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AFOSR-TR- 86-0675



AD-A174 575

NEUROELECTRIC PREDICTORS OF PERFORMANCE ACCURACY

FINAL REPORT

Grant AFOSR-85-0361

30 September, 1985 - 31 March, 1986

Approved for public release;
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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS	
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE, DISTRIBUTION UNLIMITED	
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE			
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFOSR04		5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR- 86-0675	
6a. NAME OF PERFORMING ORGANIZATION EEG SYSTEMS LABORATORY	6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION DIRECTORATE OF LIFE SCIENCES, AFOSR	
6c. ADDRESS (City, State, and ZIP Code) 1855 FOLSOM STREET, RM. 610 SAN FRANCISCO, CA 94103		7b. ADDRESS (City, State, and ZIP Code) BUILDING 410 BOLLING AFB, D.C. 20332	
8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR	8b. OFFICE SYMBOL (if applicable) NL	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR-85-0361	
8c. ADDRESS (City, State, and ZIP Code) BUILDING 410 BOLLING AFB, D.C. 20332		10. SOURCE OF FUNDING NUMBERS	
		PROGRAM ELEMENT NO. 61102F	PROJECT NO. 2313
		TASK NO. A4	WORK UNIT ACCESSION NO. —
11. TITLE (Include Security Classification) NEUROELECTRIC PREDICTORS OF PERFORMANCE ACCURACY			
12. PERSONAL AUTHOR(S) GEVINS, A.S.			
13a. TYPE OF REPORT FINAL	13b. TIME COVERED FROM 850930 TO 860331	14. DATE OF REPORT (Year, Month, Day) 860731	15. PAGE COUNT 24
16. SUPPLEMENTARY NOTATION CO-AUTHORS: MORGAN, N.H., BRESSLER, S.L., CUTILLO, B.A., WHITE, R.M., ILLES, J., GREER, D.S. & DOYLE, J.C.			
17. COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP	
0508			
0509			
		PERFORMANCE ACCURACY PREDICTION, NEUROELECTRIC EVENT-RELATED COVARIANCES, PREPARATORY NEURAL NETWORKS	
19. ABSTRACT (Continue on reverse if necessary and identify by block number)			
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20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL A. FREGLEY		22b. TELEPHONE (Include Area Code) (202) 767-5024	22c. OFFICE SYMBOL AFOSR/NL

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

SUMMARY

We have been advancing the measurement of neuroelectric substrates of human cognitive functions in relation to quality of performance. During the past year we analyzed data from healthy volunteers who performed tasks that manipulated basic cognitive and visuomotor functions, such as those critical for flying high performance aircraft. We report the existence of complex "preparatory neural networks" that may be prerequisite to accurate performance.

↳ Brain electrical patterns of seven right-handed adults were found to be different preceding accurate and inaccurate performance. Activity overlying the left frontal cortex and the motor and parietal cortices contralateral to the performing hand characterized subsequently accurate left- or right-hand performance. Additionally, strong activity overlying supplementary motor and premotor cortices preceded left-hand performance. Group patterns significantly distinguished subsequently accurate or inaccurate performance by individuals. These measurements suggest that brief, spatially distributed neural activity patterns, or preparatory sets, recorded from distinct cognitive, somesthetic-motor, and integrative motor areas of the human brain may be essential precursors of accurate visuomotor performance.

These precursors of performance accuracy were not present in even highly enhanced conventional averaged evoked potentials. Our findings suggest that important functional relations between areas of the human brain may be characterized by measuring the similarity of wave shape and timing between appropriately preprocessed low-frequency brain waves recorded from different channels at the scalp. Work is underway to verify the actual sources in the brain of these scalp-recorded patterns.

INTRODUCTION

Preparatory set for human visuomotor performance, defined as a state of readiness to receive a stimulus or make a response (Evarts et al., 1984) has been studied by a variety of disciplines. Temporal properties of preparatory sets have been measured in information-processing studies, but such studies have not focused on the underlying neural systems (Posner, 1978). Spatial properties of preparatory sets have been measured in cerebral blood flow studies, revealing increased metabolic activity for sensory-specific focus of attention in superior prefrontal, midfrontal and anterior parietal cortices (Roland, 1982). These studies, however, have been limited by the temporal resolution (1 minute or longer) of blood flow measurement techniques. Clinical neuropsychological studies have demonstrated that behaviors requiring preparatory sets rely on intact lateral frontal regions (Luria, 1966; Milner and Petrides, 1984; Stuss and Benson, 1986; Teuber, 1964), but variability in size and location of lesions has limited the spatial specificity of such studies in localizing normal function. And although scalp-recorded brain electrical and magnetic recordings provide both spatial and temporal information on neural activity underlying preparatory sets, studies of the Contingent Negative Variation (CNV), an event-related brain potential component thought to be related to preparatory set, have often yielded controversial or ambiguous results (reviewed in Gevins and Cutillo, in press; Rohrbaugh et al., 1980; Tecce, 1972).

By recording from an increased number of electrodes, and by using several signal enhancing procedures, we have measured the rapidly changing spatial patterns of mass neuroelectric activity associated with preparation and execution of precise right- and left-hand finger pressures in response to visual numeric stimuli. During the prestimulus period, we found differences between patterns associated with subsequently accurate and inaccurate performance. The results suggest, therefore, that a spatially specific, multi-component neural preparatory set, composed of an invariant left frontal component and hand-specific contralateral central and parietal components, may be essential for accurate performance of certain types of difficult visuomotor tasks.

