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BIOCYBERNETIC CONTROL IN MAN-MACHINE INTERACTION

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California University

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COMPUTER SCIENCE DEPARTMENT
School of Engineering and Applied Science
University of California
Los Angeles

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This research program aims at incorporating EEG "evoked responses" in man-machine communication. A methodology for the real-time discrimination of evoked responses by a computer in real-time has been developed. Extremely high rates of sensory stimulus identification from EEG have been achieved.

The experimental paradigm has been completely implemented on the laboratory computer system. Experiments are now in progress that involve the EEG discrimination algorithm in an actual man-machine communication procedure.

UCLA-ENG-7535

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BIOCYBERNETIC CONTROL IN MAN-MACHINE INTERACTION:
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CONTENTS

1. ORIENTATION

The present document is the interim semi-annual report for the Biocybernetic Control in Man-Machine Interaction project at UCLA conducted under Advanced Research Projects Agency Contract No. N00014-69-A-0200-4055. The project started in April 1973 under a different contract. The long-term goals were described in detail in earlier proposals (UCLA-Eng-P2465-N-73 and P-2719-C-74) and are briefly reviewed below.

The ultimate goal of the project is to implement and evaluate the incorporation of electrophysiological brain signals in selected man-machine communication procedures. The messages considered deal with perceptual, cognitive or affective aspects of the dialogues.

In conventional man-machine interaction with computer terminals the terminal provides most of the external environment and generates inputs of stimuli to the operator in the form of graphic displays or alphanumeric messages. Typically the "response" is then the selection of a keyboard sequence. This motor behavior (i.e. the next interactive step in the interchange) is decided upon (voluntary response) from the analysis of the situation. A closer coupling would be obtained, however, if one could tap the covert as well as the overt responses and, to some extent, bypass the requirement for an explicit motor output. Such generalized responses can be categorized as follows:

a) Sensory (Input-Exteroceptive)
b) Perceptual/Emotional/Cognitive (Processing-Interoceptive)
c) Motor (Output-Proprioceptive)

A closely coupled man-machine interface can be conceived as an interface that accesses some of these behavior components directly from biosignals measured on the body. This can in principle be obtained either by passively monitoring peripheral signals (respondents) such as electromyograms (EMG) or electroencephalograms (EEG) and/or by opening new (operant) channels by conditioning some of those signals in a way that would provide reliable computer access to these internal processes. Close coupling could also be obtained with subliminal muscle control or very low overhead motor behavior such as eye movement or blinks. Whenever applicable this would in fact bypass or considerably reduce motor output and the considerable overhead attached to the externalization. To that effect appropriate respondents must be found and subsequently reinforced, stabilized and placed under voluntary control by operant conditioning. Electrophysiological signals as found in the EEG appear to be the only candidate offering adequate bandwidth for the additional communication channels. The present project uses the EEG in this manner and concentrates on event-bound EEG epochs, i.e. evoked responses.

The experimental approach consists of identifying features in the EEG (evoked responses) that constitute potential codes for the direct communication of specific "messages" relevant to interactive man-computer communication. Such messages would be, for example, recognition of a clue (matching), its acceptance or rejection, the choice between (visual) alternatives, the neural control over the positioning of a pointer on a screen, etc.

Electroencephalographic signals collected on the scalp are spatio-temporal events. Because of electrodes and anatomical limitations space sampling is often coarse and time assumes the role of principal independent variable. Time functions are collected on each location or channel.

To decode the signals one must evaluate the range and bandwidth (i.e. the time windows occupied by each meaningful feature in the functions that constitute the EEG "signatures") and determine the rules of association of those features or (in linguistic terms) the "syntax". The relationship that these (accessible) brain signals offer to conscious experience and human performance (their semantic domain) must also be investigated.

The starting point of this study was the view that EEG signals are a complex structure of elementary wavelets that reflect individual and sequential events taking place in various brain structures. Because of the enormous complexity and interlinking of these events, all small fluctuations in the EEG have generally been ignored and lumped with instrumentation noise, while all the attention was concentrated on rhythmic activity or (in the case of evoked response) slow components of relatively large amplitude. Yet it is becoming evident that these sequences and patterns of distinct wavelets are time signatures that constitute observable components of the brain "state vector". Sequential rules for the appearance and configuration of the wavelets may become identified as the syntactic constraint of a neuro-electric language with a considerable potential in man-machine communication.

References-Section 1

Vidal, J.J., "New Developments in EEG Signal Processing", Proceedings of the Third Symposium on Nonlinear Estimation, September 11-13, 1972, San Diego, California.

Vidal, J.J., "Toward Direct Brain Computer Communication", Annual Review of Biophysics and Bioengineering, Vol. 2, Annual Reviews, Inc., Palo Alto, 1973.

Vidal, J.J., "The Brain Computer Interface Project", The UCLA Computer Science Department Quarterly, Vol. 1, No. 4, 1973.

2. PROGRESS TO DATE

As indicated earlier, the UCLA Biocybernetic Control in Man-Machine Interaction project has been underway at the Brain Computer Interface Laboratory (BCI) since July 1973 under ARPA sponsorship. Accomplishments to date for the ensemble of the project roughly fall into three categories, namely:

a) evoked response experiment results (2.1)

b) development of the computer system supporting the effort (2.2)

c) development of computer methodology and application software for real-time EEG identification (2.3)

The accomplishments during the first year have been described in more detail in the Final Technical Report 1973-74. The present document covers the first half of the second year (1974-75). The salient items are listed in the present section.

2.1 Evoked Response Experiment Results

With the advent of the second year the experimental program went into high gear. Some initial delays were due to system development because of the installation of a new SDS 930 system. A new pool of subjects was formed and an extensive screening program undertaken. At present, five subjects with exceptional performance have been retained. Discrimination accuracy on the standard four color (red/green/blue/yellow) experiment used in the screening revealed capability for accuracies exceeding 90% of correct response in completely randomized testing sets of trials over a single channel. Multi-channel discrimination reached 95% and even 99% in the best cases in repeated trials after new techniques for elimination of outlying responses were introduced.

Preliminary experiments have also been completed with pattern position that have definitely established the feasibility of the closed loop "visual light pen" experiment described in the next section. Discriminability on pattern position still falls short of that of color at this time. In these experiments, however, no attempt had yet been made to optimize the targets or the procedures.

2.2 Computer System Hardware Improvements

The major event in the laboratory system occurred at the beginning of the second year and was the procurement through DARO and the installation in the laboratory of a SDS 930 computer. This system came with a complete set of peripherals including two tape drives, a card reader and a high speed lineprinter. Its 16K of memory coupled with a high speed drum holding two million characters is capable of greatly improved performance for on-line data acquisition and discrimination and in addition, of handling a considerable batch processing load. Since the laboratory computer was a completely compatible SDS 920, a reconfiguration was made that turned the real-time control of experiments over to the 930 and relegated the 920 to the function of I/O processor. A special operating system was developed to interleave on-line and off-line work. Between experiments the batch capability is used for computing decision rules on training sets and performing various data reconfigurations. All useful laboratory application routines were re-written for the system and new ones introduced. In particular a BCI version of the Stepwise Discriminant Analysis, the orthogonalization procedure and a factor analysis program were written and completely debugged by January 1975.

2.3 Computer Methodology and Software Development

Several substantial improvements were obtained in the evoked response discrimination procedure. One side of the investigation dealt with determining the threshold for posterior probabilities to be chosen for creating the extra class of "don't know" responses. Increasing the threshold increased the reliability of correct responses but also increased the number of instances in which the computer declined to classify. This optimal tradeoff for a given cost function can be found from the curves relating the correctness of classification versus "don't know" frequency plotted through multiple trials. A similar inquiry was done to find the influence of the "elimination of outliers" from the training set. Outliers are responses that in the training set fall substantially outside the rest of the cluster. The procedure eliminated such responses and recalculated the decision rule. Again the threshold for outlier labeling can be varied and an optimum found, using testing set correctness as criterion.

The informational meaning of the decision rule given by the discriminant procedure was analysed theoretically and a mutual information measure was defined and added to the output of the procedure. This measure provides an objective and readily understood scale to compare within paradigms, experiments or subjects.

In prevision of cognitive experiments requiring more complex visual targets for subject stimulation, an all out effort was launched to improve the generation of graphic displays on the laboratory IMLAC graphic system. To that effect, a new compiler language (GRAL) was developed and documented. GRAL allows specification of animation images to be made in very simple statements. Compiling is done on the 360/91 to produce object codes for the IMLAC which can be transferred from CCN to the laboratory using the existing link. At the same time a special program for the generation of human faces was written and successfully debugged in IMLAC assembly language as GRAL was not available at the time. This program, developed under a different (Air Force) contract, will directly support the present work. At this time facial features are placed under keyboard control. Relatively simple modifications are being introduced that will place the control under the main laboratory computer. Facial expression can then be used as feedback stimuli in the biocybernetics loop.

References-Section 2

Vidal, J.J., "Biocybernetic Control in Man-Machine Interaction, Final Technical Report 1973-74", UCLA ENGR-7435

Gonzalez, C., and J.J. Vidal, "GRAL--A Graphic Compiler Language for Intelligent Terminals", IEEE Transactions on Software Engineering accepted for publication April 1975.

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Vidal, J.J., and Sam Reisenfeld, "Dynamic Smoothing of EEG Evoked Responses", VIIth IFIP Congress, Nice, France; September 1975.

Schwartzmann, D. and J.J. Vidal, "An Algorithm for Determining the Topological Dimensionality and Structure of Point Clusters", IEEE Transactions on Computers; accepted for publication 1975.

3. EVOKED RESPONSES RESULTS SUMMARIES

3.1 Color Experiments

Purpose

1) To develop further the methodology and performance of on-line machine decoding of brief electrical signals evoked on the human scalp by sensory events.
2) To evaluate a group of subjects in order to choose for further study those who show adequate performance.

Methods

Subjects are fifteen untrained female students (ages 19-24). Each was given a routine Ishahara test of color discrimination. Individual recording sessions were then conducted as described below. Each required about two hours.

Standard silver disc electrodes are applied with electroconductive paste at five locations on the scalp (Fpz, Pz, Oz, O_1 and O_2) and to the ear-lobes (A_1-A_2). Electrode impedance was always less than 10,000Ω. Four EEG data channels are recorded (Ch 1: Pz-A, Ch 2: Oz-Pz, Ch 3: O_1-Pz, Ch 4: O_2-Pz). The Fpz-Oz signal is used as a blink artifact detection channel; if a peak-to-peak deflection occurs which exceeds a preset level, the current epoch is aborted in order to avoid taking data corrupted by electro-oculographic activity while the subject has her eyes moving or even during brief moments of eye closure. EEG signals are amplified over a bandwidth of 1.0 to 70 Hz, and digitized every four msec. A data epoch consists of samples taken both before (400 to 960 msec depending on individual runs) and after the stimulus time (320 msec in all instances). The data taken prior to stimulation is necessary to provide a lead time whenever the orthogonalization routine of Glassman is used in subsequent processing. It is otherwise dropped at analysis time.

