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NEUROPHYSIOLOGICAL PREDICTORS OF QUALITY OF PERFORMANCE

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ABSTRACT

New signal processing technologies have been developed to measure spatiotemporal neurocognitive processes of the human brain. In one experiment, application of these technologies produced measurements of distributed preparatory sets which predicted the accuracy of subsequent performance. In another experiment, neuroelectric changes were found in Air Force test pilots during the incipient stages of fatigue before behavior had severely degraded.

THE METHOD OF EVENT-RELATED COVARIANCES (ERCs)

Overview.

We have been developing new methods for recording and analyzing task-related, spatiotemporal neurocognitive patterns from the unrelated electrical activity of the brain (refs. 1-14). Since neurocognitive processes are complex, we are concerned with spatiotemporal task-related activity recorded by many (currently up to 64) scalp electrodes in many (currently up to about 25) time intervals spanning a 4-6 second period extending from before a cue, through stimulus and response, to presentation of feedback about performance accuracy. Since goal-directed behaviors require integrated processing among many brain regions, we developed the method of event-related covariance (ERC) to measure salient aspects of the brain's distributed processing networks.

The basis for ERC analysis lies with prior animal studies that have shown that when a brain region becomes involved in task performance, synchronization of a subset of neurons in that region is manifested as a change in the waveshape of its extracellularly recorded low frequency macropotentials (review in ref. 8). Since waveshape similarity and timing of macropotentials from different areas of the brain can be measured by covariance and correlation, these measures may characterize the spatial organization of coordinated functional activity of the areas involved in a goal-directed behavior.

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Computing ERCs.

A number of steps are currently performed in computing ERCs. The first pass reduces spatial smearing and then selects intervals and trials with task-related information to enhance the signal-to-noise ratio and reduce the amount of data prior to measuring ERCs. The second pass measures ERCs on band-pass-filtered, enhanced averages from the reduced data set.

The steps include: 1) recording at least 50-100 trials of each task using at least 24 electrodes; 2) removing the effect of the reference channel and reducing spatial blur; 3) removing data with artifact contamination; 4) finding trials with consistent event-related signals and computing enhanced averages; 5) selecting digital bandpass filters and intervals for measurement by examining ERPS, amplitude distribution maps and Wigner Distributions; 6) computing multilag crosscovariance functions between all pairwise channel combinations of the enhanced averages in each selected analysis interval; 7) using the magnitude of the maximum crosscovariance function and its lag time as features characterizing the ERC; 8) estimating significance of ERCs by the standard deviation of the "noise" ERC; 9) graphing the most significant ERCs in each interval; and 10) statistically comparing ERC maps between conditions.

The results of ERC analysis are expressed as color graphs. Since color photographs are not possible in these proceedings, the interested reader is referred to the published literature cited in this paper.

Validation of ERCs.

ERC analysis has been applied to data recorded from several experiments. The validity of the method is demonstrated in analyses of visual stimulus processing and response execution intervals of a visuomotor task (refs. 5; 13). As predicted by neuroanatomical theory and clinical neuropsychological studies, ERC patterns corresponding to the visual stimulus processing interval involved posterior sites that led anterior parietal sites and premotor sites (Fig. 1).

While ERC patterns appear to reflect the functional coordination of immediately underlying cortical areas, we must emphasize, however, that the actual neural sources of the ERC patterns are, in fact, not yet completely known. Determining the distributed source network producing the scalp ERC patterns is the major focus of our current technical efforts.

APPLICATION TO PREPARATION AND PREDICTING PERFORMANCE

Procedure (refs. 5; 13).

Seven healthy, right-handed male adults participated in this study. A visual cue, slanted to the right or to the left, indicated to subjects to prepare to make a response pressure with the right or left index finger. One second later, the cue was followed by a visual numeric stimulus (number 1-9) indicating that a pressure of .1 to .9 kg should be made with the index finger of the hand indicated by the cue. Feedback indicating the exact response pressure produced was presented as a two-digit number one second after the peak of the response pressure. On a random 20% of the trials, the stimulus number was slanted opposite to that of the cue, and subjects were to withhold their responses on these "catch trials". The next trial followed 1 sec after disappearance of the feedback. Subjects each performed several hundred trials, with rest breaks as needed.

