss et al., 1998).

Most studies have not involved rigorous coherence analysis. The data have not

been interpreted in the light of the cognitive-binding concept, and the degree to which the tasks might have involved cognitive binding was not specified. We therefore decided to test for gamma coherence with a mental task that had a conspicuous binding requirement: the interpretation of ambiguous figures.

AMBIGUOUS FIGURES AS A MODEL FOR COGNITIVE BINDING

Ambiguous figures have two different and mutually exclusive percepts. The familiar ''Batman'' logo, for example, is ambiguous in that it can be seen as the black representation of a bat and also as a set of white teeth, two upper and four lower teeth. Our pilot studies testing dozens of ambiguous figures on over 20 young adult males and females (Lutes, 1995) made it clear that the subject normally only sees one of the two alternative images at first. That is, one of the two possible images is seen in the ''mind's eye'' instantly, with no particular mental effort required—a ''default'' perception. When instructed to search for the alternative perception, the person will construct a new percept by mentally binding those same visual elements in another way. The advantage of such stimuli for cognitive binding studies is that the physical stimulus is always the same.

Such figures can probe the human perceptual-cognitive system (Shepard, 1990), but no one seems to have specified just how. It would seem that ambiguous figure interpretation is a low-order creative process wherein the subject must consider alternative meanings to attach to the given element of the image. The alternatives are constrained by the image and the limited number of possible meaningful perceptions. In a higher order creative process, the alternatives could be unbounded or infinite. We predict that topographical maps of correlated EEG activity would specifically reflect the process whereby a subject constructs a percept that differs from the default interpretation, which is more of an automatism that does not require a conscious reconstruction of image elements into an alternative percept.

This premise is supported by Gestalt theory (Crock & Palmer, 1990), which holds that subjects looking at an ambiguous figure will preferentially perceive the simplest shape that is consistent with the stimulus information that is presented. Only with sustained thinking about the stimulus does the subject realize, *via cognitive binding,* that there is an alternative image. Some subjects seem to require the use of specific strategies, such as looking for visual cues in the image. They may discover these strategies on their own during continuous stimulus presentation, while for some images they have to be coached.

Solving an ambiguous-figure task could be influenced by a given subject's field dependence, which is known to be reflected in the EEG (Colter & Shaw, 1982; O'Connor & Shaw, 1978; Oltman et al., 1979; Pillsbury et al., 1967). To our knowledge, field dependence effects on EEG have apparently not been tested in situations where the subjects actually perform complex field-dependent tasks. The common metric for field dependence is the Embedded Figures Test (EFT) (Witkin et al., 1971), which requires subjects to detect an embedded, ''hidden'' geometric figure in a complex geometric image. We thus also tested a secondary hypothesis that EFT scores would correlate with the difficulty that subjects experienced in solving ambiguous-figure tasks.

MATERIALS AND METHODS

Experimental Subjects

All subjects were volunteer college students who were paid $25. To help identify any gender variables, we tested 7 males and 10 females. No subjects were tested who had consumed alcohol or any other psychoactive drug within the last 24 h prior to testing.

Embedded-Figures Test

Prior to EEG recording, each subject completed the EFT task. Scores were used to test for correlation with their difficulty in solving ambiguous-figure tasks. The measure for difficulty of solving ambiguous-figure tasks was the length of time it took subjects to report perception of the alternative image during EEG recording.

Design of the Present Study

We suspect that cognitive-binding tasks have at least three stages, one in which the binding begins, a time when it is finalized, and a working memory stage that is required to hold the results of the task long enough to state the results of the task. Frequency-coherence analysis could be applied to any of these stages, but the initial emphasis was on the brief epoch when binding was being completed, that is, the time just before the subject confirms that the task has been completed. To test our hypothesis, we presented human volunteers 10 different ambiguous figures and measured the difference in EEG correlation of specific frequencies when binding occurred with the correlation when a stimulus was first presented. The EEG was sampled as soon as each image was presented on a computer screen. Binding of an alternative-image percept was completed several to many seconds later, at which time the comparison data sample was collected. The subject informed us by a right-handed button-press when conscious binding was completed, and we confirmed that by verbal quizzing. We assumed that the relevant data were those that were present immediately prior to button-press notification of a correct task performance.

Ambiguous-Figure Stimulation

In each given session, a set of up to 15 different ambiguous figures were presented, one at a time as a computer slide show on a computer monitor that was placed 1 m away (Fig. 1). Visual stimuli were positioned just below eye level to prevent a rolling upward of the eyes, which reportedly can cause artifactual increase in alpha from a bipolar parieto-occipital scalp electrode pair in about 50% of subjects (Mulholland & Evans, 1965). The test sessions were terminated as soon as 10 successful trials were completed.

EEG data were collected continuously for several seconds before stimulus onset (to assure good EEG recording) and throughout stimulus presentation and cognitive-binding stages. An ambiguous figure was displayed on a computer monitor, and the subject was instructed to detect the alternative image. As soon as the alternative image was detected, the subject pressed a signal button that served to mark the EEG records

Example Stimuli

Man's face / naked lady

Indian face / Eskimo back
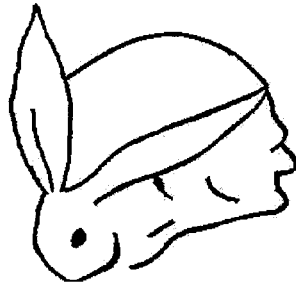
Young lady / old lady

Rabbit / Indian

FIG. 1.   Four examples of the ambiguous figures used as cognitive-binding stimuli.

so that later editing could extract a data segment immediately prior to the button-press. If subjects had not solved the problem within about 20 s, an assistant gave verbal clues to help subjects locate salient features in the image. In some cases, subjects could not solve the problem, and such trials were replaced with another image. A rest period of about 20 s elapsed between each stimulus presentation. During these times, the subject stared at a white dot in the center of a blank computer screen. They also used this time as a ''blink holiday,'' where they were free to squirm and blink eyes.