METHODS

Subjects:

Seven healthy, right-handed male adults were recruited from the community. They were each informed of the risks and benefits of the study and paid for participation.

Task:

The subjects were required to exert rapid, precisely graded pressures (forces from 0.1 to 0.9 kg), followed by immediate release, with right- and left-hand index fingers in response to visual numeric stimuli (numbers 1 to 9). Each stimulus was presented 1 second after a cue. The cue was the letter "V" that lasted 0.3 sec and was slanted at a fixed angle (30 degrees) to the right or left to indicate the required response hand. The direction of the slant was determined randomly for successive trials. The cue, stimulus and feedback about performance were presented on a Videographics-II CRT monitor located 70 cm from the subject, and were controlled for duration and visual angle.

Eighty percent of the trials were response trials. In these trials, the stimulus was slanted in the same direction as the cue, and the subject was to respond quickly with finger pressure of the indicated hand, with a force corresponding to the stimulus number on a linear scale from 1 to 9 (Table 1).

In order to help subjects calibrate their responses, the pressure produced was displayed after completion of each response. This feedback indicating exact response pressure to a tenth of a stimulus unit was presented as a two-digit number 1 second after the peak of response. The feedback number was underlined to indicate a "win" when the response error was less than the recent performance level, which was updated on-line after each trial as the average error from the preceding 5 trials for each hand separately. This criterion made it harder for the subject to win the monetary bonus (5 cents) paid for "win" trials as performance improved. Together with rest breaks, possible systematic changes in arousal level were thus minimized. Monetary penalties (10 cents) were deducted for responding to miscued "catch" trials described below.

In a random 20% of the trials, the stimulus was slanted opposite to the cue and the subject was to make no response. These miscued "catch" trials ensured that subjects attended to the cues and stimuli.


Each subject performed between 900 and 1000 trials over a period of 5 to 6 hours, with frequent rest breaks. Subjects practiced

the task, learning the motor control and the conditions of reward and penalty, in a pretesting session that continued until the performance level approached a stable asymptote.

Table 1

RIGHT/LEFT INDEX FINGER -PRESSURE TASK

CUE GET READY FOR LEFT OR RIGHT RESPONSE	STIMULUS REQUIRED RESPONSE PRESSURE	RESPONSE PRODUCE PRESSURE	FEEDBACK HOW ACCURATE?
V	1	RIGHT HAND 4 UNITS	2.5
V	3	LEFT HAND 3.3 UNITS	3.3



A horizontal scale is shown below the table, with tick marks at 0, 1, 1.5, 2, and 3. The tick mark for 1 is aligned with the 'STIMULUS' value of 1 in the first row, and the tick mark for 3 is aligned with the 'STIMULUS' value of 3 in the second row.

Recordings:

Electrodes were placed according to an expanded version of the Ten-Twenty Electrode System in which additional coronal rows of electrodes were interposed between the original rows. The anterior midline parietal electrode was used as reference. Brain potentials from 26 scalp electrodes, vertical and horizontal eye movement potentials, and flexor digitorum muscle potentials of both hands were recorded onto magnetic tape at 128 Hz from 0.75 sec before the cue to 1 second after feedback. The band pass had a 6 decibel/octave rolloff below .1 Hz and 24 decibel/octave rolloff above 50 Hz. The rolloff below .1 Hz was gradual enough to allow sensitivity to ultra-low frequency brain potential components.

Data Preparation:

The Laplacian operator, a spatial pattern enhancement technique, was applied to the brain potentials at every time point to reduce the blur distortion that results as potentials are transmitted from the brain to scalp (Hjorth, 1975; 1980). This operation removed the effect of the reference channel. Peripheral channels were not transformed because application of the Laplacian operator to an electrode requires surrounding electrodes, which are absent for channels at the edge of a recording array. Sixteen channels remained: left and right frontal (F3, F4), midline frontal (Fz), left and right antero-central (aC3, aC4), midline antero-central (aCz), left and right central (C3, C4), midline central (Cz), left and right antero-parietal (aP1, aP2), midline antero-parietal (reference; aPz), left and right parietal (P3, P4), midline parietal (Pz), and midline antero-occipital (aOz).

Two independent raters edited the data for artifacts by visual inspection of brain, eye movement and muscle potential polygraph channels. Trials with artifacts due to eye movement, head or electrode movement, or scalp muscle contamination were eliminated, as were trials with slow, bimodal, or delayed responses, or with flexor digitorum activity between the cue and the stimulus. Remaining trials (60%) were then sorted for response accuracy, and the two sets of trials were balanced according to a number of criteria in order to eliminate the confounding of inaccuracy per se with possible performance variations due to transitory and longer-lasting changes in arousal and learning. Accurate and inaccurate performance data sets consisted of trials in which the error (deviation from required pressure) for each subject was less and greater, respectively, than his mean error over the entire recording session.