Twenty-six channels of EEG data, as well as vertical and horizontal eye-movements and flexor digitori muscle activity from both arms, were recorded. All single-trial EEG data were screened for eye-movement, muscle potential and other artifacts. Contaminated data were discarded.

Intervals used for ERC analysis were centered on major event-related potential (ERP) peaks. ERCS were computed between each of the 120 pairwise combinations of the 16 nonperipheral channels in intervals from 500 msec before cue to 500 msec after the feedback.

Data sets were separated into trials in which subsequent performance was either accurate or inaccurate. Accurate and inaccurate performance trials were those in which the error (deviation from required finger pressure) was less than or greater than, respectively, the mean error over the recording session.

Results and Discussion.

ERC patterns during a 375-msec interval centered 687 msec post-cue (spanning the late Contingent Negative Variation; CNV) involved left prefrontal sites, regardless of subsequent accuracy, as well as appropriately lateralized central and parietal sites (Fig. 2). Inaccurate performance by the right hand was preceded by a highly simplified pattern, while inaccurate performance by the left hand was preceded by a complex, spatially diffuse pattern.

When the trials of each of the 7 subjects were classified by equations developed on the trials of the other 6 subjects, the overall discrimination was 59% ($p<0.01$) for right hand and 57%

($p<0.01$) for left-hand performance. For the subject with the most trials, average classification of 68% ($p<.001$) for subsequent right- and 62% ($p<.01$) for subsequent left-hand performance was achieved by testing a separate equation on each fifth of his trials, formed from the other four fifths.

An ERC pattern involving covariances from midline parietal, left parietal, midline anterocentral and right frontal and anterocentral sites was common to feedback to both accurate and inaccurate right- and left-hand responses. When responses were inaccurate, however, the feedback pattern additionally included the midline and left-frontal sites.

We suggest that our pre-stimulus ERC patterns characterize a distributed preparatory neural set related to the accuracy of subsequent task performance. This set appears to involve distinctive cognitive (frontal), integrative-motor and lateralized somesthetic-motor components. The involvement of the left-frontal site is consistent with clinical findings that preparatory sets are synthesized and integrated in prefrontal cortical areas, and with experimental and clinical evidence indicating involvement of the left dorsolateral prefrontal cortex in delayed response tasks. A midline anterocentral integrative motor component is consistent with known involvement of premotor and supplementary motor areas in initiating motor responses. The finding of an appropriately lateralized central and parietal component is consistent with evidence from primates and humans for neuronal firing in motor and somatosensory cortices prior to motor responses.

We further speculate that involvement of the midline anterocentral site following feedback to both accurate and inaccurate performance may reflect "motor recalibration" consequent to feedback information. Feedback-specific "updating" may be reflected by the involvement of the right prefrontal site for both accurate and inaccurate performance; behavioral verification, given feedback about inaccurate performance, by the left prefrontal site.

APPLICATION TO MEASURING EFFECTS OF INCIPIENT FATIGUE

<u>Procedure</u> (ref.15).

After learning and practicing a battery of tasks until their performance was stable on one day, each of five U.S. Air Force test pilots returned to the laboratory the next morning and performed the tasks for about 6 hours. Following a dinner break, they resumed task performance for an additional 6 to 8 hours.

There were four tasks in the battery, including easy and difficult continuous and discrete visuomotor tracking tasks, a simple numeric memory task, and a difficult visuomotor memory task (VMMT). Since we expected that early neural signs of fatigue would be most evident during demanding tasks, we analyzed the VMMT first. This task required subjects to remember two continuously changing numbers, in the presence of numeric distractors, in order to produce precise finger pressures. Each trial consisted of a warning symbol followed by a single-digit visual stimulus to be remembered, followed by the subject's finger-pressure response to the stimulus number presented two trials ago, followed by a 2-digit feedback number indicating the accuracy of the response. For example, if the stimulus numbers in five successive trials were 8, 6, 1, 9, 4, the correct response would be a pressure of .8 kg when seeing the 1, .6 kg for the 9, and .1 kg for the 4. To increase the task difficulty, subjects were required to withhold their response on a random 20% of the trials. These "no-response catch trials" were trials in which the current stimulus number was identical to the stimulus two trials ago.