Stimuli consist of brief (30μsec.) flashes of xenon strobe light (10^7 lux illuminance in collimated beam) projected through one of four randomly selected interference filters with peak transmission wavelengths of 620nm (Red), 575nm (Yellow), 515nm (Green) and 465nm (Blue) and a yellow (Wratten #4) background light with a luminance of 100 NITS or 10^{-2} lamberts. The stimuli are viewed either through diffusing goggles worn by the subject or by a large diffusing screen of translucent plastic placed before the subject. All experiments are conducted inside a sound attenuated, electrostatically and radio frequency shielded room. Two-hundred epochs are taken and recorded on digital tape.

Analysis

Data analysis is performed on a SDS 930 computer. Stepwise linear discriminant analysis (SDA) is used to develop four linear discriminant functions (one for each of the four color classes) which are then evaluated for each epoch in order to determine the a-posteriori probability of belonging to each group. The processing is, therefore, conducted in the laboratory on a dedicated machine in contrast to previous work in which stepwise discriminant analysis was performed using the BMD07M package running in batch mode on the IBM 360/91 at the Campus Computing Network.

The requirements for on-line processing necessitated either a modification of 07M so that it could be linked with the Monitor/Line handler routine which interfaces the BCI laboratory computers to the 360/91, or the development of a customized version which could run in our SDS 930 computer in the BCI lab. The latter route was chosen, and the in-house SDA program now possesses several features not provided by the standard BMD package. These features include:

1) The capability of selecting and labeling any 40 variables from the multi-channel EEG data input produced by the Data Handling Supervisor/Scheduler running on the 930,
2) Flexibility in the assignment of some epochs to a training set, and other epochs to a testing set,
3) Capability to read the group type of each epoch from the epoch headers provided as part of the BCI Data Format,

4) The ability to skip pre-stimulus data automatically;
5) Implementation of an a-posteriori decision threshold parameter so that epochs which do not produce a probability of belonging to any source group with a value higher than the decision threshold are classified into a new "default" category;
6) An outlier rejection routine which controls the acceptance of epochs for iterative generation of the discriminant functions. For example, only those epochs would be entered which on a prior SDA run have been correctly classified, or epochs which have been defaulted (but not misclassified) as well as those correctly classified.

The SDA program also routinely produces averages, F ratios for each variable, covariances, correlation coefficients, results at each step, evaluation of the discriminant functions (DF's) and epoch predictions, if requested on control cards. In the last version the calculation of the mutual information measure is included.

Results

For the initial evaluations, a general data window was adopted which selected 10 variables from each of four EEG channels, beginning at 80 msec latency from the stimulus, and taking every fourth variable (16 msec intervals) to 224 msec latency. SDA was given on F-to-enter and F-to-delete of 2.2, a decision threshold of 0.25 (no defaults), and told to go 10 steps, F level permitting. Usually 100 epochs were taken as a training set, with an inter epoch stepping interval of 2, that is, every other epoch of a given group type (source color) was taken to train the discriminant function. The testing set then consisted of the other 100 epochs, 25 from each group. Two confusion matrices are obtained upon evaluation of the single epoch events by the DF; one for the training set, and one for the testing set. Overall performance is defined as percentage of correct classification on the testing set. The following results were obtained:

Subject-Date	Experiment Type (G=goggles, S=screen)	% Correct
SB01 MR13	G	87
SB01 MR13	S	86
APN1 MR19	S	69
ALL1 MR25	G	76
ALL1 MR25	S	68
SAG1 MR27	G	82
SAG1 MR27	S	84
SAD1 AP03	G	81
NLM1 AP08	G	84
JMS1 AP10	G	68
SOS1 AP15	G	87
MMD1 AP15	G	71
ATW1 AP17	G	74

Data from three subjects is not included due to hardware problems which prevented accurate data collection. One additional subject's data was formatted incorrectly; this error is expected to be reversible. The average performance of all ten subjects was 78%, using a very general sample variable selection paradigm. Five of them showed performance ranging from 81% to 87% and these will be retained for further study. The variables chosen, their F levels, the discriminant functions, and the training and testing confusion matrices for these five subjects are displayed in Tables 1-5.

The data from subjectSB01, whose performance using the general 16 msec window was 87%, was analyzed more extensively in order to investigate the following areas:

1) The degree of performance to be obtained by choosing the best ten variables from 160 of 320 samples taken, rather than entering only 40 samples;

SB01 MR13-75-0 FOUR COLOR VER EXPERIMENT, GENERAL 16 MSEC. WINDOW

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
1	1,080	.16939E 02	-.69074E-01	-.77538E-02	-.21360E-01	-.22209E-01
4	1,128	.18892E 02	.76035E-01	.16087E-01	.58293E-02	.58899E-02
5	1,144	.70889E 01	.47178E-01	.20427E-01	.24993E-01	.48605E-02
11	2,080	.12256E 02	-.61796E-01	-.59554E-03	-.17758E-01	-.18303E-01
15	2,144	.83504E 01	.65404E-01	.26500E-02	.22209E-01	.99148E-02
21	3,080	.52857E 02	.86481E-01	.30784E-02	.19380E-01	.28339E-01
24	3,128	.23376E 02	-.10790E-01	-.19784E-01	.20024E-01	.25626E-01
25	3,144	.16007E 02	-.21824E-01	.31948E-03	-.31637E-01	.10857E-01
26	3,160	.12754E 02	-.16766E-01	.17582E-01	-.10067E-02	-.26954E-01
28	3,192	.62894E 01	-.80440E-02	-.17815E-03	-.52971E-02	-.25828E-01
CONSTANT			-.43591E 02	-.51934E 01	-.65809E 01	-.91398E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	25.0	.0	.0	.0	.0
YELLOW-6	96.0	.0	24.0	1.0	.0	.0
GREEN-3	92.0	.0	1.0	23.0	1.0	.0
BLUE-1	88.0	.0	.0	3.0	22.0	.0
TOTAL	94.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	25.0	.0	.0	.0	.0
YELLOW-6	80.0	.0	20.0	5.0	.0	.0
GREEN-3	88.0	.0	2.0	22.0	1.0	.0
BLUE-1	80.0	.0	1.0	4.0	20.0	.0
TOTAL	87.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 1

SAD1 VISUAL EVOKED RESPONSE EXPERIMENT AN. DATE APR 23 .M.BUCK

DATA SET IDENTIFIERS: EXPR = OC41 SUBJ = SAD1 DATE = AP03

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .250

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
3	1,112	.60713E 01	.19237E-01	.14228E-01	.31393E-02	.18950E-01
4	1,128	.80609E 01	.17142E-01	.16852E-01	-.77749E-02	-.85392E-02
5	1,144	.15001E 02	-.39176E-02	-.26977E-01	.12534E-01	-.30907E-02
13	2,112	.76047E 01	.17507E-01	.20835E-01	-.14725E-04	.17550E-01
15	2,144	.13030E 02	.43793E-01	.78391E-02	-.17240E-02	-.12141E-01
16	2,160	.14830E 02	.65495E-02	-.19705E-01	.21624E-01	.49985E-02
20	2,224	.14791E 02	-.31194E-01	-.35081E-02	-.13316E-01	-.19627E-02
28	3,192	.51069E 01	.58222E-02	-.77483E-02	-.71632E-02	-.12741E-01
35	4,144	.6[illegible]33E 01	-.10735E-01	-.10740E-01	.89864E-02	.76888E-02
36	4,160	.91789E 01	-.11350E-01	.54518E-02	-.21538E-01	-.10992E-01
CONSTANT			-.13625[illegible]	-.64923E 01	-.51043E 01	-.47631E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	92.0	23.0	1.0	.0	1.0	.0
YELLOW-6	96.0	.0	24.0	.0	1.0	.0
GREEN-3	80.0	.0	1.0	20.0	4.0	.0
BLUE-1	88.0	.0	1.0	2.0	22.0	.0
TOTAL	89.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	92.0	23.0	1.0	.0	1.0	.0
YELLOW-6	72.0	.0	18.0	2.0	5.0	.0
GREEN-3	80.0	1.0	.0	20.0	4.0	.0
BLUE-1	80.0	1.0	1.0	3.0	20.0	.0
TOTAL	81.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 2

NLM1-AP08-75-0, FOUR COLOR VER EXPERIMENT FOUR CHANNEL WINDOW

DATA SET IDENTIFIERS: EXPR = 0C42 SUBJ = NLM1 DATE = AP08

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .350

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
1	1,080	.43416E 01	.10550E-01	.30920E-01	.23186E-01	.10794E-01
5	1,144	.88905E 01	-.34493E-01	.43656E-02	-.12029E-01	-.14383E-01
6	1,160	.99072E 01	.28597E-01	-.12531E-01	.20589E-01	.17994E-01
10	1,224	.96238E 01	-.50466E-02	-.72074E-02	.10630E-01	.13548E-01
11	2,080	.49451E 02	-.27412E-01	.24808E-01	.24860E-01	.61859E-02
12	2,096	.80484E 01	.23671E-01	.26463E-02	-.18723E-02	.72293E-02
13	2,112	.87733E 01	.14350E-01	.27394E-01	.59300E-02	.78044E-02
16	2,160	.12914E 02	.93548E-02	-.14116E-01	.99606E-02	-.42393E-02
18	2,192	.88219E 01	-.12600E-01	-.22383E-01	-.63388E-02	.22165E-02
29	3,208	.48130E 01	-.85320E-02	-.14185E-01	-.25832E-02	.45144E-02
	CONSTANT		-.13127E 02	-.11178E 02	-.65706E 01	-.49436E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	96.0	24.0	.0	.0	1.0	.0
YELLOW-6	92.0	.0	23.0	2.0	.0	.0
GREEN-3	84.0	.0	1.0	21.0	3.0	.0
BLUE-1	88.0	1.0	.0	2.0	22.0	.0
TOTAL	90.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	88.0	22.0	.0	2.0	1.0	.0
YELLOW-6	80.0	.0	20.0	5.0	.0	.0
GREEN-3	92.0	.0	1.0	23.0	1.0	.0
BLUE-1	76.0	3.0	2.0	1.0	19.0	.0
TOTAL	84.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 3