Thought Control

In any study of physiological correlates of cognition, it is important to control thought (Gale & Edwards, 1985). Our paradigm provided some control by linking the trials to specific mental states and tasks. Also, we did not assume that the subject was paying attention to the thought. We required the subject to signal us when the designated thought (i.e., cognitive binding) occurred, and we checked after each stimulus to verify that the appropriate thought was employed.

To control for nonspecific effects, two types of control data were collected, taken

from a condition in which there was no task and also in an attention task that did not involve cognitive binding. No-task data were taken randomly while the subject stared at a dot in the center of a blank screen before testing began, during rest periods, and after the session, with correlations of 10 of these epochs randomly subtracted from 10 others. The attention task consisted of presenting a slow sound-pulse train of variable train duration, and the subject was instructed to button-press as soon as it was clear that the pulse train had stopped. Five of the attention control trials were conducted before presentation of ambiguous-figure stimuli and five were presented afterward.

Recording Protocol

We used a commercially available electrode cap (Electro-cap International, Eaton, OH) that had the electrodes prepositioned according to the conventional 10-20 system. Within each electrode well, we used the low-impedance electrode paste ''Quik-Gel'' (Neuromedical Supplies, Inc.). Paste was likewise placed on the ear lobes for the clip-on reference ear electrodes. Subjects were requested to avoid all body movements and eye blinking. Eye blinking was monitored with an electrode placed between the eyes, referenced to the ear. Precise eye movements could not be monitored because no extra amplifier channels were available. But as a check on eye movements, the Pz channel was substituted in two additional subjects who were tested with two eye-monitor channels, with electrodes over the upper canthus of one eye and the lower canthus of the other, each referenced to the linked ears.

Each EEG session started with a short relaxation session where we use focused breathing exercises to get the subject relaxed and conditioned to minimize artifacts. For each ambiguous figure, recording began just prior to stimulus presentation and continued until the button-press signaled task completion. This was repeated with different figures until 10 trials were successfully completed. Subjects were requested to avoid all body movements and eye blinking.

Specific Data Collection and Analysis Methods

Instrumentation. Subject recordings were taken with a UL-approved 20-channel Bio-Logic Brain Atlas data-acquisition system, under the control of that company's software that controls acquisition and editing. Frequency cut-offs were 1 to 70 Hz, with a gain of 20,000. Data were acquired at 200 samples/s, using analysis epochs in blocks of 1.28 s. In addition, we used a 60-Hz notch filter (second-order lowpass).

Each electrode was referenced to linked ear lobes. Linked ear lobes have been criticized by some theorists, but the practice is widely accepted and empirical tests have shown that linking the ears produced essentially the same signal as does an unlinked ear reference (Andino et al., 1990).

Data used in this study. For each of the 17 subjects, two segments of 256 samples (1.28 s) were collected during each of the 10 ambiguous figure trials (Fig. 2). The first segment, which we call the mode A data, was taken immediately after the stimulus presentation. The second segment, which we call the mode B data, was taken immediately before the signal button was pressed. We hypothesize that the mode B data

Raw Data for One Subject

Stimulus ON   Percept Bound

19 electrodes

Replicate 1   256 data points

Replicate 2
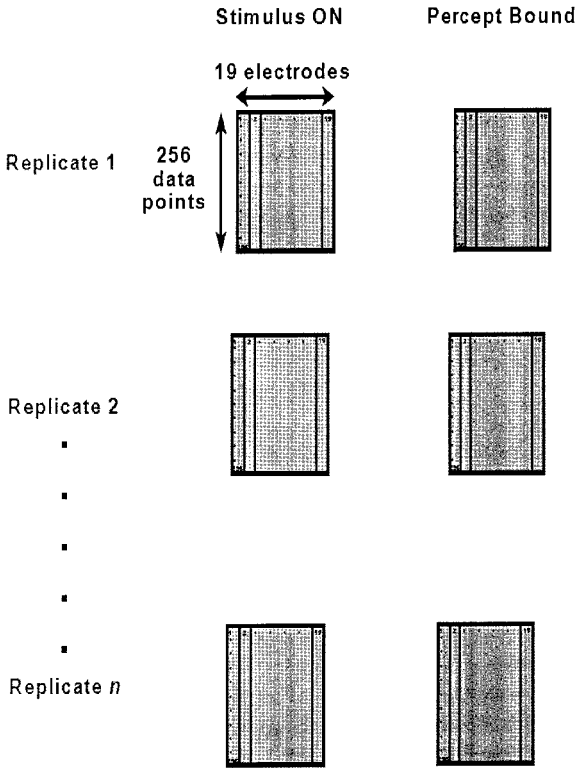
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.

.

