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A Computer-Based Laboratory Facility for the Psychophysiological Study of Psi[1]

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ABSTRACT: This paper provides the basic reference to technical resources for psychophysiological research developed by the Experiential Learning Laboratory, Department of Electrical Engineering, Duke University. Hardware and software facilities are described which permit rapid construction of efficient computer-driven protocols for a wide range of experiments, entirely in FORTRAN. All data files are written directly to digital storage in a self-describing standard format, and are thus accessible to subsequent processing by a large collection of generalized data-management, data-reduction, and statistical analysis programs. Special precautions have been taken to insure the integrity of physiological data, including development of computer-assisted daily-calibration and system-measurement procedures. The facilities described supply the necessary technical foundation for a systematic, wide-ranging, and long-term program of experimental research on physiological correlates of paranormal processes.

INTRODUCTION

Although it has not yet been clearly established that psi events bear orderly relations to physiological events, a number of theoretical and empirical considerations converge to suggest that they should, and that the relevant physiological events may in useful degree be measurable (Kelly, 1977, 1979).

The discovery of consistent relationships of this sort could in principle lead to many useful consequences, among them improved

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prediction and control, resolution of experimental ambiguities concerning time and source of psi effects, and even fundamental new insights into the mechanisms underlying psi.

To explore these possibilities, we are currently developing a program of systematic research on the physiological correlates of psi processes in human beings. The central strategy of this program is to study fluctuations in psi task performance in relation to fluctuations of bodily state, as reflected in various kinds of electrical and mechanical signals measurable at the body surface.

Although its strategy is conceptually straightforward, this kind of research is technically demanding. This is particularly true of research involving the electroencephalogram (EEG), the physiological signal which interests us the most because of its demonstrably intimate relationship to many information-processing activities of the brain. Consequently, we have devoted a large proportion of our initial effort to careful construction of a suitable base of technical resources for psychophysiological research.

This report summarizes these developments, and is intended to provide the basic technical references for subsequent experimental reports. We have attempted to organize our presentation in such a way as to make it accessible to the general reader, while maintaining adequate completeness of technical detail. Thus, both the report as a whole and its major sections begin with general introductions to the material in them, more detailed information being deferred to subsequent sections, footnotes, and parenthetical remarks; the bulk of the very detailed material has been set aside in appendices for those who have interest in such details.[2]

I. Overall Structure and Operation of the Research Facility

The facility is located within the Electrical Engineering Department of Duke University. A general layout of its organization is shown in Figure 1, the three main parts corresponding to physically separate regions of the facility.

The computer, located on the first floor of the new engineering annex building, is owned by the EE Department. The instrumentation and controlled environment rooms are in the sub-basement of the old engineering building, some hundred feet, three walls, and two floors distant. The instrumentation room contains the equipment noted in Figure 1; the experimenter is normally located in this room while monitoring an experimental session in progress. Lo-

[2] Copies of these appendices are available upon request to the authors.—*Ed.*

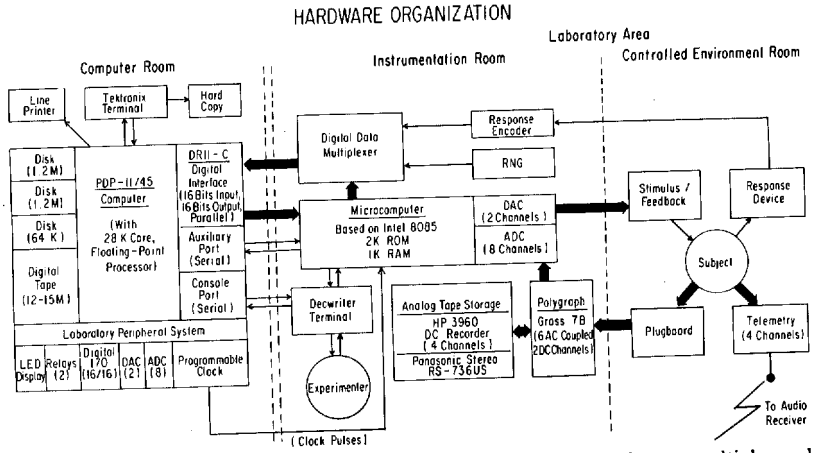

Fig. 1. General layout of the research facility. (Heavy arrows denote multichannel data paths; dashed vertical lines delimit physically separate regions of the facility.)

cated adjacent to this area is the controlled environment room where the subject is located during a session. This room is electromagnetically shielded, acoustically quiet (though not soundproof), and of pleasant decor lighted by a bank of adjustable, DC powered colored lights.

A typical experimental session runs as follows: The subject, after being appropriately outfitted with electrodes for physiological recording, is brought to the controlled environment room. Here the electrodes are connected to the polygraph via a plugboard, and various facilities are arranged for presenting stimuli and monitoring responses.