SAG1 VISUAL EVOKED RESPONSE EXP. SDA RUN DATE AP23 M. BUCK

DATA SET IDENTIFIERS: EXPR = OC45 SUBJ = SAG1 DATE = MR27

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .250

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
7	1,176	.86103E 01	-.28001E-02	-.14366E-01	-.11239E-01	.11127E-01
12	2,096	.16460E 02	-.14104E-01	.15151E-01	.14627E-03	.18067E-02
15	2,144	.25014E 02	.26654E-01	.35758E-01	-.20884E-01	-.12518E-01
19	2,208	.43662E C1	.12186E-01	.19270E-02	.12330E-01	.33797E-02
22	3,096	.55176E 01	.68966E-02	-.55048E-03	.18980E-02	.52340E-02
23	3,112	.78645E 01	.47143E-02	.35094E-02	.78951E-03	.19746E-01
25	3,144	.14439E 02	-.19096E-01	-.95040E-03	.24049E-01	.97532E-02
29	3,208	.14817E 02	.73393E-02	-.14690E-01	.25219E-01	.30497E-01
33	4,112	.18691E 02	.27685E-01	-.95332E-02	-.34436E-02	.33432E-01
38	4,192	.23540E 02	.15437E-01	.19838E-01	.15139E-01	-.28941E-01
	CONSTANT		-.82761E 01	-.52343E 01	-.47336E 01	-.55678E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	92.0	23.0	1.0	.0	1.0	.0
YELLOW-6	92.0	1.0	23.0	1.0	.0	.0
GREEN-3	92.0	.0	.0	23.0	2.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	94.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	80.0	20.0	3.0	.0	2.0	.0
YELLOW-6	84.0	.0	21.0	3.0	1.0	.0
GREEN-3	84.0	.0	3.0	21.0	1.0	.0
BLUE-1	88.0	1.0	2.0	.0	22.0	.0
TOTAL	84.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 4

SOS1-AP15-75-0, OC41 FOUR COLOR VER(4 CHANNELS, 16 MS. WINDOWS)

DATA SET IDENTIFIERS: EXPR = OC41 SUBJ = SOS1 DATE = AP15

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .250

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
1	1,080	.93797E 01	-.44250E-01	.34164E-02	-.10619E-01	-.96752E-02
8	1,192	.11749E 02	.53972E-01	.16460E-01	.25348E-01	.39052E-02
9	1,208	.73737E 01	-.20241E-01	-.87971E-02	-.53085E-02	.10311E-01
11	2,080	.11015E 03	-.24794E 00	-.48541E-01	-.86770E-01	-.80291E-01
12	2,096	.17946E 02	.55192E-01	.37621E-01	.14156E-01	.66411E-02
13	2,112	.17275E 02	-.37892E-02	-.22365E-01	-.31880E-01	.36361E-01
14	2,128	.15400E 02	.86881E-01	.49278E-01	.78447E-01	.22558E-01
21	3,080	.24960E 02	.97531E-01	.15499E-01	.30664E-01	.28126E-01
23	3,112	.26837E 02	-.14136E-01	-.51733E-02	.31911E-01	-.24505E-01
24	3,128	.10844E 02	-.26383E-01	-.17669E-01	-.44846E-01	-.61455E-02
CONSTANT			-.32239E 02	-.59442E 01	-.96742E 01	-.72193E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	25.0	.0	.0	.0	.0
YELLOW-6	88.0	.0	22.0	2.0	1.0	.0
GREEN-3	96.0	.0	.0	24.0	1.0	.0
BLUE-1	96.0	.0	1.0	.0	24.0	.0
TOTAL	95.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-3	92.0	23.0	.0	.0	2.0	.0
YELLOW-6	80.0	1.0	20.0	2.0	2.0	.0
GREEN-3	88.0	1.0	2.0	22.0	.0	.0
BLUE-1	88.0	.0	1.0	2.0	22.0	.0
TOTAL	87.0					

TABLE 5

2) Near optimal trade-off on the number of steps that the SDA program should be allowed to run for the most efficient performance;
3) A near optimal trade-off on the value of too high a threshold causes most of the epochs to be defaulted, while a low value forces some misclassifications where only default would be recorded;
4) The level of performance when the training set is taken from the first half of the data set, and the testing set from the second half;
5) The statistical significance of the obtained classification performance.

In order to select a better subset of variables to be used by SDA, four passes of the program are performed, taking every other variable from the 80 samples which are available from each EEG channel. Ten steps are allowed, thus the ten best samples of the 40 entered from each channel are obtained. These 40 selected variables from all four EEG channels are then entered into a final SDA run, and the results are obtained for each step, from 0 to 20.

Initially, step 0, the average value of each variable chosen is obtained (Table 6). Next (Table 7) is obtained the F level of the variables available to this execution. At step 0, these F levels are related to the probability p(that the relative variances measured could be obtained by chance) with degrees of freedom as shown. A $p < .01$ is obtained with a F of approximately 4. A $p < .001$ corresponds to F=6. Twenty-six variables exceed F=6, and variable 22 (channel 3, 80 msec) has an F of 125. The value of F-to-enter is, nevertheless, set at 2.2 in order to give more variables a chance to be selected. No defaults are allowed. On step One, the program selects the variable with the highest F value (22), and calculates a set of discriminant functions. These are listed in Table 8. A chi square value of 40.48 is obtained for twenty-one reds from the test set correctly classified, where 5.75 would have occurred by chance. This is significant beyond the p=.001 level, as is the eighteen yellows out of

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AVERAGE VALUE OF VARIABLES

VARIABLE INDEX	VARIABLE NAME	GRAND AVERAGE	WITHIN GROUP AVERAGES RED-8	YELLOW-6	GREEN-3	BLUE-1
1	1,032	.52708E 02	.57235E 02	.41520E 02	.59920E 02	.52880E 02
2	1,056	-.12208E 02	-.58286E 02	.96800E 01	.11080E 02	-.18680E 02
3	1,072	-.65312E 02	-.28252E 03	.30680E 02	.26520E 02	-.70680E 02
4	1,104	-.17865E 02	.19810E 02	.54000E 01	-.88840E 02	-.18000E 01
5	1,120	-.11771E 01	.12762E 03	.24440E 02	-.86800E 01	-.12748E 03
6	1,128	.67958E 02	.22171E 03	.67840E 02	.66000E 01	.28000E 00
7	1,136	.13040E 03	.29352E 03	.10252E 03	.80040E 02	.71600E 02
8	1,160	.19045E 03	.28210E 03	.90320E 02	.21964E 03	.18440E 03
9	1,208	.11908E 03	.63667E 02	.11780E 03	.14456E 03	.14144E 03
10	1,272	.21729E 02	.75714E 01	-.24240E 02	.51200E 02	.50120E 02
11	2,072	.10155E 03	.27729E 03	.19880E 02	.61200E 02	.75960E 02
12	2,080	.11258E 03	.27452E 03	.71760E 02	.90320E 02	.39640E 02
13	2,088	.45948E 02	.11529E 03	.86000E 01	.64320E 02	.66800E 01
14	2,104	-.26833E 02	-.51571E 02	-.76400E 01	.17400E 02	-.69480E 02
15	2,120	-.10458E 02	-.11757E 03	-.43200E 02	.31880E 02	.69920E 02
16	2,152	-.74708E 02	-.15590E 03	-.24120E 02	-.81120E 02	-.50680E 02
17	2,168	-.10984E 03	-.15176E 03	-.10948E 03	-.91840E 02	-.93000E 02
18	2,208	-.11269E 03	-.91095E 02	-.12740E 03	-.10652E 03	-.12228E 03
19	2,224	-.12694E 03	-.10752E 03	-.11732E 03	-.12356E 03	-.15624E 03
20	2,280	-.75115E 02	-.52095E 02	-.43840E 02	-.92920E 02	-.10792E 03
21	3,048	.49354E 02	.35857E 02	.37040E 02	.81440E 02	.40920E 02
22	3,080	.21355E 03	.58852E 03	.45680E 02	.16472E 03	.11528E 03
23	3,088	.16671E 03	.30490E 03	.38720E 02	.23232E 03	.11300E 03
24	3,096	.93156E 02	.64000E 02	.88120E 02	.21564E 03	.20000E 00
25	3,120	-.31500E 02	-.18600E 03	-.82280E 02	.20880E 02	.96680E 02
26	3,128	-.45969E 02	-.21748E 03	-.10948E 03	.44760E 02	.70880E 02
27	3,144	-.96229E 02	-.22743E 03	-.51360E 02	-.11076E 03	-.16360E 02
28	3,160	-.88885E 02	-.18362E 03	.14720E 02	-.86840E 02	-.11496E 03
29	3,200	-.10223E 03	-.38286E 02	-.11092E 03	-.63200E 02	-.18628E 03
30	3,312	.10325E 03	.11733E 03	.82360E 02	.14564E 03	.69920E 02
31	4,056	-.21219E 02	.68095E 01	-.57360E 02	-.34360E 02	.45200E 01
32	4,064	-.22302E 02	.14524E 03	-.84200E 02	-.87880E 02	-.35560E 02
33	4,072	.86656E 02	.30590E 03	-.28600E 02	.17560E 02	.86840E 02
34	4,080	.90635E 02	.33838E 03	-.17840E 02	.62960E 02	.18680E 02
35	4,096	-.82667E 02	-.10343E 03	-.13800E 03	.30400E 02	-.12296E 03
36	4,120	-.44302E 02	-.17595E 03	-.10024E 03	-.22240E 02	.10016E 03
37	4,128	-.56094E 02	-.19424E 03	-.91920E 02	.10160E 02	.29520E 02
38	4,136	-.98990E 02	-.29300E 03	-.68600E 02	-.35960E 02	-.29440E 02
39	4,144	-.15218E 03	-.27724E 03	-.76480E 02	-.17828E 03	-.96720E 02
40	4,272	-.85979E 02	-.10305E 03	-.14080E 02	-.11664E 03	-.11288E 03

TABLE 6

STEPWISE DISCRIMINANT ANALYSIS SB01 MR13-75-0

RECURSION = 3 DATA SET IDENTIFIE

NO. OF DATA = 96

F LEVEL TO ENTER = 2.200

F LEVEL OF VARIABLES, D.O.F. = 3.0, 92.0

VARIABLE INDEX	NAME	F LEVEL
1	1,032	.208727
2	1,056	2.437647
3	1,072	60.091398
4	1,104	5.311652
5	1,120	35.878864
6	1,128	34.910474
7	1,136	32.919548
8	1,160	15.202145
9	1,208	4.652525
10	1,272	3.890392
11	2,072	32.601210
12	2,080	36.271406
13	2,088	9.052933
14	2,104	5.458114
15	2,120	30.072571
16	2,152	11.926722
17	2,168	3.014460
18	2,208	.846164
19	2,224	2.300167
20	2,280	2.808844
21	3,048	1.043989
22	3,080	125.667376
23	3,088	33.140087
24	3,096	21.931118
25	3,120	57.440999
26	3,128	58.281712
27	3,144	29.102169
28	3,160	20.508486
29	3,200	16.593696
30	3,312	3.667676
31	4,056	1.633334
32	4,064	18.652152
33	4,072	35.314853
34	4,080	41.152863
35	4,096	11.395302
36	4,120	33.814405
37	4,128	24.171998
38	4,136	28.734916
39	4,144	13.110085
40	4,272	6.076171