Classifying performance separately for each individual compensated for between-subject performance differences. Hence, each data set contained trials from each subject. Outlying trials on the distribution of recent performance level were eliminated to ensure that accurate and inaccurate data sets did not differ from each other in this variable. This correction eliminated the possibility that inaccuracy would be confounded by performance variations due to transitory changes in arousal. Furthermore, accurate and inaccurate trials were evenly distributed throughout the recording session in order to eliminate confounds due to learning and tonic arousal.

To quantitate the electrical activity of the brain, we measured the covariance (similarity of waveshape) between different pairs of electrodes over brief segments (187 or 375 msec) of event-related (cue, stimulus, response, feedback) waveforms averaged from the seven subjects. This approach is based on the hypothesis that when areas of the brain are functionally related, there is a consistent pattern of waveshape similarity between their

macropotentials (Livanov, 1977; Freeman, 1975, in press; Gevins et al., 1981, 1983, 1985; Gevins, in press a). Covariances between each of the 120 combinations of the 16 Laplacian-transformed channels were computed from enhanced and filtered average waveforms. Enhanced averages were formed from sets of trials selected as follows: for each channel, sets of single-trial data samples in a 250-msec interval centered 750 msec after the cue were submitted to a mathematical pattern classification program. The program attempted to discriminate the event-related trials from a "noise" data set with statistical properties similar to the ongoing EEG in corresponding channels. In each interval significantly distinguished channels ($p < .05$) were tabulated for each person. The enhanced averages were formed from those trials in which a majority of the tabulated channels were significantly classified (Gevins et al., 1986). Covariance for each electrode pair was determined by computing the crosscovariance function between their waveform segments, lagging one channel with respect to the other from 0 to 125 msec. The value of covariance was the maximum absolute value of that function.

Covariances were analyzed to determine whether they were significantly different from noise values; we could then compare the levels of significance of each electrode pair under different experimental conditions. The maximum absolute value of covariance was converted to a significance (after square root transformation) by comparison with a noise median and an estimate of noise variance using a Tukey Biweight Scale estimate. These statistics were determined from sample distributions of the square root of zero-lag covariances between intervals centered around samples with the minimum energy envelope derived from the Hilbert transform. Duncan's correction procedure was applied to control for the 120 comparisons within each interval. Detailed signal-processing methods and analyses of stimulus-, response-, and feedback-related patterns are reported elsewhere (Gevins et al., in prep a, b).

RESULTS

Behavioral Analysis:

For right- and left-hand accurate performance, mean error (deviation from the required pressure) was .35 (range = .24 to .52) and .39 (range = .28 to .51), respectively. For right- and left-hand inaccurate performance, mean error was 1.62 (range = 1.18 to 1.96) and 1.66 (range = 1.40 to 2.18), respectively.

Mean reaction time, averaged across all subjects, was consistent among hand and accuracy conditions (610-618 msec).

Neurophysiological Analysis:

To validate the covariance analysis in a known case, the procedure described above was applied to waveforms time-registered to the onset of the finger pressure response (Deecke et al., 1985; Goldberg, 1985; Ingvar and Philipson 1977; Pieper et al., 1980; Folt et al., 1980; Roland et al., 1980). The most significant left- and right-hand covariances occurred between electrodes overlying cortical regions involved in motor execution (Figure 1). The major peak in the Laplacian waveform during the response was centered 62 msec after response onset and was about 190 msec wide; therefore a 4 to 7 Hz bandpass filter and a covariance interval of 187 msec were used. (Given the high signal strength of overt movement and the resulting large number of significant response-related covariances, only the top standard deviation of significant covariances could be shown in Figure 1 without creating an overly complex display.)

Considering all significant covariances, left-sided covariances were significantly greater than the comparable right-sided ones by the Student's t-test at $p < .0001$ ($t=18.5$) for the right-hand response. Significant right-sided covariances were significantly greater than the left at $p < .0001$ ($t=21.5$) for the left-hand response. The right antero-central electrode site did not appear in the left-hand pattern in Figure 1 because its significance was slightly below the one standard deviation cutoff.

The patterns of covariance in Figure 1 presented much more spatially discrete information than did their corresponding amplitude maps. Amplitude maps were made by determining the average amplitude of the Laplacian waveform for each electrode site over the same interval used to calculate covariances, and interpolating between sites. Amplitude is represented on a color scale with red representing the maximum and violet the minimum, and is presented on the same diagrams as the covariance patterns for ease of comparison. In the 187-msec interval centered on the peak of the response (62 msec after response onset), right- and