In the adjacent instrumentation room, the experimenter first makes preliminary adjustments of relevant equipment, and then, using the downstairs console, initiates a dialogue with the remote computer. This dialogue may include, for example, tests of the hardware random number generator (RNG), adjustment of audio feedback tones, and tests of the response-monitoring devices. It invariably includes a standard daily calibration procedure for the physiological measurement system (see below, Section III.D.1.). The experimenter then invokes the relevant "real-time" experimental control program and supplies it with information about the experimental session to be run; for example, session and subject identifications, and experimental parameters such as number of trials, number of physiological channels to be sampled, length of sample periods, etc.

With the instrumentation correctly adjusted and the control program suitably initialized, the experiment proper can begin

whenever the subject feels ready.[3] From this point forward, the experimenter's function is principally to monitor the physiological instruments and to intervene in the event any abnormal conditions should develop. The experiment is otherwise entirely under the supervision of the remote computer program, which controls such processes as generation of targets, collection of responses, sampling of physiological channels, and writing of data records to computer storage as dictated by the experimental protocol.

The analysis of the physiological data in particular is generally too complex to be carried out concurrently with data collection, and is instead normally carried out later in a separate stage by applying the data management, data reduction, and statistical analysis capabilities outlined below in Section III.B.

II. Hardware Components

Here we give further details on the hardware organization, emphasizing major items of equipment that can be purchased in variable configuration, plus specialized or novel components of the hardware system that are not available commercially.

A. Computer

The central computer, which we share with other members of the Electrical Engineering Department, is a Digital Equipment Corporation (DEC) PDP–11/45. It has 28K 16-bit words of core memory, supplemented by an (FP–11B) floating-point processor.[4] Storage devices include two (RK05) removable cartridge disks each capable of handling up to 1.2 million words of data, an (RC11) fixed-head disk with 64K words capacity (used mainly for specialized utility functions), and a (Digidata Maxidek 1730) digital

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[3] The presence of large amounts of formidable-looking apparatus tends to create a heavy "technological" atmosphere which some subjects may find intimidating on first contact. Our experience so far, however, suggests that this is not a serious problem. We always spend a good deal of time with new subjects to help them to feel relaxed and comfortable with us and with the laboratory, and we generally work intensively with each selected subject over an extended period of time. Under these circumstances any initial difficulties seem to dissipate quite rapidly.

[4] We wish to thank the Parapsychology Foundation for a special equipment grant which made possible the purchase of the last 12K of core; this was essential to implementation of the software capabilities described below. We also thank the Arthur Vining Davis Foundations for supporting purchase of the floating-point processor and digital tape drive, which jointly make it practical to apply these software capabilities to the large volume of data generated by psychophysiological experiments.

tape drive (1600 BPI, approximately 12–15 million words per 2400' tape). The main controlling console is a (Tektronix 4013) graphics terminal, which has an associated copying facility (Tektronix 4610) for making permanent records of visual displays as desired. When large volumes of printed output are generated, as for example in statistical analyses of physiological data, they are directed to a small line printer (Data Products LP 2310) which prints up to 80-character lines at speeds of up to 250 lines per minute.

As shown in Figure 1, communication between the PDP–11 and the equipment in the instrumentation room downstairs takes place through several devices. First, the DR11–C is a general-purpose digital input-output device reserved solely for our use, which controls in parallel 16 lines of digital input and 16 lines of digital output. As described in more detail below (in subsections D, E) it is used primarily for transmitting upstairs to the PDP–11 sampled physiological data and other kinds of information generated during an experiment. However, it can also be used to send data in the other direction as well. For example, we can use this device to display in the laboratory physiological data being received upstairs by the PDP–11; this assures rapid detection of gross malfunction in the data acquisition system.

Second, two sets of serial input-output ports are used. The "console" port can be connected with the DECwriter terminal in the laboratory, thus permitting the PDP–11 to be controlled remotely as described earlier. The "auxiliary" port enables the PDP–11 to control the 8085 microprocessor; for example, it is used to load into the 8085, automatically, particular pre-programmed subroutines required for a given experiment (see subsection E).

Finally, a number of other facilities are available through a DEC-supplied hardware facility called the Laboratory Peripheral System (LPS–11). Our LPS–11 contains the following: First, a (KW11–P) programmable clock, which is crystal-controlled to permit precise regulation of the timing of all experimental events such as the spacing of successive physiological samples, generation of targets, etc. The "ticks" of this clock are also delivered simultaneously to the 8085 via a special dedicated line. Other facilities include an 8-channel analog-to-digital converter (no longer used—see subsection D); two channels of digital-to-analog conversion, used for returning various kinds of signals to the laboratory; two relays, which can be used to control stimulus devices in the neighborhood of the PDP–11 (for example, a stroboscope); another 16-bit parallel digital input/output unit (not used); and a simple numerical display of light-emitting diodes (LED), which can be used, for example, in debugging programs or to display target numbers to "agents" in GESP experiments.