Trials early in the recording session with accurate finger pressures formed the "Alert" data set. Trials from early in the evening, when performance was just starting to decline, formed the "Incipient Fatigue" data set. For each subject, trials with relatively inaccurate responses were then deleted from the Incipient Fatigue data set so that the final Alert and Incipient Fatigue data sets consisted of trials with equivalently accurate performance. This crucial step allowed measurement of neuroelectric patterns associated with incipient fatigue while controlling for those due to variations in performance accuracy.

EEGs were recorded with either 33 or 51 channels with a nylon mesh cap. Vertical and horizontal eye movements were also recorded, as were the responding flexor digitori muscle potentials, electrocardiogram and respiration. Three-axis Magnetic Resonance Image scans were made of 3 of the 5 subjects.

Grand-average (over the five pilots) event-related potentials (ERPs) were time-locked to presentation of the numeric stimulus. Incipient-Fatigue ERPs were subtracted from Alert ERPs in order to highlight changes due to fatigue. Spatiotemporal neuroelectric patterns were then quantified by measuring ERCs between all 153 pairwise combinations of the 18 nonperipheral electrodes. ERCs were measured across brief segments of grand-average Alert-minus-Incipient-Fatigue subtraction ERPs. The first ERC interval was 500 msec wide and was centered 312 msec before the numeric stimulus. The next two ERC intervals were 187 msec wide and were positioned with respect to the N125 and P380 ERP peaks elicited by the numeric stimulus.

Results and Discussion.

A number of significant Alert-minus-Incipient-Fatigue ERCs were found during the 500-msec prestimulus interval. Midline central, left parietal, left anteroparietal, right anterior parietal and right posterior parietal electrodes were the major ERC foci. There were no significant ERCs in the interval centered at 62 msec post-stimulus. The ERCs computed over the P380 no-response difference ERP were focused on the midline anterocentral, and right anterior and posterior parietal electrodes.

Since ERCs are signs of functional interrelationships between brain areas, the ERC changes with Incipient Fatigue suggest that dynamic functional neural networks associated with specific cognitive functions are selectively affected during early fatigue. During the prestimulus interval, when subjects were maintaining the last two visually presented numbers in working memory and preparing for the next stimulus, ERCs decreased in number in the Incipient Fatigue condition. The lack of ERC differences between Alert and Incipient Fatigue conditions during the interval centered a 62 msec suggests that the "exogenous" stages of visual stimulus processing are relatively unaffected by early fatigue. However, during the later post-stimulus interval of trials requiring an inhibition of the response, ERCs again decreased in number with Incipient Fatigue. ERCs involving anterocentral and right parietal electrodes characterized the difference between Alert and Incipient Fatigue conditions. Since precentral, central and parietal areas are implicated by neuropsychological studies in the integration of numeric, visuospatial and visuomotor processes, the subtraction ERCs suggest a change in neural systems responsible for maintaining a representation of the magnitudes of the two visually presented numbers in working memory, and for inhibiting the response based on a comparison with working memory.

Taken together, the data suggest that although neural systems responsible for primary visual stimulus processing are relatively unaffected by incipient fatigue, cortical associative areas responsible for higher cognitive functions such as working memory rehearsal, preparation, and motor inhibition are altered prior to appreciable degradations in performance.

CONCLUSIONS

The bimanual task results demonstrate that the human brain, unlike a fixed-program computer, dynamically "tunes" its distributed, specialized subsystems in anticipation of the need to process certain types of information and take certain types of action. When these preparatory sets are incomplete or incorrect, subsequent performance is likely to be inaccurate. The fact that classification of performance accuracy improved when equations were formed and tested on the same subjects suggests that single-subject equations formed from large numbers of normative trials may make ERC patterns useful for on-line prediction of subsequent behavior.