Replicate *n*

FIG. 2. Illustration of how coherence was calculated as the difference between that present when binding occurred (the alternative image was perceived) and when the stimulus first came on.

capture the cognitive binding, while the mode A data measure the background activities prior to the binding stage. Therefore cognitive binding could be detected by comparing suitable statistical parameters, such as pairwise correlation coefficients of the mode B data with those of the mode A data.

All data segments were screened visually for spikes, sudden large fluctuations, and other artifacts that could be associated with movements. No data were used during eye blinks. Our prerecording relaxation routine eliminated most muscle potential artifact, and data were not used that contained detectable muscle artifact. High-frequency correlations at other electrode sites are unlikely to be muscle artifact when muscle artifact is not visually evident from the temporal leads, which overlie the proximate source of scalp muscle potential.

The general analytical strategy involved calculating the wavelet nodes for the stimulus-onset condition and the state when cognitive binding occurred. This was done for each of the 19 electrodes and was repeated for each of the 10 trials. Then we calculated correlation coefficients for each electrode pairing in the stimulus-on and perceptual-binding modes. This was repeated for each of the 10 replicates. The matri-

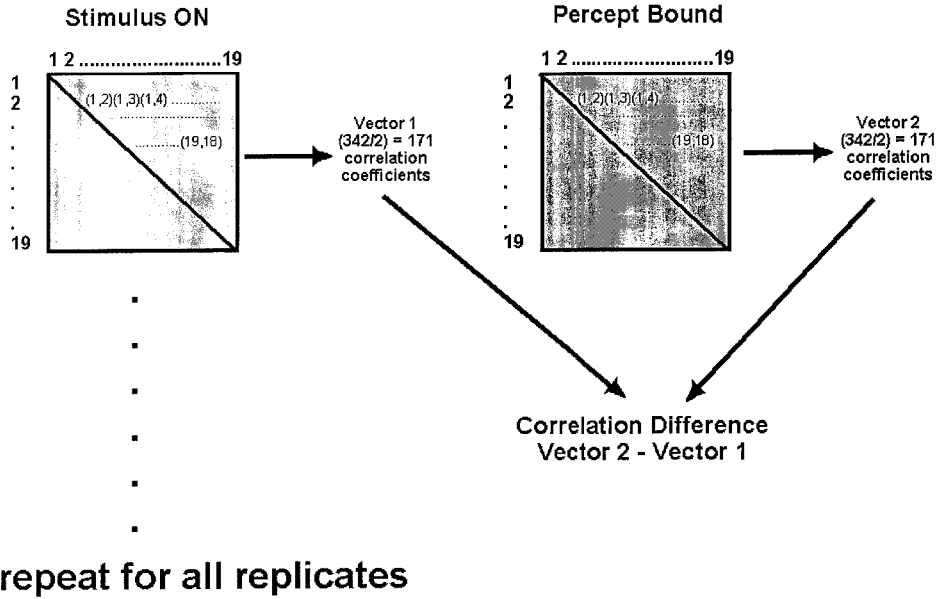## Correlation Coefficients for One Subject

FIG. 3. Illustration of how probability values were calculated. Each horizontal slice of the cube provided the variance data for calculating correlation differences across all replicates and subjects for a given electrode pair.

ces of wavelet correlation coefficients were then subtracted so that what we ultimately tested was the correlation difference (Fig. 3). Each electrode pairing was tested separately in a paired t test where for each electrode pair, probability values were calculated for the correlation differences across all replicates and subjects (Fig. 4). The same statistical analysis was performed on the two sets of control data. Frequency correlation differences at a criterion level of .01 that occurred with stimulus-induced data that were absent in the two control tests were considered as biologically significant.

Data analysis. Filters from the wavelet-packet (WP) analysis (Daubechies, 1992; Strang & Nguyen, 1996; Ba_ar et al., 1999) were employed to extract multiresolution components of different frequencies from the raw EEG signals. Due to their flexible time–frequency localization properties, the WP filters are able to extract transient as well as persistent frequency components of the input signal. A WP filter, indexed by the WP node, can be easily chosen to satisfy a given time–frequency resolution requirement. A bank of WP filters can be employed to provide variable time–frequency resolutions if the time–frequency properties cannot be specified a priori. This flexibility makes the WP method more advantageous than the traditional tools of Fourier analysis for our purpose because we could not have advance information about the time–frequency locations of the signal of interest.

The WP filters are tree structures and can be defined recursively by the scales. At

Probability Calculations
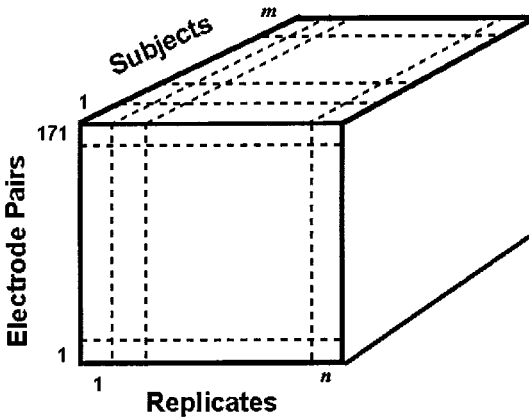
For each electrode pair, P values calculated for the correlation differences across all replicates and subjects.