B. Polygraph

The core of the physiological measurement system is a Grass (Model 7B) solid-state polygraph. It has eight channels of amplification: two DC preamplifiers (7P1B), four wide-band AC-coupled preamplifiers (7P5B), and two wide-band AC-coupled preamplifiers with integrators (7P3B). All channels use Model 7DAE driver amplifiers. Auxiliary equipment includes the Grass (EB24) electrode plugboard and (7ESP24) electrode selector panel.[5]

C. Analog Tape Recorders and Telemetry Units

Many kinds of physiological experiments generate enormous volumes of data. Analog recorders are widely used for bulk storage of raw physiological data, and we initially planned to follow this practice, taking advantage of the 4-channel Hewlett-Packard instrumentation recorder, which was already on hand. Although this approach proved fairly satisfactory, it became evident that a completely digital system would be greatly superior. By recording data directly in digital (sampled) form, one eliminates a variety of small but not negligible sources of experimental error. These include such things as irregularities of tape transport speed and tape orientation, additive environmental noise, and other imperfections of analog environments related to problems such as providing accurate timing signals and reliable mechanisms for encoding and decoding responses (Bendat and Piersol, 1971, Chapter 7; Walter, 1972; see also Vos, 1977).

However, analog recording methods still have occasional uses in our work. The main use is to provide access to data collected in other laboratories, or under field conditions, using radio telemetry methods developed in our laboratory by Fritz Klein. These methods encode physiological signals as modulations of an FM carrier, using pocket-sized amplifier/transmitter units and audio tape recording. The basic techniques are described in detail elsewhere (Klein, 1976b) and some preliminary examples of their many possible applications in parapsychological research are contained in Palmer (1979) and Solfvin, Roll, and Kelly (1977).[6]

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[5] We wish to express our gratitude to W. G. Roll and the Psychical Research Foundation for making this essential equipment available to us. It replaces the Grass Model 79B which we used initially.

[6] Our current prototype telemetry units, which were constructed using funds supplied by the John E. Fetzer Foundation, allow us to collect either two channels of EEG, or EKG and GSR. We are presently seeking funds to construct an expanded and improved system, particularly for use in poltergeist investigations.

D. Microprocessor and Data-Conversion System

A critical feature of any computer-based physiology lab is the analog-to-digital conversion (ADC) process, which supplies the interface between continuously varying physiological signals and their discrete numerical representation inside the computer. For example, in order to maintain adequate fidelity in the digital representation of EEG signals, they must be measured accurately at typical rates of from 128 to 512 equally-spaced samples per second on each EEG channel (see Vos, 1977).

ADC systems can be implemented in a large variety of ways. One basic decision concerns the physical location of the ADC process with respect to the signal source. Ideally ADC should occur close to the source to minimize possibilities of noise corruption in the analog data. One way of achieving this is to have the main computer itself located right in the laboratory. This of course was not feasible for us economically, nor could we purchase a smaller computer of the PDP–11 family to serve the same purpose. Instead, since the already available central computer was equipped with an LPS–11 that included ADC capability (see above), we began by developing a low-cost system for transferring physiological data from the lab to the PDP–11 via analog channels.[7] Although this system generally worked reliably during the time when it was in use, we continued to be concerned that the length of the transmission lines, coupled with the variety and intensity of possible noise sources in the engineering environment, made the potential for corruption of the analog data intolerably high. As part of our general concern for maximizing data reliability, we therefore continued to look for cost-effective alternative solutions. This past year we were able to abandon the analog system in favor of a microcomputer system which performs ADC in the laboratory and transmits data to the PDP–11 in digital format via the DR11–C (see subsection E). This system has proved highly effective in suppressing contamination from outside sources.

The microcomputer is based on an Intel 8085 microprocessor. Although it is small, rather slow, and by no means a general-purpose laboratory computer, it can perform a variety of useful functions in addition to ADC (for example, triggering the RNG, delivering stimulus or feedback information via its two digital-to-analog converters, etc.), and it can also be used locally, indepen-

[7] We thank James W. Davis for valuable technical advice, and FRNM for funds to implement the resulting designs. The actual construction was carried out by Ross Dunseath and Steven Suddharth.

dently of the PDP–11, for simple kinds of experimental tasks (see Appendix 1 for further details).

The ADC system[8] itself uses a Datel (ADC–HZ12B) converter with 12-bit resolution. That is, the instantaneous voltage on a sampled channel can in principle be characterized by one of $2^{12} = 4096$ possible numerical values. In our system, the noise level amounts to somewhat less than one bit, so that we have effectively 11 significant bits of signal; in general, eight bits is regarded as minimally adequate, and 10 bits is excellent. One other special feature which we designed in, and which should be mentioned here, is that each input channel to the converter works in a "sample-and-hold" manner—that is, when the ADC system is triggered, the contents of all channels are simultaneously "frozen" for sequential conversion by the analog-to-digital converter. This feature eliminates any possibility of interchannel phase distortion arising from sampling lags between successive channels, and strengthens the technical foundation for investigations of relationships between brain areas (Clusin, Giannitrapani, and Roccaforte, 1970; Cooper, 1975).