TABLE 7

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DISCRIMINANT FUNCTIONS AFTER 1 STEPS, WITH D.O.F. = 3.0, 92.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.12567E 03	.56054E-01	.43508E-02	.15689E-01	.10980E-01
	CONSTANT		-.17881E 02	-.14857E 01	-.26784E 01	-.20192E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	95.2	20.0	.0	1.0	.0	.0
YELLOW-6	68.0	.0	17.0	2.0	6.0	.0
GREEN-3	60.0	1.0	6.0	15.0	3.0	.0
BLUE-1	12.0	.0	9.0	13.0	3.0	.0
TOTAL	57.3					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	91.3	21.0	.0	2.0	.0	.0
YELLOW-6	75.0	.0	18.0	1.0	5.0	.0
GREEN-3	41.7	.0	5.0	10.0	9.0	.0
BLUE-1	24.0	.0	6.0	13.0	6.0	.0
TOTAL	57.3					

TABLE 8

twenty-four. Green classification fails to achieve significant accuracy, as does blue, with only one variable selected.

It can be seen how the DF operates: The average value of variable 22 is larger for red than for any other color, and smallest for yellow. The coefficient for the red DF is also larger than the coefficient for any other group, and the yellow coefficient is the smallest. As shown in Section 4, the coefficients in the decision rule covary with the average values. (They would coincide if the variables were independent and of variance One). The coefficients are used to calculate the a posteriori probabilities of belonging to each group for each epoch tested. The decision goes to the group that gets the maximum probability, providing it exceeds the given default threshold.

On step 2, variable 26 (channel 3, 128 msec) enters with an F of 41.8, and the F level for variable 22 drops from 125.7 to 96.5. Overall performance rises from 57.3% to 75% on the testing set (Table 9). Now both red and yellow epochs are being correctly classified virtually every time.

Steps 3, 4, 5 and 6 add more variables from channel 3. (See Tables 10,11 12 and 13). Performance improves to 94% correct. When, on step 7 (Table 14) a variable from channel 1, 120 msec is added, the F levels of the prior variables are seen to drop; the largest drop occurs in variable 26, channel 3 at 128 msec, demonstrating a correlation between these variables, larger at the closest latency. The classification performance at step 7 does not change from step 6.

Step 8 (Table 15) adds another variable from channel 3, 312 msec, and the performance improves to 95.8%. At the ninth step (Table 16), a variable from channel 2 is added, and performance rises to 97.9% correctly classified from the testing set and 99% from the training set, a remarkable set of figures indeed. This performance is not improved by adding the tenth variable (Table 17), and the eleventh (Table 18). Instead, improving the training set classification accuracy to 100% results in a

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DISCRIMINANT FUNCTIONS AFTER 2 STEPS, WITH D.O.F. = 3.0, 91.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.96483E 02	.60849E-01	.62694E-02	.15267E-01	.10024E-01
26	3,128	.41821E 02	-.40494E-01	-.16201E-01	.35609E-02	.80698E-02
	CONSTANT		-.23695E 02	-.24163E 01	-.27234E 01	-.22501E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	95.2	20.0	1.0	.0	.0	.0
YELLOW-6	84.0	.0	21.0	2.0	2.0	.0
GREEN-3	52.0	1.0	3.0	13.0	8.0	.0
BLUE-1	60.0	.0	4.0	6.0	15.0	.0
TOTAL	71.9					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	45.8	.0	8.0	11.0	5.0	.0
BLUE-1	56.0	.0	1.0	10.0	14.0	.0
TOTAL	75.0					

TABLE 9

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DISCRIMINANT FUNCTIONS AFTER 3 STEPS, WITH D.O.F. = 3.0, 90.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.10385E 03	.61476E-01	.16188E-02	.92625E-02	.12373E-01
24	3,096	.30678E 02	-.22431E-02	.16648E-01	.21495E-01	-.84082E-02
26	3,128	.44410E 02	-.39623E-01	-.22671E-01	-.47924E-02	.11337E-01
CONSTANT			-.23713E 02	-.33978E 01	-.43595E 01	-.25004E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	80.0	.0	20.0	2.0	3.0	.0
GREEN-3	80.0	1.0	3.0	20.0	1.0	.0
BLUE-1	84.0	.0	1.0	3.0	21.0	.0
TOTAL	85.4					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	91.7	.0	22.0	1.0	1.0	.0
GREEN-3	58.3	.0	8.0	14.0	2.0	.0
BLUE-1	84.0	.0	.0	4.0	21.0	.0
TOTAL	83.3					

TABLE 10

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 4 STEPS, WITH D.O.F. = 3.0, 89.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.94263E 02	.68213E-01	-.36110E-03	.12802E-01	.17778E-01
24	3,096	.30040E 02	-.67093E-02	.17961E-01	.19148E-01	-.11992E-01
26	3,128	.55391E 02	-.26383E-01	-.26561E-01	.21632E-02	.21960E-01
28	3,160	.20700E 02	-.33134E-01	.97371E-02	-.17408E-01	-.26585E-01
	CONSTANT		-.27155E 02	-.36950E 01	-.53095E 01	-.47162E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	96.0	.0	24.0	1.0	.0	.0
GREEN-3	88.0	1.0	1.0	22.0	1.0	.0
BLUE-1	84.0	.0	1.0	3.0	21.0	.0
TOTAL	91.7					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	91.7	.0	22.0	1.0	1.0	.0
GREEN-3	75.0	.0	2.0	18.0	4.0	.0
BLUE-1	76.0	.0	1.0	5.0	19.0	.0
TOTAL	85.4					

TABLE 11

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 5 STEPS, WITH D.O.F. = 3.0, 88.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.88818E 02	.67318E-01	-.10052E-02	.87464E-02	.17771E-01
24	3,096	.32299E 02	-.53605E-02	.13931E-01	.25260E-01	-.11980E-01
26	3,128	.42623E 02	-.23122E-01	-.24214E-01	.16941E-01	.21989E-01
27	3,144	.12173E 02	-.77653E-02	-.55879E-02	-.35183E-01	-.68831E-04
28	3,160	.16388E 02	-.30930E-01	.11323E-01	-.74196E-02	-.26565E-01
	CONSTANT		-.27261E 02	-.37498E 01	-.74798E 01	-.47162E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	96.0	.0	24.0	.0	1.0	.0
GREEN-3	88.0	.0	2.0	22.0	1.0	.0
BLUE-1	88.0	.0	1.0	2.0	22.0	.0
TOTAL	92.7					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	91.7	.0	22.0	1.0	1.0	.0
GREEN-3	91.7	.0	1.0	22.0	1.0	.0
BLUE-1	88.0	.0	1.0	2.0	22.0	.0
TOTAL	92.7					

TABLE 12

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 6 STEPS, WITH D.O.F. = 3.0, 87.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
22	3,080	.39326E 02	.65567E-01	.42229E-02	.33159E-02	.85445E-02
23	3,088	.87942E 01	.47698E-02	-.14242E-01	.14793E-01	.25133E-01
24	3,096	.32473E 02	-.81454E-02	.27247E-01	.16622E-01	-.26654E-01
26	3,128	.41021E 02	-.22086E-01	-.27307E-01	.20154E-01	.27447E-01
27	3,144	.11440E 02	-.73491E-02	-.68306E-02	-.33892E-01	.21241E-02
28	3,160	.18305E 02	-.31862E-01	.14107E-01	-.10311E-01	-.31477E-01
	CONSTANT		-.27309E 02	-.41815E 01	-.79457E 01	-.60608E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	88.0	.0	2.0	22.0	1.0	.0
BLUE-1	92.0	.0	.0	2.0	23.0	.0
TOTAL	94.8					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	87.5	.0	2.0	21.0	1.0	.0
BLUE-1	92.0	.0	.0	2.0	23.0	.0
TOTAL	94.8					

TABLE 13

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 7 STEPS, WITH D.O.F. = 3.0, 86.0

EPOCHS ACCEPTED UNCONDITIONALLY.

INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
			GROUP NAMES			
5	1,120	.68703E 01	.23513E-01	.10709E-02	.66815E-02	-.14153E-01
22	3,080	.38661E 02	.68121E-01	.43392E-02	.40416E-02	.70074E-02
23	3,038	.88267E 01	.29832E-02	-.14324E-01	.14286E-01	.26208E-01
24	3,096	.32076E 02	-.48344E-02	.27397E-01	.17563E-01	-.28646E-01
26	3,128	.29752E 02	-.16503E-01	-.27053E-01	.21740E-01	.24087E-01
27	3,144	.94587E 01	-.57008E-02	-.67555E-02	-.33424E-01	.11320E-02
28	3,160	.16161E 02	-.36215E-01	.13909E-01	-.11548E-01	-.28857E-01
	CONSTANT		-.29000E 02	-.41850E 01	-.80822E 01	-.66733E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	88.0	.0	2.0	22.0	1.0	.0
BLUE-1	92.0	.0	.0	2.0	23.0	.0
TOTAL	94.8					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	87.5	.0	2.0	21.0	1.0	.0
BLUE-1	92.0	.0	.0	2.0	23.0	.0
TOTAL	94.8					

TABLE 14

SBOI MR13 75

DISCRIMINANT FUNCTIONS AFTER 8 STEPS, WITH D.O.F. = 3.0, 85.0

EPOCHS ACCEPTED UNCONDITIONALLY.

INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
5	1,120	.10114E 02	.37265E-01	.82763E-02	.17187E-01	-.13379E-01
22	3,080	.36839E 02	.69756E-01	.51961E-02	.52910E-02	.70994E-02
23	3,088	.88849E 01	-.59778E-03	-.16200E-01	.11550E-01	.26007E-01
24	3,096	.31781E 02	.36688E-02	.31853E-01	.24059E-01	-.28168E-01
26	3,128	.29782E 02	-.21588E-01	-.29717E-01	.17856E-01	.23801E-01
27	3,144	.12024E 02	-.21679E-01	-.15127E-01	-.45630E-01	.23322E-03
28	3,160	.16129E 02	-.33384E-01	.15392E-01	-.93850E-02	-.28698E-01
30	3,312	.89915E 01	.43453E-01	.22767E-01	.33196E-01	.24443E-02
	CONSTANT		-.34744E 02	-.57619E 01	-.11435E 02	-.66915E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	92.0	.0	1.0	23.0	1.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	97.9					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	91.7	.0	2.0	22.0	.0	.0
BLUE-1	92.0	.0	.0	2.0	23.0	.0
TOTAL	95.8					

TABLE 15

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 9 STEPS, WITH D.O.F. = 3.0, 84.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
5	1,120	.14056E 02	.36168E-01	-.17229E-02	.21501E-01	-.22295E-01
17	2,168	.67994E 01	-.26443E-02	-.24084E-01	.10389E-01	-.21474E-01
22	3,080	.36244E 02	.69960E-01	.70506E-02	.44910E-02	.87529E-02
23	3,088	.92126E 01	-.87469E-03	-.18722E-01	.12638E-01	.23758E-01
24	3,096	.32157E 02	.33840E-02	.29258E-01	.25178E-01	-.30481E-01
26	3,128	.32951E 02	-.22267E-01	-.35905E-01	.20524E-01	.18284E-01
27	3,144	.16441E 02	-.20666E-01	-.59022E-02	-.49609E-01	.84587E-02
28	3,160	.16506E 02	-.32726E-01	.21384E-01	-.11970E-01	-.23355E-01
30	3,312	.10387E 02	.4303[illegible]E-01	.18940E-01	.34847E-01	-.96818E-03
	CONSTANT		-.34757E 02	-.68256E 01	-.11633E 02	-.75372E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	96.0	1.0	.0	24.0	.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	99.0					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	95.8	.0	.0	23.0	1.0	.0
BLUE-1	96.0	.0	.0	1.0	24.0	.0
TOTAL	97.9					

TABLE 16

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 83.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
5	1,120	.15454E 02	.45679E-01	-.33304E-02	.22496E-01	-.22831E-01
17	2,168	.73413E 01	.66230E-02	-.25650E-01	.11358E-01	-.21997E-01
22	3,080	.24293E 02	.69380E-01	.71485E-02	.44304E-02	.87856E-02
23	3,088	.90532E 01	-.18008E-02	-.18565E-01	.12541E-01	.23810E-01
24	3,096	.32040E 02	-.14638E-03	.29855E-01	.24809E-01	-.30282E-01
26	3,128	.32252E 02	-.19896E-01	-.36305E-01	.20773E-01	.18151E-01
27	3,144	.16365E 02	-.23907E-01	-.53544E-02	-.49949E-01	.86414E-02
28	3,160	.17234E 02	-.39759E-01	.22573E-01	-.12706E-01	-.22959E-01
30	3,312	.99191E 01	.44459E-01	.18699E-01	.34996E-01	-.10486E-02
34	4,080	.64437E 01	.28637E-01	-.48399E-02	.29973E-02	-.16142E-02
	CONSTANT		-.39921E 02	-.69731E 01	-.11689E 02	-.75536E 01

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	96.0	.0	.0	24.0	1.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	99.0					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	95.8	.0	.0	23.0	1.0	.0
BLUE-1	96.0	.0	.0	1.0	24.0	.0
TOTAL	97.9					

TABLE 17

SB01 MR13 75

DISCRIMINANT FUNCTIONS AFTER 11 STEPS, WITH D.O.F. = 3.0, 82.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
5	1,120	.15921E 02	.47269E-01	-.87243E-02	.18621E-01	-.28437E-01
17	2,168	.80000E 01	.88284E-02	-.33132E-01	.59837E-02	-.29772E-01
22	3,080	.15741E 02	.68256E-01	.10962E-01	.71700E-02	.12749E-01
23	3,088	.80683E 01	.20050E-02	-.31477E-01	.32654E-02	.10392E-01
24	3,096	.23023E 02	-.60569E-02	.49907E-01	.39214E-01	-.94437E-02
26	3,128	.31750E 02	-.21818E-01	-.29785E-01	.25457E-01	.24927E-01
27	3,144	.14195E 02	-.21362E-01	-.13988E-01	-.56151E-01	-.33116E-03
28	3,160	.19261E 02	-.44163E-01	.37513E-01	-.19730E-02	-.74320E-02
29	3,200	.44833E 01	.12450E-01	-.42238E-01	-.30343E-01	-.43896E-01
30	3,312	.97576E 01	.45101E-01	.16523E-01	.33433E-01	-.33103E-02
34	4,080	.70974E 01	.29648E-01	-.82699E-02	.53323E-03	-.51788E-02
	CONSTANT		-.40210E 02	-.10296E 02	-.13404E 02	-.11142E 02

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	100.0	.0	.0	25.0	.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	100.0					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
		CLASSIFIED AS				
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	95.8	.0	23.0	1.0	.0	.0
GREEN-3	91.7	.0	1.0	22.0	1.0	.0
BLUE-1	96.0	.0	.0	1.0	24.0	.0
TOTAL	95.8					

TABLE 18

slight drop of the testing set classification performance (to 95.8%), a sure sign that the last improvement was idiosyncratic. Further steps add no more to the performance, step 20 giving the same results as step 11 (Table 19). The chi square values for the tenth step testing confusion matrix give a $p < .001$ that such results could be obtained by chance.

It was concluded tentatively at least, that no more than ten steps should be needed for highly accurate single evoked response classification under the present experimental conditions, a value that is consistent with evidence from other quarters (e.g. previous function analysis studies).

If the cost of an error is higher than that of non-classification, then those epochs which do not have a very high probability of belonging to one of the source groups can be defaulted, through use of the a posteriori decision threshold parameter. For instance, when this parameter is set to .999, no classification errors are made (Table 20) for subject SB01, but the price for 100% classification accuracy is a 23% default rate. If the training set is taken as the first 96 epochs, and the testing set the next 96 epochs, the performance drops only slightly, to 95.8% correct (Table 21). Here again, 100% classification accuracy is achieved by setting the decision threshold to .998 and 34% of the epochs are then defaulted (Table 22). Subsequent tests, using the mutual information measure defined in Section 4, indicated that an optimal trade-off value of the threshold parameter was to be found between .4 and .6.

DISCRIMINANT FUNCTIONS AFTER 20 STEPS, WITH D.O.F. = 3.0, 75.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
3	1,072	.59844E 01	-.38494E-01	-.52875E-02	.19257E-01	-.84256E-02
4	1,104	.24537E 01	.51816E-02	-.95258E-02	-.59620E-02	.17444E-01
5	1,120	.13614E 02	.98540E-02	-.72300E-02	.31254E-01	-.52919E-01
8	1,160	.47649E 01	.21151E-01	.11382E-02	.35293E-01	.36391E-01
17	2,168	.13643E 02	.52865E-02	-.34000E-01	.52725E-01	-.47900E-02
21	3,048	.68150E 01	-.30542E-01	.64985E-02	.23373E-01	-.38798E-02
22	3,080	.15260E 02	.64948E-01	-.11391E-01	.10172E-01	.18200E-01
24	3,096	.15897E 02	.70989E-03	.48997E-01	.59321E-01	-.94827E-03
25	3,120	.32413E 01	-.76366E-02	-.24289E-01	-.21061E-01	.14022E-01
26	3,128	.16639E 02	-.26531E-01	-.31073E-01	.53155E-01	.26891E-01
27	3,144	.24722E 01	-.40969E-01	-.77780E-02	-.45026E-01	-.12419E-01
28	3,160	.64528E 01	-.26095E-01	.30961E-01	-.14987E-01	.31132E-04
29	3,200	.61716E 01	.16379E-01	-.29223E-01	-.47588E-01	-.53005E-01
30	3,312	.75488E 01	.40851E-01	.21333E-01	.36147E-01	-.76138E-02
34	4,080	.42109E 01	.31763E-01	-.62084E-02	.79515E-02	-.39757E-03
35	4,096	.50488E 01	-.17324E-01	-.31580E-01	.16780E-03	.29173E-03
38	4,136	.11308E 02	-.10231E-01	.82287E-03	.45222E-01	.42973E-02
39	4,144	.95264E 01	-.20195E-02	.95057E-02	-.42158E-01	-.13082E-01
	CONSTANT		-.49454E 02	-.12592E 02	-.22859E 02	-.16538E 02

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	25.0	.0	.0	.0
GREEN-3	100.0	.0	.0	25.0	.0	.0
BLUE-1	100.0	.0	.0	.0	25.0	.0
TOTAL	100.0					

TESTING CONFUSION MATRIX IEPT = 5 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	95.8	.0	23.0	.0	1.0	.0
GREEN-3	91.7	.0	1.0	22.0	1.0	.0
BLUE-1	96.0	.0	.0	1.0	24.0	.0
TOTAL	95.8					

TABLE 19

COMPLETED 20 STEPS OF ANALYSIS

SB01 MR13 75 FOUR COLOR VEP EXPR.   A POSTERIORI DECISION THRESHOLD .999

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 83.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
5	1,120	.15454E 02	.45679E-01	-.33304E-02	.22496E-01	-.22831E-01
17	2,168	.73413E 01	.66230E-02	-.25650E-01	.11358E-01	-.21997E-01
22	3,080	.24293E 02	.69380E-01	.71485E-02	.44304E-02	.87856E-02
23	3,088	.90532E 01	-.18008E-02	-.18565E-01	.12541E-01	.23810E-01
24	3,096	.32040E 02	-.14638E-03	.29855E-01	.24809E-01	-.30282E-01
26	3,128	.32252E 02	-.19896E-01	-.36305E-01	.20773E-01	.18151E-01
27	3,144	.16365E 02	-.23907E-01	-.53544E-02	-.49949E-01	.86414E-02
28	3,160	.17234E 02	-.39759E-01	.22573E-01	-.12706E-01	-.22959E-01
30	3,312	.99191E 01	.44459E-01	.18699E-01	.34996E-01	-.10486E-02
34	4,080	.64437E 01	.28637E-01	-.48399E-02	.29973E-02	-.16142E-02
	CONSTANT		-.39921E 02	-.69731E 01	-.11689E 02	-.75536E 01

TRAINING CONFUSION MATRIX   IEPA = 4   NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	21.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	19.0	.0	.0	6.0
GREEN-3	100.0	.0	.0	15.0	.0	10.0
BLUE-1	100.0	.0	.0	.0	19.0	6.0
TOTAL	100.0					

TESTING CONFUSION MATRIX   IEPT = 5   NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	23.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	20.0	.0	.0	4.0
GREEN-3	100.0	.0	.0	13.0	.0	11.0
BLUE-1	100.0	.0	.0	.0	18.0	7.0
TOTAL	100.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 20