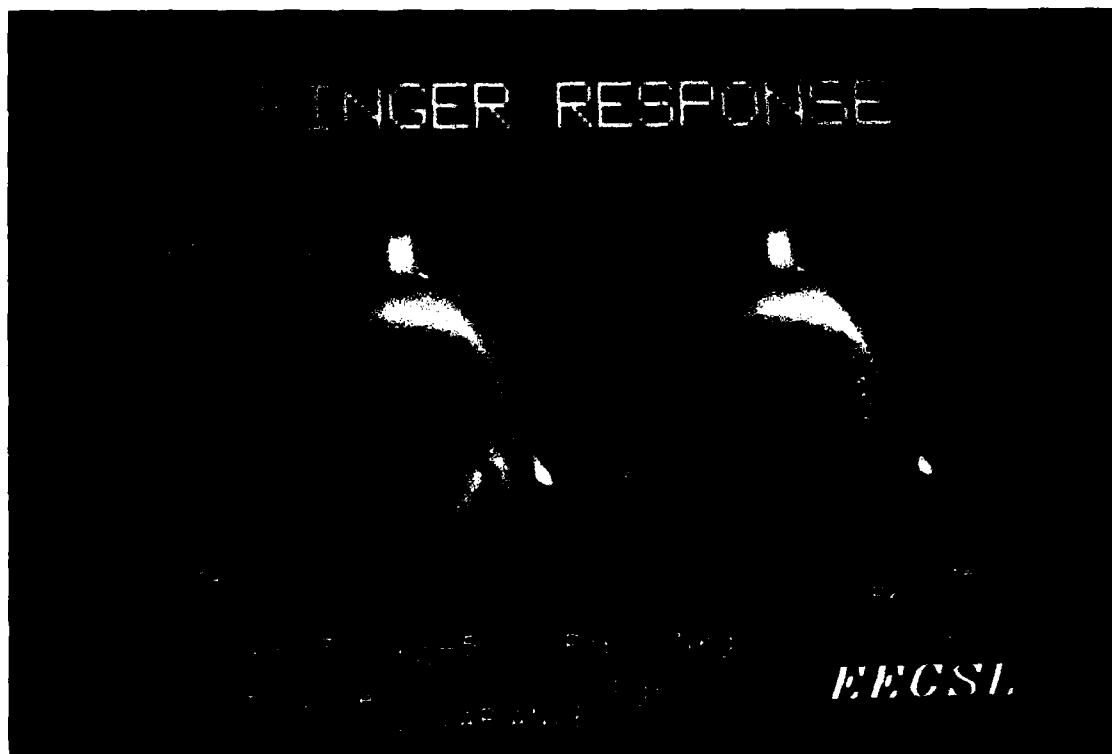


Fig. 1. View of the most significant between-channel covariance patterns (colored lines), looking down at the top of the head, from the wave at the peak of the response, superimposed on colored maps of that wave's amplitude. The motor-related wave was measured during a 187-msec interval centered on the peak of left-hand (A) and right-hand (B) index finger pressures from seven right-handed men. The thickness of a covariance line is proportional to the negative log of its significance (from .05 to .00005). A violet line indicates a positive covariance (motor-related waves with the same polarity), while a blue line indicates a negative covariance (motor-related waves with opposite polarities). The color scale at the left, representing wave amplitude, covers the range from the minimal to maximal values of the two maps. All covariances involve the site overlying supplementary and premotor cortices. There is a strong lateralization of frontal, central and antero-parietal covariances over the hemisphere contralateral to the responding hand, consistent with the lateralization of the amplitude maps.

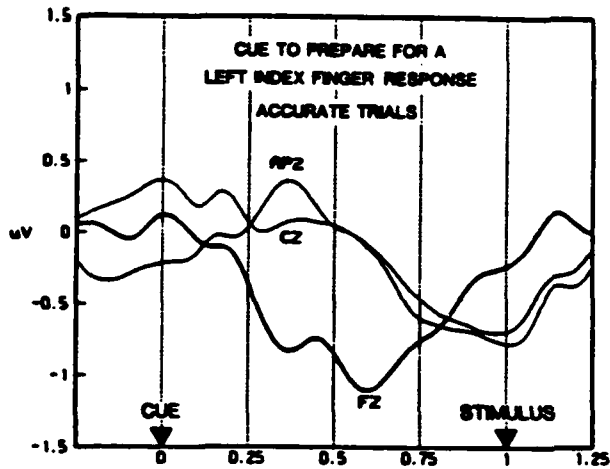
left-hand covariance patterns were near mirror-images. In both patterns, all covariances involved the midline antero-central site overlying the premotor and supplementary motor cortices. Covariances between this site and the left frontal, antero-central, central and antero-parietal sites for right hand responses, and between corresponding right hemisphere sites (except right antero-central) for the left hand, were all consistent with known motor-related cortical areas.

The procedure was then applied to the cue-to-stimulus period to study preparatory sets. A delta (up to 3 Hz) lowpass filter and a covariance interval width of 375 msec were used to study the low-frequency CNV component (Figure 2). Comparison by the Student's t-test of mean squared amplitude, measured on each Laplacian waveform (over the same 500 to 875 msec post-cue interval as was used for the covariance) between subsequently accurate and inaccurate conditions of each hand was not significant ($p > 0.05$).

Similarity between the sets of CNV amplitudes, or between covariance maps, was measured with an estimate of the correlation and its confidence-interval. For the small number of repeated measures, a normal distribution could not be confirmed. Therefore, robust, resistant estimates were calculated using a distribution-independent "bootstrap" Monte Carlo procedure (Efron, 1982), that generates an ensemble of correlation values from randomly selected choices of the repeated measures. When the distributions of CNV amplitudes from subsequently accurate and inaccurate conditions were compared by this procedure, the correlations were 0.84 ± 0.16 preceding right hand performance, and 0.83 ± 0.14 preceding left hand performance. These results indicate that discriminating between subsequently accurate and inaccurate waveforms based on the mean squared amplitude of the averaged event-related CNV waveforms is not possible.