E. Digital Multiplexer

Most data from the lab enter the PDP–11 computer through the DR11–C. Only one digital data source at a time may be connected directly to the computer through this device. However, usually several digital devices need to be used together in a given experiment (the 8085 data acquisition system plus RNG and/or one or more respondent devices). To accomplish this, the single DR11–C input port may be shared by routing the data from the several devices through a digital multiplexer. This device determines precedence and presents the data to the DR11–C port from one device at a time in sequence. Conflicts between devices are resolved by assigning a fixed priority order to the sources and sending the bits from the highest priority device first. The source of data is identified by a 3-bit "address" attached to the data themselves as they are fed into the DR11–C. Up to eight digital sources may be attached to the multiplexer and thus share the one DR11–C input port.

F. Hardware Random-Number Generator (RNG)

Since the fundamental work of Schmidt (1970, 1973; see also Davis and Akers, 1974), hardware randomization devices have

[8] This part of the system was constructed by Ross Dunseath, who was also responsible for parts of its design.

become a standard fixture in many parapsychology laboratories. We have also built such a device, primarily for use in studies of the physiological correlates of performance in a fast PK test. Our RNG uses a noise source to produce random bits at rates above 1000 per second, and its output has shown excellent approximation to ideal randomness.[9]

III. Software Components

Thus far we have focused primarily on the hardware components of the facility. In fact, however, by far the greater proportion of our developmental effort has gone into construction of software resources for psychophysiology-psi research. These resources consist of a collection of computer programs which allow us to exploit effectively the available hardware in collecting, managing, and analyzing physiological data.

Two main interrelated design objectives have guided this software development work. The first is *generality*. Our aim has been to develop software resources for what we foresee as a long-term program of systematic research on physiological correlates of psi processes. Accordingly, rather than developing highly specialized software for running each new experiment and analyzing the resulting data, we set out to develop a set of general-purpose research tools that can henceforth be used in a wide variety of contexts without further modification. Our second objective is *ease of use*. Most people trained in experimental fields have little experience with computer programming, particularly systems-level programming. Yet these are precisely the sort of people we hope will be able to use our system effectively. Our aim has therefore been to make the complexities of the software reasonably transparent to users, in the sense that they can readily command the major resources of the system for their own research purposes without having to invest large amounts of relatively unproductive effort in mastering unpleasant details of a computer-science nature. A corollary aim was to make the system readily exportable, in the sense that its effective use should be minimally dependent on the continued availability of its creators or similar personnel.

The present software system represents, we believe, a good first approximation to realization of these aims. However, certain limitations were unavoidable. Generality and ease-of-use must always

[9] Our thanks to Helmut Schmidt for consulting with us on design considerations for RNGs. The final version of our RNG was designed and built by Jack Hebrank. Technical details are provided in Appendix 2.

be traded off against the amount of storage needed for data and the speed of execution of a program. An easy-to-use system with many seldom-used features usually requires much computer storage space and may run notoriously slowly. Thus, in our system, which must handle large amounts of data in a relatively small computer, certain niceties had to be avoided. The rapid execution necessary in the data acquisition system also required certain compromises. True exportability is also a problem in a program written in an assembly language for a particular piece of hardware. The data acquisition system is such a program and its ability to be shared with other labs is thus quite limited. Despite these limitations, however, the overall system has proved to be fairly exportable,[10] and it meets our current needs in terms of generality and ease of use. We now describe this software in some detail.

The overall organization of the software system is outlined in Figure 2, details of which will become clear as we proceed. The system has two main parts—a collection of facilities for constructing and executing programs which control experiments and acquire data on-line; and a collection of data management, data reduction, and statistical analysis programs.

A. Real-Time Data Acquisition System

The major component of the real-time system is a collection of assembly-language subroutines which allows construction, entirely in FORTRAN IV, of computer programs for on-line control of any of a wide variety of experiments.

Using these facilities, an experiment is organized as a temporal structure of *events* controlled by the programmable LPS clock. Associated with each *event* is a user-provided FORTRAN subroutine which typically performs some elementary activity such as generating a target, receiving a response, storing sampled physiological data, etc. The real-time subroutines provide for defining events and their attributes (such as repetititon rate and priority of execution), scheduling and cancelling events, and starting and stopping the clock and setting its "tick" or interrupt rate.

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[10] The current Duke implementation runs under the single-user Disk Operating System (DOS). However, parallel versions of all our software have also been developed for the parapsychology laboratory of the University of Utrecht, in The Netherlands, which runs the multiple-user RSX–11M operating system. Technical details of the DOS real-time software are contained in Appendix 3. The first two authors wish to express their thanks to Martin Johnson and Sybo Schouten, and to the Parapsychology Foundation, for supporting nine months of work at the Utrecht laboratory.