SB01 MR13 4 COLOR VEP EXP. FIRST HALF VS. SECOND HALF . AP 25, M. BUCK

DATA SET IDENTIFIERS: EXPR = 0C41

NO. OF VARIABLES = 40 WGT. D.O.F. = 96.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .250

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 83.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	RED-8	YELLOW-6	GREEN-3	BLUE-1
3	1,072	.10081E 02	-.59918E-01	-.16802E-02	.40974E-02	-.13594E-01
4	1,104	.92262E 01	.33689E-01	-.21239E-02	-.13910E-01	.24566E-01
5	1,120	.15242E 02	-.20966E-01	.76328E-03	.45309E-02	-.55014E-01
6	1,128	.94567E 01	.90918E-01	.15685E-01	.10962E-01	.32760E-01
22	3,080	.20124E 02	.94046E-01	.12470E-01	.16920E-01	.23643E-01
23	3,088	.56605E 01	.16924E-01	-.89115E-02	.16344E-01	.19173E-01
24	3,096	.87529E 01	.55347E-02	.18783E-01	.96249E-02	-.19711E-01
25	3,120	.19753E 02	-.33593E-01	-.21081E-01	-.78049E-02	.23433E-01
28	3,160	.15540E 02	-.58320E-01	.14162E-02	-.25766E-01	-.31667E-01
40	4,272	.46445E 01	-.17030E-02	.56732E-02	-.11727E-01	-.14957E-01
CONSTANT			-.54822E 02	-.39615E 01	-.81830E 01	-.11918E 02

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	18.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	24.0	.0	.0	.0
GREEN-3	91.3	.0	2.0	21.0	.0	.0
BLUE-1	100.0	.0	.0	.0	31.0	.0
TOTAL	97.9					

TESTING CONFUSION MATRIX IEPT = 97 NEPI = 96

SOURCE	PERCENT CORRECT	RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	24.0	.0	.0	.0	.0
YELLOW-6	96.0	.0	24.0	1.0	.0	.0
GREEN-3	96.2	.0	.0	25.0	1.0	.0
BLUE-1	90.5	.0	.0	2.0	19.0	.0
TOTAL	95.8					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 21

S381 MR13 4 COLOR VEP EXP. FIRST HALF VS. SECOND HALF . AP 25, M. BUCK

DATA SET IDENTIFIERS: EXPR = 0C41

NO. OF VARIABLES = 40 WGT. D.O.F. = 96.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .997

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 83.0

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES RED-8	YELLOW-6	GREEN-3	BLUE-1
3	1,072	.10081E 02	-.59918E-01	-.16802E-02	.40974E-02	-.13594E-01
4	1,104	.92262E 01	.33689E-01	-.21239E-02	-.13910E-01	.24566E-01
5	1,120	.15242E 02	-.20966E-01	.76328E-03	.45309E-02	-.55014E-01
6	1,128	.94567E 01	.90918E-01	.15685E-01	.10962E-01	.32760E-01
22	3,080	.20124E 02	.94046E-01	.12470E-01	.16920E-01	.23643E-01
23	3,088	.56605E 01	.16924E-01	-.89115E-02	.16344E-01	.19173E-01
24	3,096	.87529E 01	.55347E-02	.18783E-01	.96249E-02	-.19711E-01
25	3,120	.19753E 02	-.33593E-01	-.21081E-01	-.78049E-02	.23433E-01
28	3,160	.15540E 02	-.58320E-01	.14162E-02	-.25766E-01	-.31667E-01
40	4,272	.46445E 01	-.17030E-02	.56732E-02	-.11727E-01	-.14957E-01
	CONSTANT		-.54822E 02	-.39615E 01	-.81830E 01	-.11918E 02

TRAINING CONFUSION MATRIX IEPA = 4 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	18.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	14.0	.0	.0	10.0
GREEN-3	100.0	.0	.0	13.0	.0	10.0
BLUE-1	100.0	.0	.0	.0	25.0	6.0
TOTAL	100.0					

TESTING CONFUSION MATRIX IEPT = 97 NEPI = 96

SOURCE	PERCENT CORRECT	CLASSIFIED AS RED-8	YELLOW-6	GREEN-3	BLUE-1	DEFAULT
RED-8	100.0	24.0	.0	.0	.0	.0
YELLOW-6	100.0	.0	12.0	.0	.0	13.0
GREEN-3	100.0	.0	.0	11.0	.0	15.0
BLUE-1	100.0	.0	.0	.0	16.0	5.0
TOTAL	100.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 22

3.2 Pattern Position Experiments

Purpose

The color stimuli used in the first experiment were always selected by the computer. The pattern-position experiment was designed to allow stimulus selection either by computer, for a training series, or by the subject, for use in controlling a separate "application program" once the computer has established a set of discriminant functions using BCI/SDA.

Methods

The methods of EEG data collection are identical to those described in the color Experiment. The only difference is in the stimulus arrangement. A brief flash trans-illuminates a checkerboard pattern, 1 3/4" square, at a pupil/display plane distance of 46", thus subtending a 2.2^{o} visual angle. The individual checks subtended a 12' visual angle. Four solid state diode lamps (LED's) are positioned at the top, bottom, left and right edges of the checkerboard, 1 cm in front of the checkerboard. The checksize, and checkerboard size were chosen following C.T. White (1968) in order to produce large evoked responses at the scalp. A red filter was used behind the checkerboard to benefit from the previously observed better consistency of red responses, and a blue-green background was continually on, to further enhance retinal red response; the background was superimposed on a large area over the checkerboard. The implementation of the present experiment is open loop. For each run, 200 epochs are taken, with the computer randomly selecting one of the four fixation lights for presentation on each trial. The subject is instructed to fixate steadily on the light selected until one second after the flash. Thus the proximal stimulus occupies one of four partly overlapping retinal positions on each trial.

Analysis

The data were analyzed by stepwise discriminant analysis exactly as in the Color Experiment. One half of the epochs were taken for a training set, and the other 100 epochs were then classified using the DF obtained on the training set. A general four channel, 16 msec interval variable selection paradigm was again used.

Results

As in the Color Experiment, evaluation of performance is based on the percent of correct classification of epochs from the testing set, with no defaults.

Subject-Date	EXPR	Performance
NLM1-AP08-75	CB41	74%
MHDI AP15-75	CB41	63%
ATW1 AP17-75	CB41	86%

(Detailed results from subject ATW are shown in Table 23)

Table 24 shows the performance obtained when the a posteriori decision threshold is raised to .900. A classification accuracy of 92% is achieved, with 25% defaults. This performance, while not yet equal to that obtained for color stimuil, is quite good, and can doubtlessly be substantially improved.

Discussion

Regan (1973) has speculated that the use of large (14^0 diameter) stimuli, rather than foveal stimuli, would produce less intersubject variation in evoked responses obtained from stimuli of varying retinal position. Therefore, it is intended to repeat the Pattern Position Experiment with a larger checkerboard, in order to find the most efficient stimulus for the purpose of on-line evoked response classification. Other improvements

ATW1-AP17-75-0, PATTERN-POSITION EXP. 4 CHANNEL GEN,L WINDOW,16 MSEC.

DATA SET IDENTIFIERS: EXPR = CB41 SUBJ = ATW1 DATE = AP17

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .250

DISCRIMINANT FUNCTIONS AFTER 10 STEPS, WITH D.O.F. = 3.0, 87.C

EPOCHS ACCEPTED UNCONDITIONALLY.

VARIABLE INDEX	VARIABLE NAME	F LEVEL	GROUP NAMES UP	DOWN	LEFT	RIGHT
3	Ch 1,112 ms	.73779E 01	.25088E-01	-.13389E-01	.22914E-02	.10933E-01
4	1,128	.12931E 02	-.15063E-01	.33287E-01	.44236E-02	.13028E-01
5	1,144	.30526E 02	-.43069E-01	.20345E-01	-.30284E-01	.97073E-02
8	1,192	.10088E 02	.29214E-01	.75250E-02	.31654E-01	-.67744E-02
15	2,144	.12338E 02	.25155E-01	-.28995E-02	.44400E-02	.20406E-01
23	3,112	.11439E 02	.13641E-01	-.29091E-01	-.20995E-02	-.45336E-02
25	3,144	.53536E 02	.34319E-01	-.28860E-01	.23870E-01	-.20345E-01
27	3,176	.10428E 02	-.93601E-02	.29590E-01	.11591E-01	.52092E-03
28	3,192	.14191E 02	-.19368E-01	-.11372E-01	-.31993E-01	.84467E-02
39	4,208	.69586E 01	-.17077E-01	.51192E-03	-.15295E-02	-.17353E-01
CONSTANT			-.95687E 01	-.86774E 01	-.47035E 01	-.62407E 01

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS UP	DOWN	LEFT	RIGHT	DEFAULT
UP	100.0	25.0	.0	.0	.0	.0
DOWN	92.0	.0	23.0	1.0	1.0	.0
LEFT	92.0	1.0	1.0	23.0	.0	.0
RIGHT	100.0	.0	.0	.0	25.0	.0
TOTAL	96.0					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS UP	DOWN	LEFT	RIGHT	DEFAULT
UP	72.0	18.0	1.0	5.0	1.0	.0
DOWN	92.0	.0	23.0	.0	2.0	.0
LEFT	92.0	.0	2.0	23.0	.0	.0
RIGHT	88.0	2.0	1.0	.0	22.0	.0
TOTAL	86.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 23

ATW1-AP17-75-0, PATTERN-POSITION EXP. 4 CHANNEL GEN,L WINDOW,16 MSEC.

DATA SET IDENTIFIERS: EXPR = CB41 SUBJ = ATW1 DATE = AP17

NO. OF VARIABLES = 40 WGT. D.O.F. = 100.00

F LEVEL TO REMOVE = 2.200 POSTERIORI THRESHOLD = .900

TRAINING CONFUSION MATRIX IEPA = 1 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS UP	DOWN	LEFT	RIGHT	DEFAULT
UP	100.0	22.0	.0	.0	.0	3.0
DOWN	100.0	.0	22.0	.0	.0	3.0
LEFT	95.2	.0	1.0	20.0	.0	4.0
RIGHT	100.0	.0	.0	.0	21.0	4.0
TOTAL	98.8					

TESTING CONFUSION MATRIX IEPT = 2 NEPI = 100

SOURCE	PERCENT CORRECT	CLASSIFIED AS UP	DOWN	LEFT	RIGHT	DEFAULT
UP	73.7	14.0	.0	4.0	1.0	6.0
DOWN	100.0	.0	22.0	.0	.0	3.0
LEFT	100.0	.0	.0	15.0	.0	10.0
RIGHT	94.7	.0	1.0	.0	18.0	6.0
TOTAL	92.0					

COMPLETED 10 STEPS OF ANALYSIS

TABLE 24

of the target are possible, in particular the use of a diamond shape which will eliminate retinal overlap between positions. It is also expected that the orthogonal transformation of the multi-channel data, which did not perform well with color, should be of advantage in this series because of the spatial dependence. Finally this procedure is about to be performed on-line using a graphic program to provide subject feedback. Spectacular improvement in reliability is expected in this case because of the operant conditioning inherent to the procedure.