The fatigue experiment results demonstrate the existence of "leading indicator" neuroelectric patterns which precede serious degradation of performance consequent to extended performance of a very difficult task.

These studies demonstrate the potential of new neuroelectric signal processing technologies for measuring useful predictive information about the quality of performance. With further development, it should be possible to transition these technologies from the pure research enviornment of the laboratory to application in flight simulators, and eventually in cockpits.

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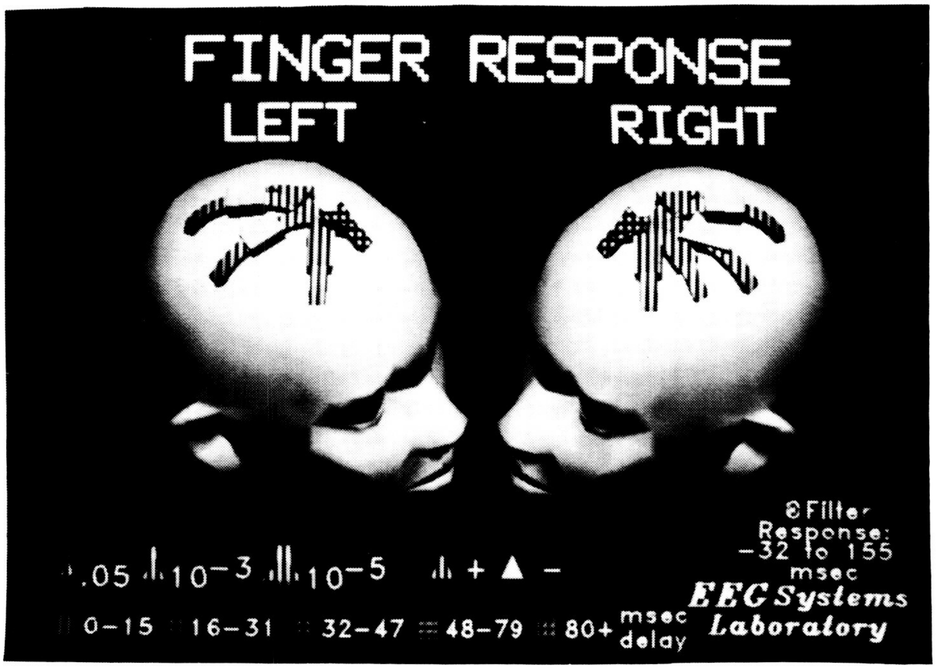

Figure 1: View of the most significant, event-related covariance patterns from the wave at the peak of a finger response. The motor-related wave was measured during a 187-msec interval centered on the peak of the left-hand and right-hand index finger pressures from theta-band filtered, seven-subject averages. The thickness of a line is proportional to tis significance (from .05 to .00005). Line pattern indicates the time delay (lag time of maximum covariance), and the arrow points from the leading to the lagging channel. ERC patterns for movement-registered timeseries also corresponded to prior functional neuroanatomical knowledge: the midline precentral electrode that overlies the premotor and supplementary motor cortices was the focus of all movement-related ERC patterns, and the other most significant ERCs involved pre- and post-central sites appropriately contralateral to the responding hand. Moreover, the pattern for the Motor Potential clearly reflected the sharply focused current sources and sinks spanning the hand areas of motor cortex.