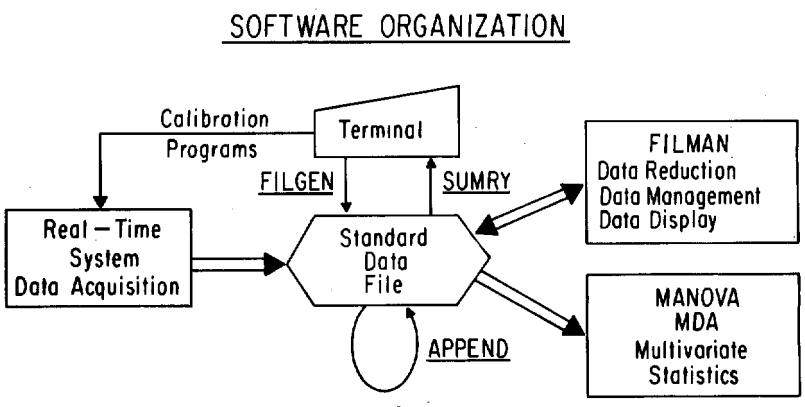

Fig. 2. Overall organization of the software system.

During execution, whenever the clock "ticks," whatever processing is going on is interrupted and, in effect, "put on hold." The real-time system then takes over and inspects an internal list to determine whether any events are scheduled to occur. If any are found, the subroutines associated with these events are executed in the order specified by the event priority. Then, following the processing of any scheduled events, execution of the interrupted program may resume. This clock-driven priority hierarchy assures accurate timing for critical events, while allowing several overlapping processes to share the computer as they need it. It thus permits maximally efficient use of the machine. By contrast, in most existing systems the user requests a service such as data sampling and then must wait idle until the service is completed and control returns to his program, even if the service itself is only using the machine intermittently while it is active (see, e.g., Donchin and Heffley, 1975).

These principles govern real-time program execution not only in the PDP–11, but also in the downstairs microcomputer which operates partly independently and in parallel. Whenever the clock "ticks," the 8085 processor is also activated. Normally at this point the conversion of the physiology to digital form is accomplished and then the results transferred to the PDP–11 via the digital multiplexer and DR11–C. In addition, however, the 8085 may cause other events (so-called "remote events") to occur. These remote events are similar to the events executed at the PDP–11 and may include (in addition to the A to D conversion event) the driving of feedback devices and/or triggering the RNG, for example. When running an experimental protocol, before the experiment itself begins, the PDP–11 loads the 8085 (via the auxil-

iary serial port) with the proper program data to execute the remote events required by the particular experiment. Prior to this time, the remote events (which are really 8085 assembly language subroutines) have been written and compiled in proper format using a cross-assembler available on the PDP–11. Thus, although the 8085 may be used as a "stand-alone" computer, all program development, storage, and execution is actually handled on the PDP–11.

Auxiliary subroutines provided by the real-time system allow FORTRAN access to various parts of the LPS such as the analog and digital input-output facilities, LED display, and relays. Another important group of routines is concerned with the formation and use of *queues*, or circular data buffers. This useful data structure (analogous in operation to the ticket line at the theatre in that the data enter the queue at one end and are removed from the other) allows us to maintain a continuously updated record of physiological data from the immediate past. This is particularly important when we want to look at physiological patterns preceding some occurrence whose timing is not known in advance—for example, a self-initiated response in an ESP task.

Our experience with these facilities so far suggests that they can be effectively used by persons with moderate skill in FORTRAN, and that initial programming time for new experiments will typically range between a few hours and a few days, even for quite intricate experiments. Also, once the basic structure of an experimental control program is written, modifications are usually quite easy to make, thus reducing the effort involved in "shaking down" a new experimental protocol. (Further details of the real-time system are given in Appendix 3.)

B. Interactive Data Management, Data Reduction, and Statistical Analysis System

This part of the system is written almost entirely in FORTRAN, and thus is relatively machine-independent and exportable. It is designed to allow users to process data from virtually any kind of experiment (although many of its facilities are specialized for psychophysiological research and would not be as useful in other applications), and demands roughly the same order of user sophistication required for effective use of commercially distributed "canned" statistical packages such as SAS or BMD.

A key concept underlying the generality of the system is that of the *standard file format* (details are given in Appendix 4). Real-time programs are normally designed to write their output directly in the standard form. All subsequent processing is then carried out

by programs which read standard-file inputs and (optionally) write standard-file outputs.

Data files in standard form are self-describing—that is, the actual data records are preceded by header records which describe the structure and content of the file. In fact, only the very first record is fixed in structure, and by reading it the system learns enough to be able to read correctly the whole remainder of the file. Thus, a great variety of data files can be accommodated within a single uniform system of data management and data analysis routines.

Individual data records themselves have two main parts—the actual data-points (which might be the values of digitalized physiological samples, estimates of EEG power spectra, or any of a wide variety of other possibilities), and identification information. Identification information is carried in what we call *grouping-variables*, which are in effect much like *factors* or *classification-variables* in the analysis-of-variance and experimental-design sense. To illustrate, if we think of an ESP experiment as consisting of a series of trials, then each trial can be categorized in various ways—for example, by what target was generated, what response was made, and whether the response was a hit or a miss. This kind of information is stored in the grouping-variables.