FIG. 4. Layout of the format for data.

scale 1, there are two basic WP filters, $F_0(z)$ and $F_1(z)$, which are low pass and high pass, respectively. At scale 2, there are four WP filters: $F_{00}(z) = F_0(z) * F_0(z^2)$, $F_{01}(z) = F_0(z) * F_1(z^2)$, $F_{10}(z) = F_1(z) * F_0(z^2)$, and $F_{11}(z) = F_1(z) * F_1(z^2)$. In general, at scale L, there are 2^L WP filters indexed by a binary code of length L that we call the node. The WP filter at node (d1,d2, . . . , dL) is defined by $F_{\{d1,d2, \ldots, dL\}}(z) = F_{d1}(z) * F_{d2}(z^2) * \ldots * F_{dL}(z^{2(L-1)})$. In applying the filters to the data, we employed the wrap-around technique to handle the data boundaries. The choice of $F_0(z)$ and $F_1(z)$ corresponds to the so-called 30th-order coiflet (Daubechies, 1992).

Given the output of the WP filters, the cross-electrode correlation coefficients were used as a measure of coherence (or synchronization) of the extracted EEG components between different electrodes. The entire sequence of 256 data points from each sample was used in calculating each correlation coefficient. Mathematically, the wavelet coherence was calculated as follows. Let $X_i(t)$ and $X_j(t)$ be the (zero-mean) EEG signals from electrodes i and j. Let $F\{\cdot\}$ denote a WP filter. Let $Yi(t) = F\{Xi(t)\}$ and $Y_j(t) = F\{X_j(t)\}$ be the output from the filter F when $X_i(t)$ and $X_j(t)$ are filtered. Then, the wavelet coherence is defined as the cross-correlation coefficient between $Y_i(t)$ and $Y_j(t)$, i.e.,

$$\rho_{ij}(F) = \text{corr}\{Y_i(t), Y_j(t)\} = \frac{E\{Yi(t) * Yj(t)\}}{[E\{|Y_i(t)|^2\} * E\{|Y_j(t)|^2\}]^{1/2}}.$$

This coherence measure is analogous to the traditional spectral coherence except that the correlation coefficients are calculated from the output of the WP filters rather than the Fourier transform. By definition, the spectral coherence at a given frequency

is the correlation coefficient between the outputs of a narrow-band filter centered at that frequency. The filter is complex valued and so is the resulting correlation coefficient. Spectral coherence has an amplitude component and a phase component. The phase represents the ''delay'' of the spectral components of the input time series at the given frequency. Quite often, one is concerned only with the amplitude of the spectral coherence when the ''delay'' interpretation of the phase is not important, i.e., when the only interest is to know the strength of the linear relationship rather than the amount of delay in one series as possibly a delayed copy of the other. The wavelet correlation in our article only uses the simultaneous (rather than lagged) correlation coefficient. It is not designed to detect delays.

For a given WP filter, the WP correlations were calculated for all pairs of electrodes. The procedure was repeated for all replicate trials and subjects and for both data segments.

Given the computed WP correlation values, a statistical analysis was carried out to test our cognitive-binding hypothesis. Mathematically, the null hypothesis of the test states that the WP correlation coefficients of the EEG signal in mode A (background mode) do not differ from that in mode B (binding mode). The hypothesis was tested separately for each electrode pair. Because of the possible correlation between the mode A data and the mode B data for a given subject, we used the paired t test, rather than the two-sample t test, for each electrode pair. In doing so, we assumed that the data from different trials and subjects are statistically independent.

Mathematically, for electrodes i and j, let d_{ij} and s_{ij} denote the sample mean and the sample standard deviation of the differences between the ij-th WP coherence of the mode A data and the ij-th WP coherence of the mode B data, averaged over $n = 17 \times 10 = 170$ repeated experiments (Fig. 2). The test statistic is therefore

$$t_{ij} = \frac{d_{ij}}{s_{ij}/(n-1)^{1/2}}.$$

Under the null hypothesis, t_{ij} has a student T distribution with $n - 1$ degrees of freedom, which was used to compute the p values, i.e., the probabilities of false positive). The same statistical analysis was performed on the thought-control data.

The computer program was written and debugged in the statistical software application known as S-Plus with the wavelet module (Bruce & Gao, 1996). In the analysis, a bank of five WP filters indexed by the WP node was used. The effective frequency bands of these filters are 12.5 Hz each, covering the range of 0 to 62.5 Hz.