4. THEORETICAL CONSIDERATIONS

4.1 Stepwise Discrimination and the Decision Rule

Consider the discrimination of a training set consisting of M epochs, represented by N time samples. The initial data set thus consists of M N-vectors:

$$X = \{X_m\} = \{x^j_{mn}\} \qquad m = 1, 2 \ldots M \; ; \quad n = 1, 2 \ldots N$$

Where j = (1,2...J) is an index that designates the training groups. There are J such groups (the "input alphabet") in the training set; M_j is the number of epochs in group j and obviously;

$$\sum_j M_j = M$$

The mean for groups i and j will be represented by the vectors;

$$\bar{X}^i = \{\bar{x}^i_n\} \quad ; \quad \bar{X}^j = \{\bar{x}^j_n\}$$

(n can be replaced by k)

The classification is conducted in two sections. First a step-wise discriminant procedure selects K samples, from the original N, that have optimal discrimination properties. There is no loss of generalities in placing these samples at the beginning;

$$X = \{x^j_{mn}\}$$

with m = 1,2...K. The training set is thus now reduced to M K-vectors;

Second, a discriminant function g(X) is obtained for each group. The function is a measure of the posteriori probability $p(j|X_m)$ that a given epoch X_m belong to group j given X_m. Thus if

$$g_j(X_m) > g_i(X_m)$$

for all $i \neq j$; then this epoch would have to be [illegible]red in group j according to the posteriori probabilities. Discriminant functions are actually obtained from the training set, which instead, provides the probability $p(X_m, j)$ of occurrence of a given observed epoch X_m which is known to belong to group j; then:

$$g_j(X_m) = p(X_m, j)\,p(j) \tag{1}$$

Specifically a logarithmic form is calculated which leads to different numerical values for the function g but has the same properties:

$$g_j(X_m) = \log p(X_m, j) + \log p(j) \tag{2}$$

which, assuming normal distributions with different means but equal variance (for each group) takes the form:

$$g_j(X_m) = -\frac{1}{2} D_j^2(X_m) + \log p(j)$$

D^2 is the squared Mahalanobis distance. For an epoch X_m, this distance to the mean for group j is given by;

$$D_j^2(X_m) = (M-J)\sum_n \sum_k (x_{mn} - \bar{x}_n^j)\, a_{nk}\, (x_{mk} - \bar{x}_k^j)$$
$$n = 1, 2 \ldots K \quad ; \quad k = 1, 2 \ldots K \tag{3}$$

a_{nk} is derived from the original within group cross-product matrix;

$$W = \begin{vmatrix} W_{11} & W_{12} \\ W_{21} & W_{22} \end{vmatrix} \tag{4}$$

W is first partitioned; the contributions of the K selected first samples are vested in W_{11}; and W_{11} is inverted yielding;

$$A = |W_{11}|^{-1} = \{a_{nk}\} \tag{5}$$

with n,k = 1,2...K

A confusion matrix can then be established that shows the number of epochs M_{ji} that came from group j and whose posterior probability was larger for group i.

In the testing phase the discriminant functions $g_j(x)$ are evaluated for j = 1,2...J, on-line, in real-time for each incoming epoch x and classified accordingly. The posteriori probabilities of belonging to each group are also calculated;

$$p(j|x) = \frac{p(j)\,\mathrm{Exp}\left[D_j^2(x)\right]}{\sum_{i=1}^{J} p(i)\,\mathrm{Exp}\left[D_i^2(x)\right]} \tag{6}$$

4.2 The Mutual Information Transfer

Let $A = \{a_1, \ldots a_J\}$ be the input alphabet (e.g. the set of color labels for the stimulus flashes). The a-priori entropy of the alphabet is given by:

$$H(A) = \sum_j p(a_j) \log_2 \frac{1}{p(a_j)} \qquad j = 1,2 \ldots J \tag{7}$$

Let $B = (b_1 \ldots b_J, b_{J+1})$ be the output alphabet (e.g. the set of classes established by a corresponding set of decision functions over the EEG measures (the recorded evoked responses). The decision functions map A into B, where b_j corresponds to a_j for each j=1..J and where b_{J+1} represents an additional default class.

Next, one defines:

$$H(A|b_i) = \sum_j p(a_j|b_j) \log_2 \frac{1}{p(a_j|b_i)} \tag{8}$$

as the a posteriori entropy of the input alphabet given the event b_i. The sum over all b's gives the "equivocation" of A with B:

$$H(A|B) = \sum_i p(b_i) H(A|b_i) \tag{9}$$

$H(A|B) = 0$ for a completely deterministic mapping ($A \rightarrow B$); reciprocally $H(A|B) = H(A)$ if the mapping is completely random, i.e. is B is independent of A.

From there the mutual information I(A,B) between the two alphabets or sets of events is defined as:

$$I(A,B) = H(A) - H(A|B)$$

I is non-negative and varies between zero (independence) and H(A). H(A) has an upper bound, which therefore, also holds for I(A,B);

$$\max H(A) = \log_2 N \text{ bits}$$

reached when;

$$p(a_j) = \frac{1}{N} \quad ; \quad j = 1, 2 \ldots J \tag{10}$$

Thus, the mutual information provides a single number that characterizes the performance of the channel (i.e. of the experimental paradigm) that can be directly compared to the number of bits embodied in the input channel (i.e. H(A) = 2 for a four color experiment).

It can be shown that mutual information is reciprocal I(A,B) = I(B,A). I(A,B) can also be expressed in terms of the <u>conditional mutual information</u> $I(a_j,B)$ defined for each a_j such that;

$$I(A,B) = \sum_j p(a_j) I(a_j, B) \tag{11}$$

with

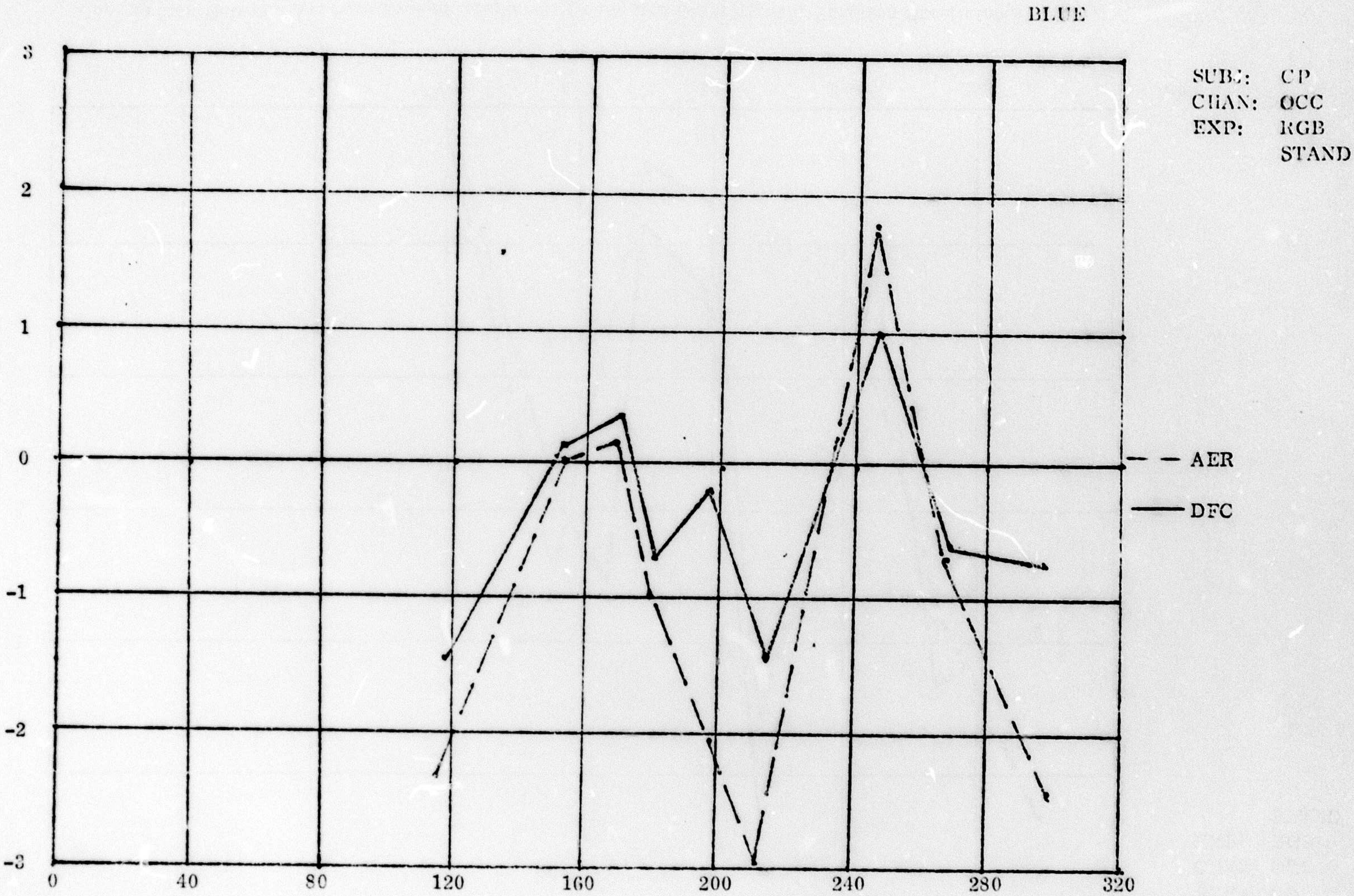
$$I(a_j, B) = \sum_i p(b_i|a_j) \log_2 \left[\frac{p(b_i|a_j)}{\sum_j p(b_i|a_j) p(a_j)} \right] \tag{12}$$

This expression is practical because it can be estimated directly (row by row) since $\tilde{p}(b_i| a_j)$ figures in the confusion matrix generated by each experiment.