Another important aspect of data-records is that they are organized into *sets* to reflect the likely possibility of multiple-channel physiological recording. To continue with our illustrative experiment, suppose we recorded six channels of physiology during a short period prior to each response. In that case, each ESP trial would be represented in the raw data file by a record-set consisting of six data records, one for each physiological channel. Apart from channel number, the grouping-variable values would be identical within each record-set, but the data-values would differ from record to record depending on what activities were occurring in the corresponding physiological leads. Data files arising from a non-physiological experiment would of course typically have only one channel, and the data values would be those of whatever dependent variables were measured in the experiment.

The primary instrument for management, display, and analysis of data is a master program called FILMAN. FILMAN processes a standard input file by applying one each of three categories of routines—routines for record-set selection, routines for operating on grouping-variables, and routines for operating on data-points. The system contains a large basic set of generally useful routines (described in Appendix 5), and new ones for special purposes can fairly easily be added.

During an initialization phase, FILMAN first asks for an input

data file and then requests users to specify one routine from each of the three categories to be used in processing that file. It also requests users to specify which channels they wish to process, and which data-points within channels. FILMAN then loads the desired routines from the disk and begins to process the input file one record-set at a time. If the chosen record-set selection routine determines that the current record-set is to be processed, then FILMAN executes the selected grouping-variable and data-point operations for the selected channels and data points.[11] Depending on which point-processing routine was selected, an output data file may also be written; if so, it is itself a standard file and hence accessible for further processing, either by FILMAN itself or by other routines such as the statistical analysis programs.

We remark here that the analysis of EEG data in particular is a very complex and still rather poorly understood subject. There are really two aspects to the analysis of task- or state-related EEG differences: first, feature-extraction, or reduction of the raw EEG to some hopefully more compact and physiologically revealing representation; and second, pattern-recognition, or use of the extracted features to discriminate the relevant tasks or states. Within our system, these aspects are handled largely separately. All of the feature-extraction or data-reduction takes place in FILMAN. Holding no very fixed views at present concerning the relative merits of alternative feature-extraction methods, we have endowed FILMAN with the capacity to apply most major techniques presently known or thought to be useful. These include in particular spectral analysis (Adey, 1965, 1970; Bendat and Piersol, 1971; Dumermuth, 1973), period analysis (Klein, 1976a; Saltzberg, 1973), and analysis of raw EEG amplitude distributions (Adey, 1970; Elul, 1969).

The pattern recognition part of the problem is itself open to a vast variety of possible approaches, and may ultimately prove to be an important area of investigation in its own right (e.g., see Nilsson, 1965). For the present, however (and no doubt as a good first-order approximation to still more elaborate techniques that may come later), our statistical treatment of physiological data will be carried out within the framework of the multivariate general linear model (Morrison, 1967; Timm, 1975). In brief, this model absorbs all the familiar univariate statistical designs into one over-

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[11] FILMAN uses a specially modified version of the FORTRAN overlay system, in which the *load* and *execute* phases are separated. In this way the selected routines are loaded into specific regions of core at initialization time and then executed in place repeatedly, rather than having to be reloaded for each record-set in turn.

arching theory, extends it to cases in which there are multiple dependent variables, and provides a unified computational framework for all cases. The multivariate extension is important in our work because we typically use *batteries* of physiological measures to attempt to discriminate the kinds of differences that interest us. For example, continuing with our hypothetical ESP experiment, kinds of questions to be answered by statistical analysis would include whether vector-valued observations such as EEG power spectra, or coherence and phase relations between pairs of channels at multiple frequencies, differ systematically for hitting and missing ESP responses.

With this as background, we now describe our statistical analysis programs, which have to run stand-alone because of their size. We have two main programs, each originally developed and published by other workers. Each has been subjected to what we will call the "basic modification"—namely, modification to allow input of standard files, with channel and point selection. The uniform availability of channel and point selection mechanisms throughout the data analysis system, it should be noted, effects great economies in analysis because the analysis of K channels is carried out in parallel, as it were, rather than requiring the K-fold repetition of an essentially identical analysis sequence. In addition we eliminate the costs in processing time and storage space that would arise if specially tailored files containing just the right data points and channels had to be created for each new application of the statistical analysis programs.

The first and simpler program is a multiple discriminant analyzer (MDA) adapted from Overall and Klett (1972). It performs a one-way multivariate analysis of variance (MANOVA), like the ordinary one-way univariate ANOVA, but extended to multiple dependent variables or criteria. We have expanded the maximum number of criteria to 40 (in order to accommodate large parts of the EEG frequency spectrum simultaneously), added a variety of optional data transform operations (to improve the distributional properties of extracted EEG features), and added significance tests on individual criteria (to help identify sources of significance in multivariate results). The final change is an optional "random replicates" feature. This feature permits arbitrary numbers of reanalyses of a single data-file, each time randomly permuting the assignments of record-sets to groups rather than using their true group identities. This mechanism can be used to provide what amounts to a brute-force non-parametric test circumventing all distributional assumptions (approximates a randomization test). We will also use it to study the distributional properties of statistics based on features such as EEG power spectral estimates.