RESULTS

EEG Correlation Differences

Correlation differences of numerous electrode pairs met a $p < .01$ criterion (over all 17 subjects and all 10 replicates) in the ambiguous-figure tasks, but very few to no such statistically significant correlation differences were seen with either control task (Fig. 5). The correlation change was evident in all frequency bands, particularly in the frequencies above 37.5 Hz. In every case of significant correlation changes, the change was positive; that is, there was an increase in the degree of correlation
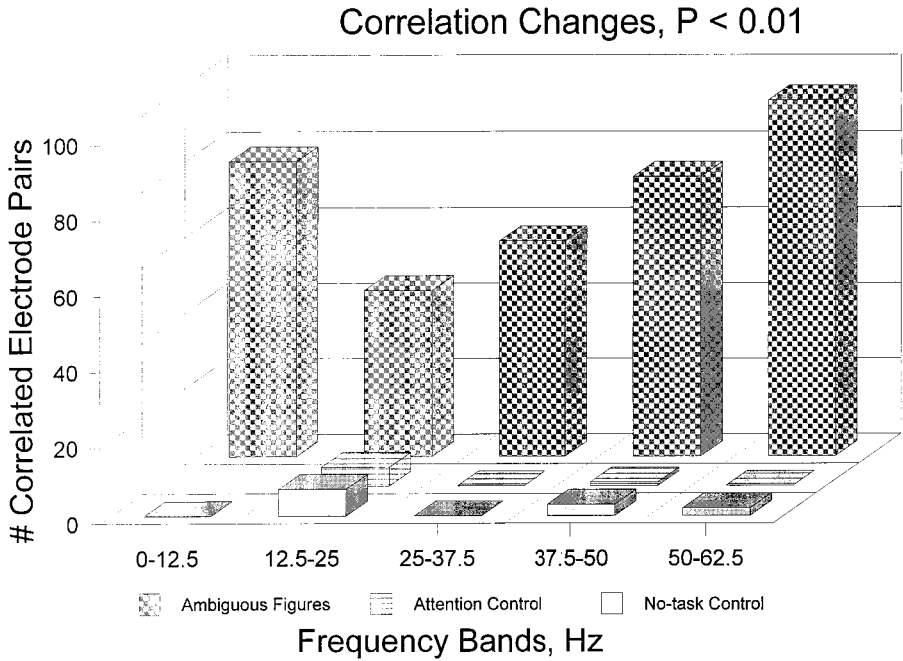
FIG. 5. Number of electrode pairs with a mean change in coherence between stimulus onset and the final phase of cognitive binding that reached a $p < .01$. Of the 171 possible electrode pairings, large numbers had criterion-level change at each of the wavelet nodes tested. No such changes were evident in either the no-task group or the attention control group, where the task was to button-press as soon as a sound-pulse train stopped.

when the alternative image was about to be perceived (mode B) and when the stimulus was first presented (mode A). The magnitude of increased correlation was typically on the order of 10% or more.

Probability assessments of multiple-electrode data are inevitably confounded by the multiple comparisons. However, causal inspection of the group differences in number of electrode pairs meeting the criterion level of change makes it clear that a real treatment difference was attributable to the ambiguous-figure task.

The data indicate that coherent oscillations occur in frequencies as low as the alpha band and as high as 62.5 Hz. Tallies of electrode pairs with .01 level of correlation change revealed that the changes were topographically widespread (Fig. 6). At all frequency levels, performance of the ambiguous-figure task was associated with increased correlation between both ipsilateral and contralateral sites. In all but the highest frequency band, the contralateral correlation change was more widespread than was the ipsilateral change. Significant correlation changes were commonly not present between electrodes of nearest neighbors, as might be expected from volume conduction effects. Rather, many of these correlation changes were between electrodes that were greater than one electrode location away. More pronounced correlation changes involved frontal, parietal, central, and occipital regions of both hemispheres (Figs. 7 and 8).
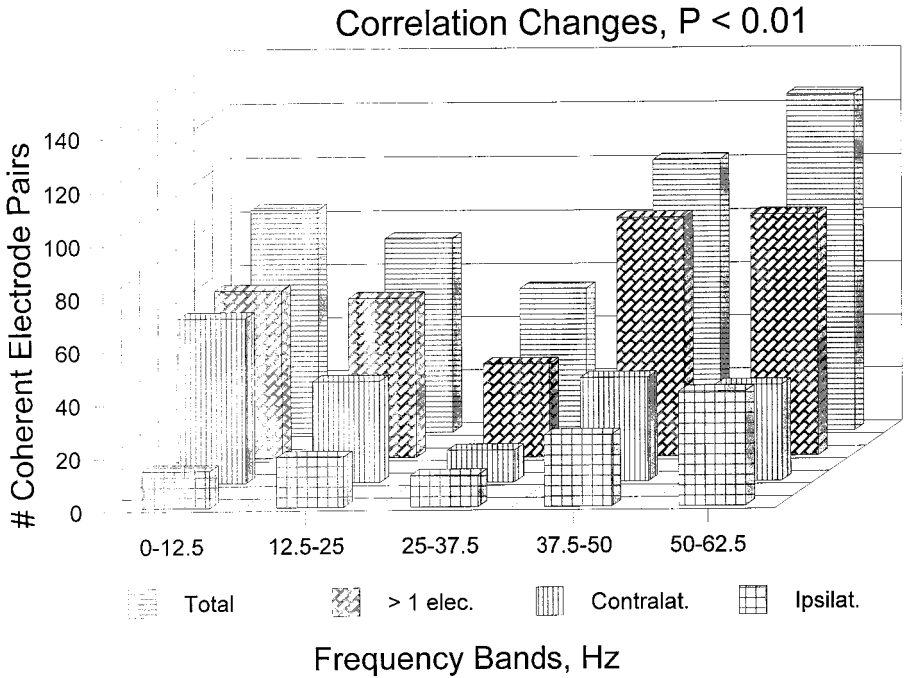
Correlation Changes, P < 0.01

FIG. 6. As in Fig. 5, except showing the number of electrode pairs that had criterion-level correlation changes where the electrodes were not adjacent, that is, separated by more than one electrode. Of the total pairs, most involved electrodes that were not adjacent. Also shown are the number of electrode pairs where one member of the pair was ipsilateral and where one member was contralateral. At all frequencies, except the highest frequency band, contralateral projections dominated.

Ambiguous-Figure Performance and Field Dependence

The time it took to realize the alternative image varied considerably within certain subjects. Some images were recognized within a second or two while others could take a minute or more, even with coaching. There was also considerable variation among subjects. Across all subjects, median ''realization times'' ranged from a minimum of 2.8 s to a maximum of 41 s, with 10.1 s as the median.