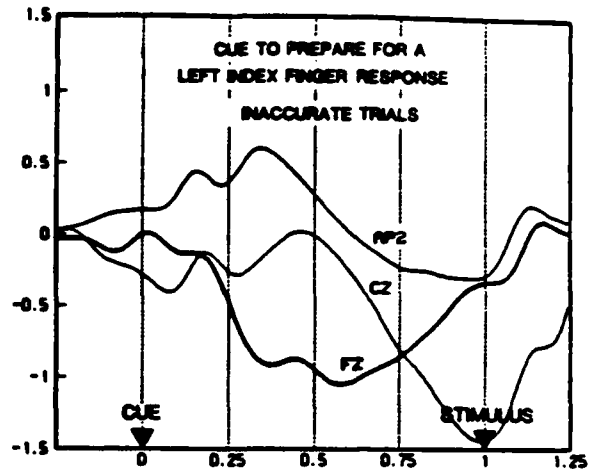
During this same period, however, well-defined between-channel covariance patterns related to subsequent accuracy were discovered. They first appeared in the interval centered 500 msec after the cue and became well-differentiated between accurate and inaccurate conditions in the 500 to 875 msec interval (centered 313 msec before stimulus onset) spanning the late component of the CNV. The lack of muscle potential and eye movement signals in these intervals confirm that these patterns were neural in origin (Figure 3).

Covariance patterns during the period between the cue and stimulus (Figure 4) were distinct from those related to overt finger responses. During the interval from 500 msec to 875 msec after the cue onset, covariance patterns associated with subsequently accurate right-hand performance involved predominantly left hemisphere sites, particularly left frontal, central, parietal, and antero-parietal sites. These 4 sites were the most prominent in that the numbers of significant covariances in which they were involved each exceeded one half of the maximum



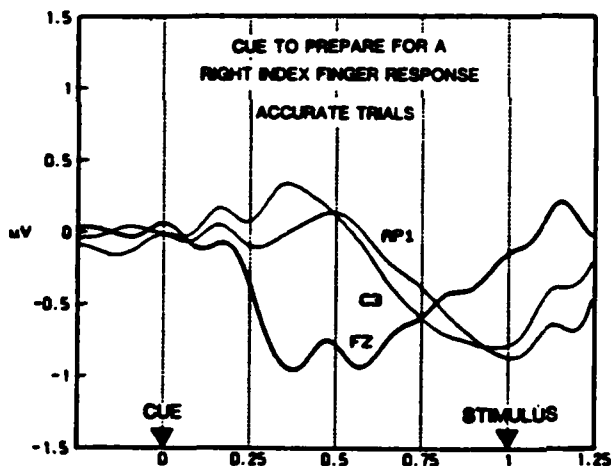
7 PEOPLE, 252-274 ACCURATE TRIALS
DELTA BANDPASS, 30-JUL-65, EEG SYSTEMS LABORATORY

(a)



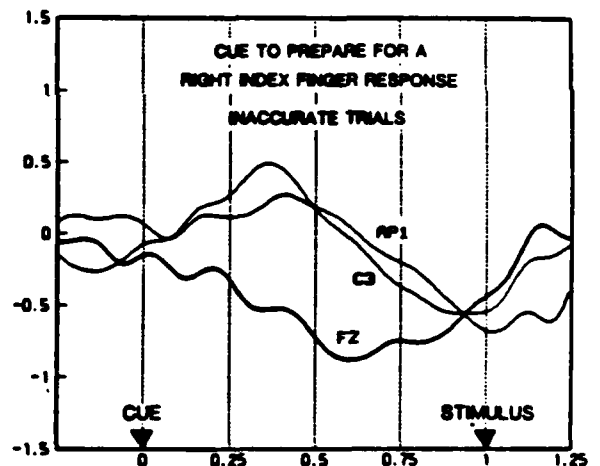
7 PEOPLE, 254-284 INACCURATE TRIALS
DELTA BANDPASS, 30-JUL-65, EEG SYSTEMS LABORATORY

(b)



7 PEOPLE, 281-300 ACCURATE TRIALS
DELTA BANDPASS, 30-JUL-65, EEG SYSTEMS LABORATORY

(c)



7 PEOPLE, 282-304 INACCURATE TRIALS
DELTA BANDPASS, 30-JUL-65, EEG SYSTEMS LABORATORY

(d)

Fig. 2. Amplitudes of the contingent negative variation (CNV) computed during the cue-to-stimulus period. Amplitudes between filtered (below 3 Hz), event-related Laplacian waveforms, averaged from seven subjects, are not significantly different for the comparison of left-accurate (A) with left-inaccurate (B) conditions, or right-accurate (C) with right-inaccurate (D) conditions.