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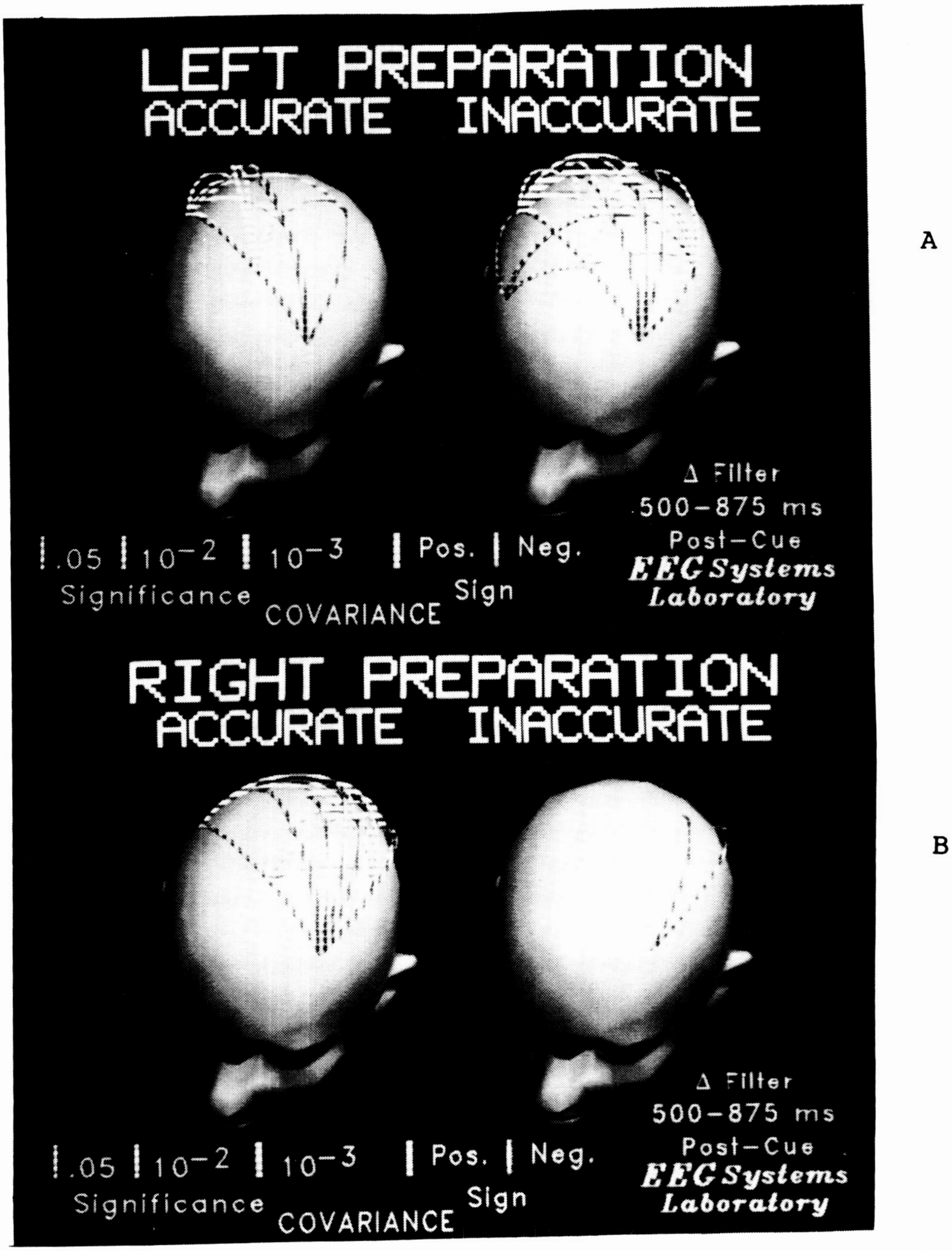

Figure 2: View of the most significant ($p<.05$), between-channel CNV event-related covariance patterns from an interval 500 to 875 msec after the cue for subsequently accurate and inaccurate left-hand (A) and right-hand (B) performance by seven right-handed subjects. The thickness of a line is proportional to its significance (from .05 to .005). Line pattern indicates whether covariance is positive (lighter lines) or negative (darker lines). Covariances involving left-frontal and appropriately lateralized central and parietal electrode sites are prominent in patterns for subsequently accurate performance of both hands. Magnitude and number of covariances are greater preceding subsequently inaccurate left-hand performance; fewer and weaker covariances characterize subsequently inaccurate right-hand performance.