There was also a wide range in EFT scores, ranging from a low of 9.4 to a high of 58.4, with mean of 32.1 and a median of 30.3. The hypothesis of a correlation between EFT scores and realization time was not supported by the calculated correlation coefficient of −.05.

DISCUSSION

To our knowledge, our study is the first of its kind involving ambiguous figures. Ba_ar-Ergolu et al. (1996) did report study of an ambiguous stroboscopic motion display in which subjects dynamically switched perceptions and signaled with a button press when pattern reversals occurred. During such perceptual changes, frontal 30- to 50-Hz activity increased. EEG coherence was not measured, nor were frequen-
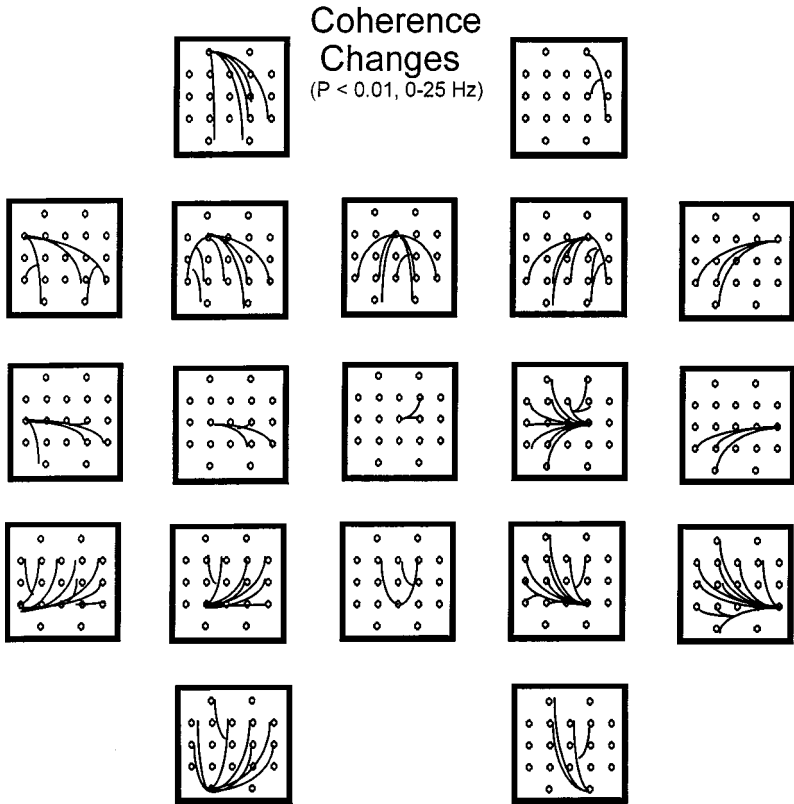
FIG. 7. Topographic summary of $p < .01$-level coherence increases across all replicates; all subjects, 0–25 Hz. Values weighted by inverse of the variance.

cies outside the gamma band. The authors regarded perceptual switching to be the real cognitive stimulus. However, in the context of cognitive binding theory, the switching would be seen not as the stimulus, but as the response (of binding).

Data of the present study lead to several conclusions: (1) many statistically significant ($p < .01$) correlation changes occurred; (2) the statistically significant correlations were always positive; that is, the coherence increased during cognitive binding; (3) many electrode signals from both hemispheres had significant contralateral correlation changes; (4) most of the statistically significant correlation changes were not with adjacent sites but with sites relatively distant; (5) certain electrodes in both hemispheres and all the midline electrodes revealed correlation changes at multiple frequencies; and (6) channels most likely to contribute muscle potential artifact (8 and 12, T3 and T4) had no significant correlation changes at any frequency above 12.5 Hz.

Coherent EEG occurs in sleep and seizures, and yet we see it here in tasks that can only be performed during normal alert wakefulness. How can we explain this seeming paradox? To get EEG coherence, regardless of cause, there must be synchrony of cortical populations, which may well be widespread. So, maybe the point
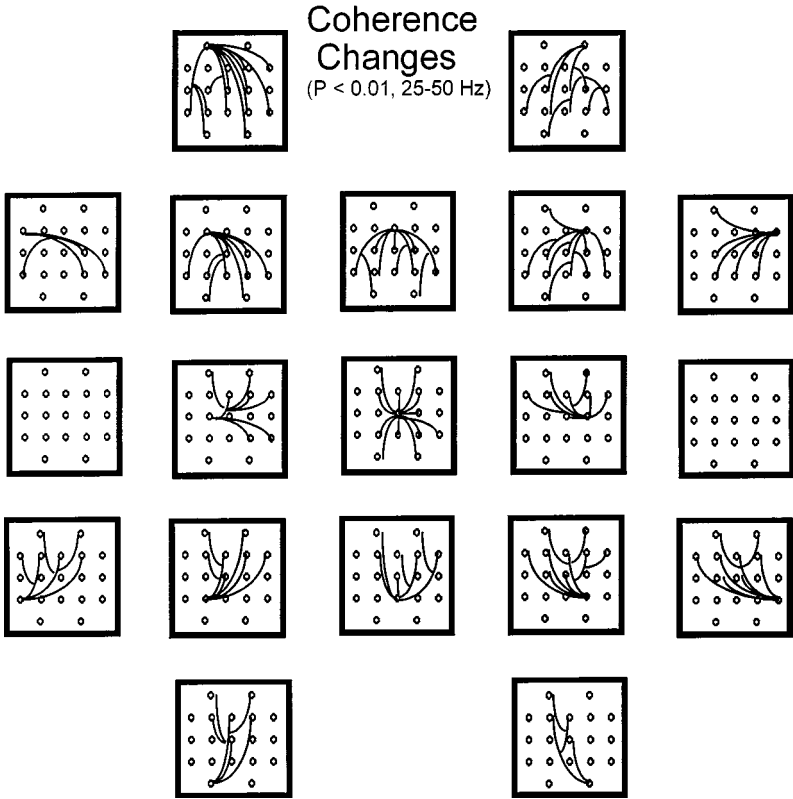
FIG. 8. Topographic summary of $p < .01$-level coherence increases across all replicates; all subjects, 25–50 Hz. Values weighted by inverse of the variance.