The heart of our data analysis system is an adaptation of the widely known MANOVA program originally written by Elliot Cramer in 1965, based principally on an algorithm published by Bock (1963). MANOVA is an extremely general program for least-squares analysis of linear models. Apart from size restrictions it can analyze any analyzable experimental design, univariate or multivariate, orthogonal or non-orthogonal, including all the various kinds of unbalanced, incomplete, and nested designs. In analyzing factorial designs it permits various kinds of special single or multiple degree of freedom contrasts in the main effects and interactions. It also permits optional transformations of criterion variables, as in our version of MDA. Finally, it can perform analysis of covariance, multiple regression, and canonical correlation. In short, it is a very powerful general-purpose instrument for the analysis of experimental data. It is also reasonably well documented and for most applications quite easy to use.

The version we began with had already been adapted to run on another small computer, the IBM 1130. In adapting it to our purposes we have made a number of major changes in program structure beyond those needed to make the "basic modification." By suitably restructuring the program to use storage more efficiently, we have been able to implement a version which runs in approximately 24K core and will handle up to 40-variable problems. As indicated above, this expansion of the maximum number of criteria is essential because it allows us to analyze realistically large collections of physiological measures simultaneously. In order to secure it we had to compromise on other characteristics of the implementation, but our version will still handle up to four factors with a maximum of eight levels each, or a total of not more than 30 non-vacant cells. These specifications are quite sufficient to cover our presently anticipated needs; in fact, in its most critical specification (number of variables), our version is equivalent to that implemented on our regional computer (IBM 370).

C. Auxiliary File-Handling Routines

A few additional utility routines for manipulating data files should be mentioned (see also Figure 2). SUMRY merely writes file header information to the user terminal and line printer for identification and checking. APPEND adds records from one standard file to those of another, conformable file (i.e., one sufficiently similar in structure—having the same number of grouping variables, same number of channels, same number and format of datapoints, etc.). It can be used, for example, to add individual subject or session files to a master file. Finally, FILGEN is a program

allowing creation of standard files from the user terminal. It can be used to input test data for new FILMAN programs, or to bring small amounts of experimental data collected in other environments into the system for analysis. Larger amounts of non-physiological data can also readily be brought into the system via special-purpose programs (see, for example, Schouten and Kelly, 1978).

D. Programs for Calibration of the Physiological Measurement System

Physiological signals such as the EEG are extremely small, on the order of microvolts, and between our recording electrodes on the scalp and the output from the MANOVA program there stretches a long chain of instruments and processes, some of which are individually very complex. The integrity of the basic measurement system, from scalp electrodes to numbers inside the computer is particularly critical, and it is vulnerable to corruption at many points along the way. Even with meticulous attention to detail, technical problems of various kinds occasionally but inevitably occur. To reduce such problems to a minimum, we have invested considerable effort in developing procedures for calibrating our measurement system and studying its properties. We will briefly describe the main features of these procedures.

1. *Daily calibration routines.* The measurement system should establish a fixed and known correspondence between the magnitude of physiological signals appearing at the inputs to the polygraph preamplifiers and the numbers which emerge from the A-to-D converter at the computer interface. This correspondence defines the sensitivity of the measurement system. Many psychophysiology laboratories simply use the manual and visual calibration controls on the polygraph itself. Procedures of this sort may be sufficient for clinical purposes and for simple kinds of experimentation, but they certainly do not provide a sufficiently precise foundation for work involving computer analysis of the EEG (Clusin et al., 1970; Walter, 1972).

In our system the daily calibration process is pegged to a precise external reference—namely, the DC calibration signals generated by our H/P instrumentation recorder. After a preliminary manual adjustment of the polygraph drivers, this DC signal is used to calibrate any one of the data acquisition channels. A program is then run which uses this channel to measure an adjustable 10 Hertz signal source. This AC signal, now of precisely adjusted amplitude, is reduced in size by a passive voltage divider and presented simultaneously to the inputs of all polygraph channels. Each polygraph output is attached in turn to the data acquisition channel it

will use in the course of the experiment and this combination is adjusted under program control. Daily calibration is completed by running a program which measures all channels simultaneously, producing statistical averages for each channel's offset and gain.

The product of this calibration process is an updated version of a special disk file containing calibration data which are then read and displayed by whatever real-time experimental program is being executed. Offsets are invariably close to zero, and gains to unity. These values are used to correct received physiological signals for the measured deviations from ideal calibration in the channels in which they appear.

2. *System measurement routine.* Ideally, all channels of the measurement system should respond identically to identical input signals (assuming identical arrangement of the channel bandpass controls); that is, the frequency and phase response characteristics of all channels should be as nearly identical as possible. To the degree that this condition is not met, physiological effects may be obscured or confused with measurement system artifacts.

Although the daily calibration procedure described above is greatly superior to simple visual methods, and effectively equalizes system response at the frequency of the calibration signal, it is far from guaranteeing homogeneity of response at other frequencies within the EEG band. To cite an unfortunate example, Clusin et al. (1970) reported discovering massive and previously unsuspected interchannel differences when spectral analysis was performed on a *single* pre-recorded EEG signal passed simultaneously through all channels of their 16-channel electroencephalograph. Estimates of corresponding spectral magnitudes differed by as much as 44% across channels, and there were phase differences on the order of 45 degrees.