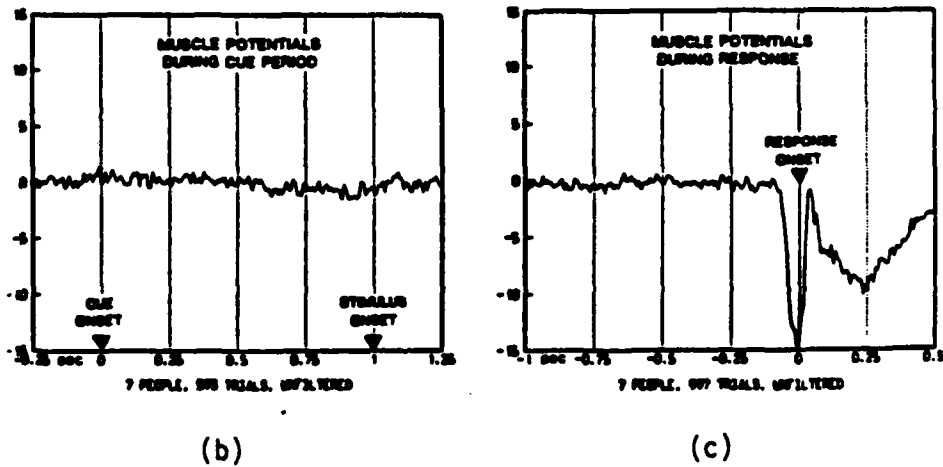
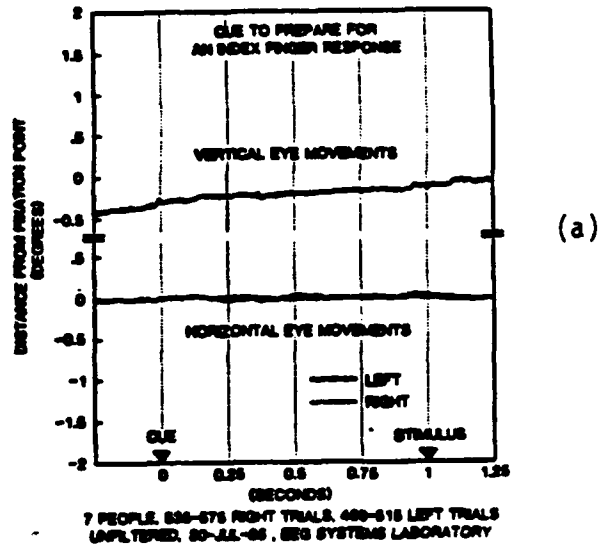


Fig. 3. Averaged vertical and horizontal eye-movement signals during the cue-to-stimulus period for right- and left-hand trials from the seven subjects (A). Averaged muscle potential signals from right flexor digitorum during the cue-to-stimulus period (arbitrary units) (B). Muscle potentials during overt movements were many times larger (C). (Averaged muscle potential signals from left flexor digitorum showed the same relation.) Since there is no evidence of eye or muscle movements during either right- or left-hand preparation, the covariance patterns in Fig. 4 are not due to overt movements.

Fig. 4. View of the significant ($p < 0.05$) between-channel contingent negative variation (CNV) covariance patterns, looking down at the top of the head, superimposed on maps of CNV amplitude. Measurements are from an interval 500 to 875 msec after the cue for subsequently accurate and inaccurate left-hand (A) and right-hand (B) visuomotor task performance by seven right-handed men. The thickness of a covariance line is proportional to its significance (from .05 to .005). A violet line indicates the covariance is positive while a blue line indicates that the covariance is negative. Covariances involving left frontal and appropriately contralateral central and parietal electrode sites are prominent in patterns for subsequently accurate performance of both hands. The magnitude and number of covariances are greater preceding subsequently inaccurate left-hand performance and are more widely distributed compared with the left-hand accurate pattern. For the right-hand, fewer and weaker covariances characterize subsequently inaccurate performance. The amplitude maps are highly similar for the four conditions, and do not indicate any of the specific differences evident in the covariance patterns.