is not so much the coherence as such but the frequencies and specific topographical distribution of the coherence. This issue is also raised by the report of Steriade et al. (1996b), who reported that in sleeping cats, fast oscillations of cortical, thalamo-cortical, and thalamic reticular neurons occur selectively during the depolarizing component of slow-sleep and anesthesia. During arousal, these oscillations are continuous. Coherence distributions across the cortex were not studied.

We hypothesized that cognitive binding would require high-frequency coordination among widespread, distributed areas and that this would not be the case for mental activity that does not require binding. The data support this conclusion, except that we also observed task-specific correlation differences in low-frequency bands and at multiple frequencies for given electrode pairs. The original ideas that were derived from unit activity studies may need to be modified when applied to the EEG.

Widespread Coherence across Multiple-Frequency Bands

The rather large numbers of electrode pairs with increased correlation differences as image percepts became bound suggests a widespread engagement of multiple cortical populations in performing the task. However, we do acknowledge that the refer-

encing system would have a great impact on the extent of coherence. We do not feel that it is useful to explore this issue in detail here because (1) linked ears are the most common way EEGs are recorded and (2) the real point is that the coherence seen is task specific. We do suggest that follow-up studies compare various referencing systems, especially an averaged reference. However, since all we computed were the changes in correlation, we wonder if the reference system had much impact on detecting the change. Both mode A and mode B segments were referenced in the same way, so the change must be real.

In the present study, significant coherence changes occurred ipsilaterally and contralaterally, and commonly this involved correlation between areas over visual cortex with frontal areas. This could be expected, given that the binding process for ambiguous figures involves not only stimulus registration by visual cortex, but also more abstract analytical processes of a new set of salient features in the image, interpretation of alternative meanings, decision about the correct meaning, and a conscious realization that the problem has been solved and could now be reported (by buttonpress).

The increased coherence across the full frequency spectrum was unanticipated by our original hypothesis. Nonetheless, there is abundant evidence of low-frequency coherence associated with cognitive tasks, although to our knowledge none of these studies used tasks that we think required cognitive binding. One recent report suggests that slow-frequency EEG oscillations are important for maintenance and retrieval of short-term memory, rather than just serving as an ''idling'' rhythm, as traditionally thought (Jensen et al., 1998). In humans performing a modified Sternberg task in which two, four, or six items had to be held in short-term memory, oscillation in the alpha band (10–12 Hz) increased over parietal cortex with the number of items to be remembered. Synchronization with 4- to 6-Hz oscillations also occurred, especially over frontal cortex. Interelectrode coherence, however, was not measured. Another recent study has identified cognition-related coherent oscillations in low-frequency bands. When subjects responded to spoken proper names and common nouns, coherence in the theta band increased over left frontal areas with names, whereas processing common nouns was associated with coherence changes in the right hemisphere in both delta and theta bands (Weiss et al., 1998).

Other studies that implicate low frequencies as well as gamma frequencies, including the intracranial EEG studies recently reported (Klopp et al., 1999), indicate that human face delayed-recognition memory tasks were associated with multiple coherences of activity in the lingual-fusiform cortex with multiple other sites across a wide band of frequencies ranging up to 50 Hz. Also, sound-pattern stimuli (music, language, and miscellaneous sounds) reportedly evoke synchronous and coherent activity patterns across multiple scalp regions, particularly frontal regions (Crock & Palmer, 1990). There was a lateral progression of intensity from the cortical vertex for lower frequencies of oscillation to mostly right primary auditory cortical areas for high-frequency (gamma) oscillatory frequencies. Theta band coherences were recently reported by Sarnthein et al. (1998) in a human delayed-response working memory task. Finally, in a recent study of visual selective attention, multiple coherent EEG oscillatory components were observed to be differentially modulated by specific cognitive events (Makeig et al., 1998). Across alpha, beta, and gamma bands, oscilla-

tory components were consistently but differentially affected by specific cognitive events.

In our study not only were correlations at $p < .01$ seen across all frequency bands, but at some of the electrode pairs, correlation changes were seen at several or all of the frequencies. For example, FP1, F3, Fz, F4, F7, Cz, P4, and T6 correlated with some of the same electrodes at multiple frequencies. Other electrodes revealed much different coherence patterns at different frequencies (Fp2, C3, Cz, C4, T6, P3, Pz, O1, and O2). Such results could indicate that different components of the task are processed via different coherent frequencies, even at the same cortical sites.