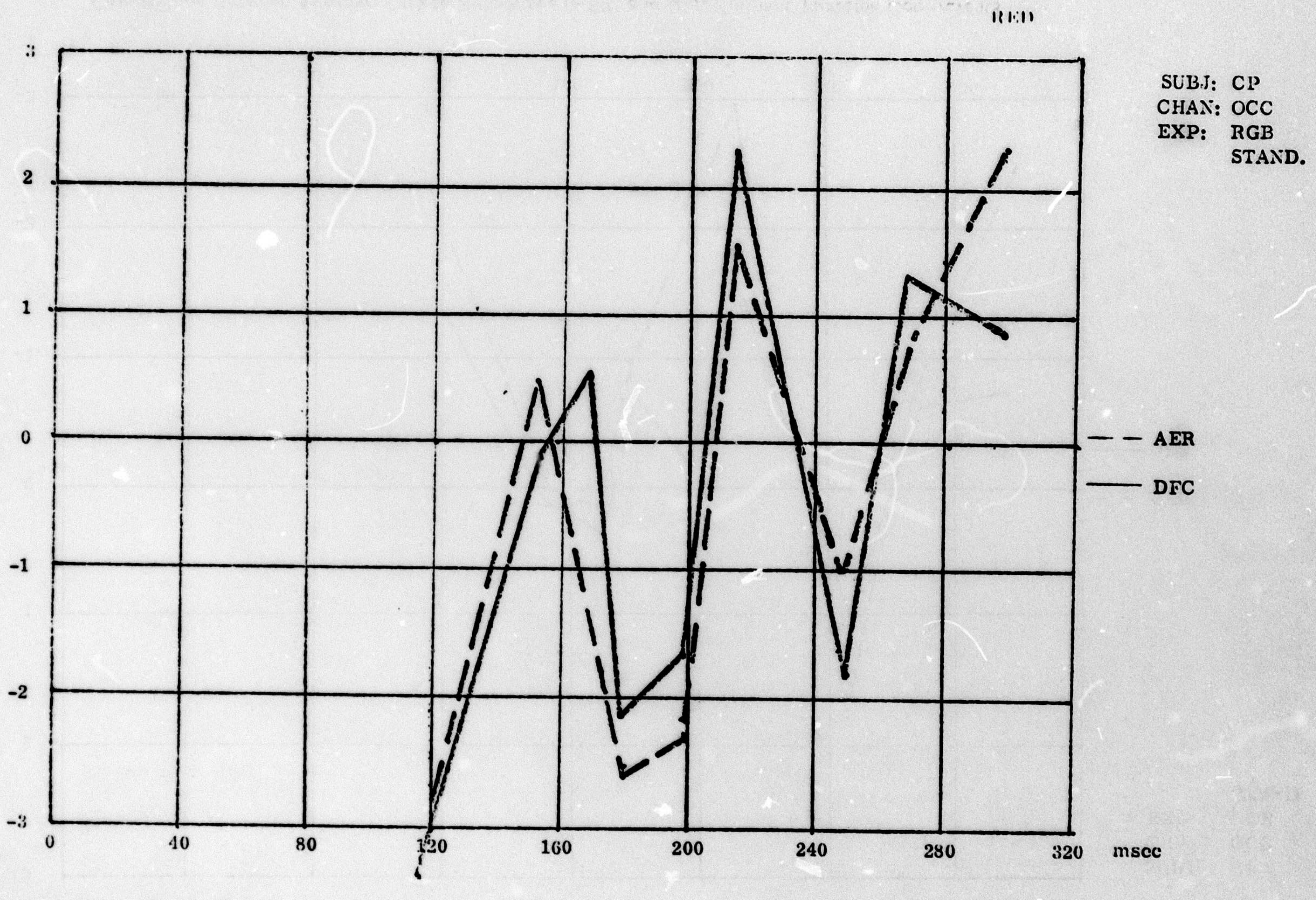
The conditional estimate $\tilde{I}(a_j,B)$ calculated for each row from (12) measures separately the capability of each input condition or class to get through the channel. Since $p(a_j)$ may not be the same for all j, the upper bound H(A) ,valid for I(A,B) does not hold for its components $I(a_j,B)$; rather;

$$\max I(a_j, B) = \log_2 \frac{1}{p(a_j)} \quad ; \quad j = 1, 2 \ldots J \tag{13}$$

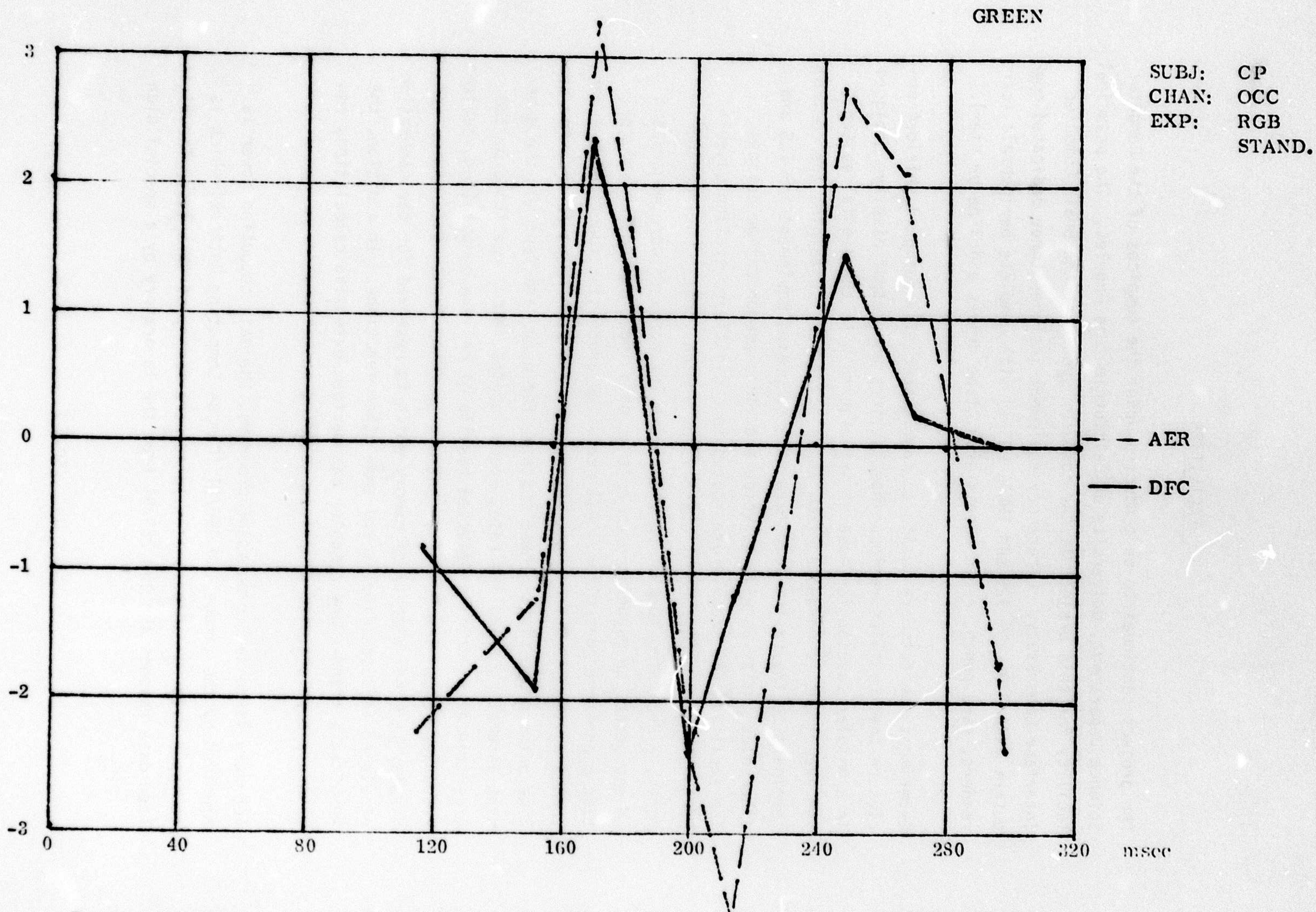
Mutual information calculations are now incorporated in the BCI Stepwise Discriminant Analysis program.



Comparison Between Average Evoked Responses (AER) and Discriminant Function Coefficients (DFC)



Comparison Between Average Evoked Responses (AER) and Discriminant Function Coefficients (DFC)



Comparison Between Average Evoked Responses (AER) and Discriminant Function Coefficients (DFC)

5. FACILITIES

The project continues to be conducted under the auspices of the Computer Science Department, University of California, Los Angeles, The principal facility for this project is the computer system at the Brain Computer Interface Laboratory. Laboratory equipment includes three dedicated computers (XDS 930, XDS 920 and IMLAC PDS-1) with complete peripherals (card readers, card punch, rapid access drum, tape drives and line printer).

Experiment subjects are monitored from a specially designed shielded enclosure that contains various input devices and output displays designed in a modular fashion for ease of interfacing with the digital system. The experiment is conducted from an adjacent room containing the control terminals to the system computers, the recording equipment for EEG and other biosignals, as well as voice and video communication devices. The amplified EEG signals are routed to a digitizing station capable of handling 50 simultaneous channels of analog input. During experiments, a dedicated XDS 930 computer with 16K words of core memory and 2M characters on magnetic drum acts as data input controller and real-time experiment controller. All real-time processing functions are performed by the 930 which also creates complete experiment records for off-line batch processing. These contain, for each data "epoch", the experiment parameters (sampling rate, epoch lengths, etc.) specified by the experimenter as well as selected results of on-line computation, subject responses, etc. The 930 also controls an IMLAC PDS-1 minicomputer and display terminal with 8K of memory which is reserved for the generation of visual feedback display and some other functions. In addition, the PDS-1 as a stand-alone computer can perform extensive calculations and generate sophisticated graphics including animation.

For very large data processing programs, the main computing power is provided by the campus IBM 360/91 (Campus Computing Network) which is equipped with an exceptionally large core memory of 4M bytes. The digitized data reaches the IBM 360/91 from the laboratory by a special high speed data line that is used to write and read directly into and from the 360/91 core. The data transfer is controlled with a separate processor (XDS 920) to allow buffering and transfer without interference with experiments. A monitor program in the 360/91 controls both the data flow and the processing protocol from a privileged position with respect to the 360/91 operating system software, thus insuring immediate execution. Complex programs such as spectral or functional analysis of the signals can be performed and the results fed back to the laboratory with minimum turn-around time. The "awakening" of this software system and all subsequent file handling are placed under the campus time-shared system (URSA) and controlled by an IBM 3277 terminal in the laboratory.

Finally, the BCI laboratory computer system has wired-in direct access to the ARPA Network. The Network is being used for accessing and transmitting data to distant facilities (such as MIT-MULTICS) and for communication with other Biocybernetic research groups.