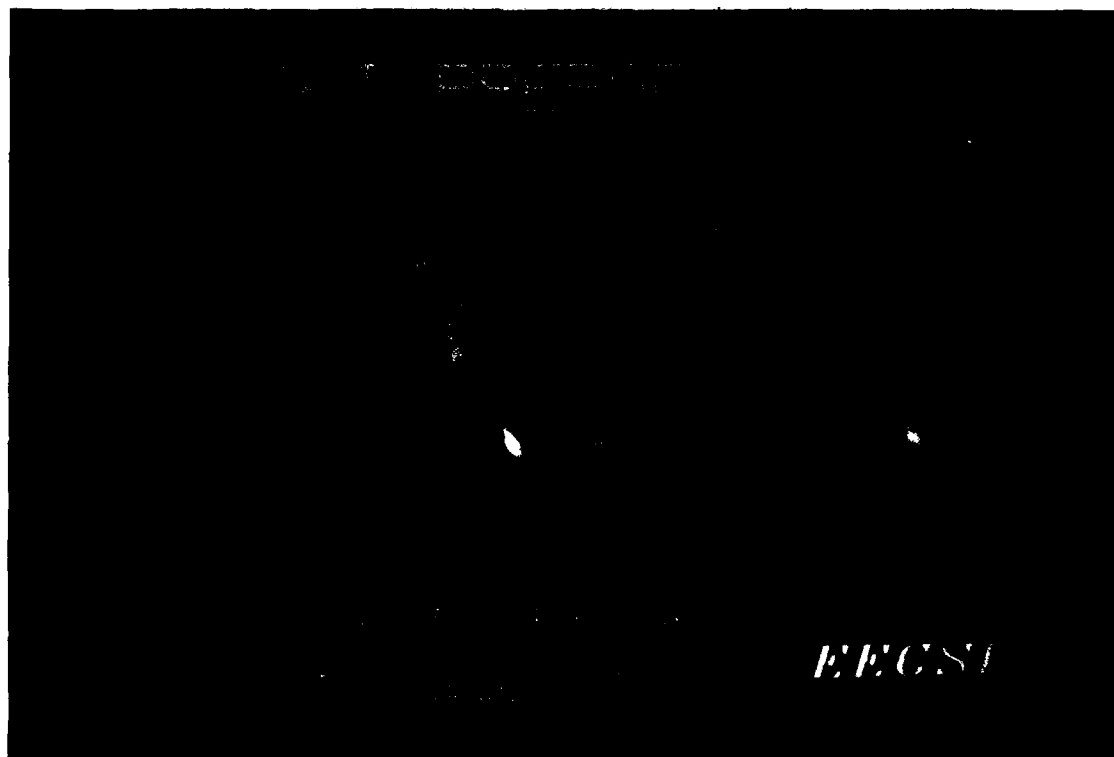


Figure 4(A)

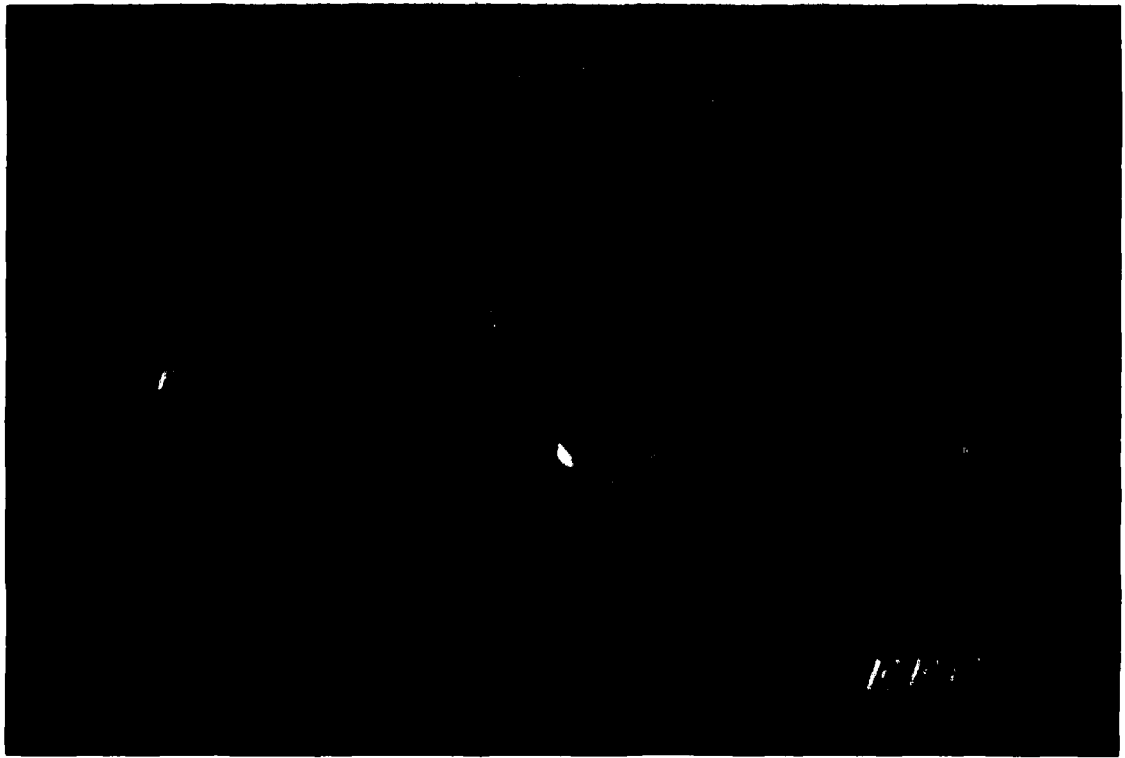


Figure 4(B)

number at any site (9 for the antero-parietal site). The other sites in the pattern were involved in one third, or less, of that maximum. The same criterion was used to judge which sites were prominent in the left-hand pattern. All 24 significant covariances involved sites on the left side and 18 (75%) were exclusively on the left side. The covariance pattern preceding subsequently accurate left-hand performance for this interval involved predominantly right-sided sites. Of 18 significant covariances in this pattern, 13 (72%) involved right hemispheric sites. The right-sided central, parietal and antero-parietal sites were most prominent, compared to corresponding prominent contralateral sites for the right-hand accurate pattern. The left frontal site was prominent preceding both left- and right-hand performance. The midline central and antero-central sites were prominent in the left-hand pattern, but were not among the most prominent in the right-hand pattern.

Only two significant covariances were related to subsequently inaccurate right-hand performance in this interval, namely, left parietal and antero-parietal to left frontal. In contrast, the subsequently inaccurate covariance pattern for the left hand was more bilateral and complex than the subsequently accurate pattern. In addition to the cue-to-stimulus period, the post-stimulus and post-feedback periods also showed differences related to accuracy, but the response period did not (Gevins et al., in prep. a,b).