Controls Suggest Task Specificity

The negative results from the attention controls could indicate that being alert is not sufficient to produce multiple, widespread coherence. Because both the attention and no-task controls failed to show the widespread distribution of correlation change as did ambiguous figure tasks, the results must be considered as task specific. That does not mean that other kinds of tasks, especially those involving cognitive-binding processes, could also be associated with widespread EEG correlation change.

Also, fewer electrode pairs showed significant correlation changes in the intermediate band of 12.5–37.5 Hz (Figs. 5 and 6) than in either lower or higher bands. We do not know if this difference is specific to the kind of binding task that we used.

Of necessity, we could not devise fully adequate controls. Our attention control task was based on auditory stimuli rather than a visual task. But it did involve collecting data just before a button-press, so button-pressing cannot be a factor in the observed task specificities. This issue has been addressed elsewhere (Ba_ar-Eroglu et al., 1996), where it was pointed out that button-press ''artifacts'' are not as likely to be a problem in designs like ours where the test sessions contain no planning of finger movements nor data collection during the actual button-press.

Eye and Temporal Muscle Artifacts Seem Unlikely

Artifactual sources of this coherence must be considered, but seem to be improbable. First, there is the possibility of contamination from temporal muscle potentials. However, this would not account for correlation increases that we saw in the slow-frequency bands. Also, recall that the temporal leads (T3 and T4) were the only ones that did *not* show significant high-frequency coherence changes with other sites at the criterion probability level. Moreover, we only collected data that were visually free of muscle potential over the more likely temporal sites, which were recorded at the same gains as the other scalp sites.

Another possibility is eye movement potential. But the pattern of eye movements most certainly differed among the 10 images, which differed in the spatial location of the salient features for task completion. We usually monitored eye blinks rather than orbit movements for the purpose of making certain that we did not collect data at times when eye blinks would have contaminated the scalp EEG.

Eye movements were monitored casually by a single electrode placed between the eyes. This monitor signal was intended to insure that we did not sample data during a blink artifact. In the absence of blinks, the eye monitor amplitude was on the order

of one-third that of EEG amplitude. Thus, if anything, signal in the eye channel would be more likely to be contaminated by nearby frontal EEG electrodes than the reverse situation. Correlation analysis was not performed on this eye-monitor channel. However, two additional subjects were tested in the same way as the first 17, except that there were two eye-monitor channels (electrodes placed at upper and lower lateral canthus), and each eye channel (referenced to the ears) was tested for correlation with all the other channels. No consistent correlation changes involved either eye electrode in either subject in any frequency band, even though multiple other correlations at $p < .01$ were evident, both anteriorly and posteriorly. If eye-channel correlation changes had been seen with frontal EEG electrodes, then the issue of volume-conducted contamination would be a possibility, but even there it is more likely that EEG would contaminate the eye signal because the EEG signal was so much larger.

Relation of EEG Synchrony to Multiple-Unit Activity Synchrony

The EEG is an algebraic summation of unit activity and its associated postsynaptic changes in the region closest to the electrode, although remote sites may project signal over large distances, especially high-voltage, low-frequency activity. As mentioned, stimulus-driven multiple-unit activity shows a conspicuously high degree of correlation with nearby field potential, indicating that the EEG is largely a ''low''-frequency envelope of population unit activity. The correlation between local cortical field potentials and multiple-unit activity has most recently been confirmed by (Destexhe et al., 1998). Such correlation was seen in various cortical sites of cats in various stages of sleep and wakefulness, and the correlation held even at the high gamma frequencies of field potentials that predominated during alert wakefulness. Thus, it seems reasonable to conclude that coherent EEG between a pair of scalp electrodes signifies that the units underlying that region are firing synchronously. That of course could only be confirmed for ambiguous figure binding by repeating the studies in conscious humans with implanted microelectrodes in multiple sites.

Lack of Correlation between Ambigous Figure Tasks and EFT Measures of Field Dependence

Apparently, the task requirements are different. The most obvious difference is that solving an ambiguous-figure task requires the subject to search for meaning. On the contrary, disembedding images in an EFT task involves purely a sensory detection of differences in geometric design. Field dependence logically should influence the difficulty by which subjects can decipher ambiguous figures. This opens the possibility that there are dimensions to field dependence that are not measured by the EFT test.

CONCLUSIONS

We believe that these data support the idea that the EEG responses in cognitive binding are widely distributed. In cognitive binding, we might expect that multiple loci would have to be involved in sensory registration, memory, and problem solving. The binding of sensory, contingency, contextual, and memory events in cognitive-

binding phenomena must be more complex than the sensory binding of elements of a single stimulus, as in a visual image, for example. Cognitive binding involves not only the registration of sensory elements but also the cognitive processes associated with each stimulus in the set that produces cognitive binding. If registration of the elements within a single stimulus requires synchronous discharge of units in the various cortical columns that register the extracted components of the stimulus, then perhaps that same principle of synchronicity operates and is even magnified in the registration and recombination of disparate sensory and cognitive elements that underlie cognitive binding.

The broad range of frequencies at which coherence change occurred was unexpected. We speculate that the brain may generate different coherent oscillatory frequencies for specific components of a binding task. Of course, we cannot rule out the possibility that increased coherence among multiple sites is influenced by the turning OFF of additional independent signal sources, thereby increasing the correlation measure of small common/coherent activity.

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