The signal strength of pre-stimulus covariances was much smaller than those during overt responses, that is, the scale of significance was three orders of magnitude smaller. The smaller number of pre-stimulus covariances allowed all significant covariances to be shown in Figure 4. Comparison by the Student's t-test of the sets of subsequently accurate and inaccurate covariances was significant at $p < .001$ for both left- ($t=5.57$) and right-hand ($t=7.70$) comparisons. The "bootstrap" correlation between covariance patterns preceding subsequently accurate and inaccurate performance from channel pairs that were significant for either condition was 0.57 ± 0.09 for the right hand, and 0.10 ± 0.14 for the left hand. The t-test and "bootstrap" correlation results, taken together, suggest that the left-hand accurate and inaccurate conditions differ both in scale and in pattern, while the right-hand results differ only in scale. Unlike the between-channel covariance patterns, the CNV amplitude maps were highly similar for both accuracy conditions and hands, and were not useful in determining what areas would covary.

Using statistical pattern classification procedures, covariances shown in Figure 4 were considered as possible variables to distinguish subsequent performance accuracy. The classifier was a nonlinear, adaptive, two-layered decision network (Gevins, in press b; Gevins and Morgan, in press; Gevins et al., 1981, 1983, 1985) that decided from CNV-interval between-channel covariances of each trial whether subsequent performance was accurate or inaccurate. This algorithm produced, by a recursive procedure,

classification equations consisting of weighted combinations of the decisions of discriminant functions, which themselves consisted of weighted combinations of a subset of the covariance values of Figure 4. Cross-validation of the equations was performed by testing equations on data that were not used to derive them. Significance was determined according to the binomial distribution. (Details of the application of pattern classification procedures to the analysis of brain signals are presented in Gevins, in press b, and Gevins and Morgan, in press). These conservative procedures notwithstanding, we must caution that the degree of generalization of these results to the population at large is unknown and can only be determined by additional studies with new subjects.

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. Discrimination of subsequent right-hand performance accuracy was above 57% for 6 subjects and was 50% for the seventh. For left-hand performance, discrimination for 3 subjects ranged from 56% to 67%, and was 53% or below for 4 subjects (who had fewer trials overall). Average classification of each fifth of the trials from the 4 subjects with lowest left-hand discrimination, using equations from the other four fifths, was 61% ($p < 0.001$). This suggests that the 4 subjects had similar covariance patterns preceding left-hand performance, which were different from the other 3 subjects. The greater uniformity for right- over left-hand discrimination suggests that there are similar covariance patterns among the strongly right-handed subjects preceding accurate and inaccurate right-hand performance, and a divergence of patterns preceding left-hand performance. While there were differences in discriminative power between individuals, overall the group preparation patterns were clearly effective in deciding an individual's subsequent performance accuracy. For the one subject with the most trials, average classification of 68% ($p < 0.001$) for subsequent right- and 62% ($p < 0.01$) for subsequent left-hand performance was achieved by testing a separate equation on each fifth of his trials, formed from the other four fifths.

DISCUSSION

Although the origin of these event-related between-channel covariance patterns of preparatory sets is not known, our results suggest that preparation for accurate performance in a visuomotor task involves several brain components (Ruchkin et al., 1986): a cognitive component manifested by invariant activity at the left frontal covariance site, a hand-specific somesthetic-motor component manifested by the contralateral central and parietal sites, and an integrative motor component manifested by activity at the midline central and antero-central sites. The last component was strong in the pattern preceding accurate left-hand performance and weaker in that preceding accurate right-hand performance. For both hands, preparatory covariance patterns were different from those accompanying actual response execution. Covariance patterns preceding inaccurate performance by each hand differed markedly. The relative lack of significant covariances preceding inaccurate right-hand performance may be interpreted as evidence for a weakened preparatory set. By contrast, the complex, anatomically diffuse but strong patterns in the left-hand condition suggest that inaccurate performance by the nondominant hand of strongly right-handed subjects may result from erroneous, possibly confounded, preparatory sets.

Our evidence for distributed, coordinated, preparatory components of human visuomotor performance is consistent with previous studies of this aspect of behavior. The involvement of the left frontal site is consistent with evidence that preparatory sets in humans are synthesized and integrated in left dorsolateral prefrontal cortices (Fuster, 1984; reviewed in Goldman-Rakic, 1984; Luria, 1966; Milner and Petrides, 1984; Stuss and Benson, 1986; Teuber, 1964). The finding of an appropriately lateralized parieto-central somesthetic-motor component is consistent with data that show neuronal firing patterns in the motor cortex of nonhuman primates, and localized potentials in the somesthetic cortex of humans, preceding motor responses (Evarts et al., 1984; Mountcastle, 1978; Lee et al., 1986). Finally, a midline antero-central integrative motor component is consistent with involvement of premotor and supplementary motor regions in initiating existing motor schemes and establishing new ones (Roland, 1982, 1985a, 1985b).

Our results demonstrate that the human brain, unlike a fixed-program computer, dynamically "programs" its distributed, specialized subsystems in anticipation of the need to process a certain type of information and take a certain type 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 covariance patterns useful for on-line prediction of subsequent behavior.

ACKNOWLEDGMENTS

In addition to the Life Sciences Directorate of the Air Force Office of Scientific Research, the technical developments which produced these results were supported by the Air Force School of Aerospace Medicine, the National Science Foundation, the National Institutes of Neurological Diseases and Strokes, and the Office of Naval Research. In addition to the authors listed on the title page, programming was performed by Robert S. Tannehill and Gerald M. Zeitlin.

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