Intending to avoid this kind of problem, we have set out to measure carefully our system response. Our technique, detailed in Lenz and Kelly (1980), uses trains of specially designed test signals consisting of computer-generated impulses of modified $\sin x/x$ form, with known spectra. These test signals are sent from computer to lab, passed through the relevant polygraph channels, and sent back up to the computer for recovery, averaging, and spectral analysis of the average recovered impulse responses. The frequency and phase response functions of all channels are thus precisely measured, and can be compared with each other, with polygraph technical specifications, and with theoretical expectation.

Applications of this procedure to our six AC-coupled EEG channels at several bandpass and sensitivity configurations have yielded excellent results showing that the system functions of these channels are highly homogeneous. Consequently, equation of system

response at a single frequency, as effected by our daily calibration procedure, *does* in fact approximately equate system response at all other frequencies in the relevant bandpass.

IV. Prospects

This completes our outline of the research resources we have developed to date. The system is also open-ended in the sense that it can readily absorb additional hardware and software components as these become available, with minimal modification of the existing software.

Certainly we can imagine numerous extensions and improvements of our current system. Nevertheless, the facility as already described comes gratifyingly close to meeting the design criteria we established when we first began working on this project five years ago. These resources are sufficiently powerful to support a serious and systematic research effort on the psychophysiology of psi.

Many readers may have wondered why so much computing power is required for this research. It will help in closing to provide more concrete quantitative feeling for the sheer numerical scale of the domain in which we are operating. Consider as a typical example our remote photic stimulation experiment (Kelly and Lenz, 1976). In its current form a single session of that experiment can generate (100 trials) $\times$ (8 seconds per trial) $\times$ (128 samples per second per channel) $\times$ (8 channels) or over 800,000 words of raw EEG data, more than two-thirds of the usable space on a disk. If we now compute an intermediate file of complex Fourier coefficients, even preserving only frequency components up to 32 Hz, that file will consume another 800,000 words of storage. From it we may compute autospectral and cross-spectral parameters at varying frequency resolution. Looking at cross-spectra, for example, there are $N(N-1)/2$ possible pairings of N channels, or 28 pairs for the case we are considering. For each specified pair of physiological channels we may store, for all specified frequency bands and for every trial, the transfer function, coherence, phase, and complex cross-spectrum information that collectively characterizes the relationship between the activities in those leads during the experimental session. Finally, multivariate statistical analysis of large multichannel files of extracted EEG features is itself a heavy computational task involving a matrix inversion and the solution of an eigenvalue problem for each hypothesis tested, with total running time roughly proportional to the square of the number of variables used in the analysis.

This computational load *can* be managed on our computer, particularly since the arrival of the digital tape drive and floating-point processor. However, it should be entirely clear that we are working in a world that is quantitatively utterly remote from that of traditional parapsychological experiments.

At the same time, it must be acknowledged that this is in part an expression of our essentially complete ignorance of the physiological basis of psi processes. We do not know what we are looking for, and so we must be prepared to look as widely and as searchingly as possible. It is conceivable, though we think unlikely, that with inspired guesswork one might arrive at similar research outcomes using much simpler procedures and approaches than ours. And certainly one of our main hopes is that we will learn enough through research to determine what simplifications may be feasible and appropriate for later investigations.

Meanwhile, however, our single strongest intuition is that the key to psychophysiological understanding, not only of psi functions but of all human mental functions, lies in the analysis of momentary relationships between brain areas (see also Luria, 1973). The system we have described constitutes the most elaborate resource parapsychologists have yet had at their disposal for this kind of research. If physiological signals derived from the cortex do indeed harbor traces of psi processes, then we believe we now have research tools powerful enough to detect and study them.

References

ADEY, W. R. Computer analysis in neurophysiology. In R. W. Stacy and B. D. Waxman (Eds.), *Computers in Biomedical Research.* (Vol. 1.) New York: Academic Press, 1965. Pp. 223–263.

ADEY, W. R. Spontaneous electrical rhythms accompanying learned responses. In F. O. Schmitt (Ed.), *The Neurosciences: Second Study Program.* New York: Rockefeller University Press, 1970. Pp. 224–243.

BENDAT, J. S., and Piersol, A. G. *Random Data: Analysis and Measurement Procedures.* New York: Wiley, 1971.

BOCK, R. D. Programming univariate and multivariate analysis of variance. *Technometrics*, 1963, 5, 95–117.

CLUSIN, W., GIANNITRAPANI, D., AND ROCCAFORTE, P. A numerical approach to matching amplification for the spectral analysis of recorded EEG. *Electroencephalography and Clinical Neurophysiology,* 1970, 28, 639–641.

COOPER, R. Measurement of time and phase relationships of the EEG. In G. Dolce and H. Kunkel (Eds.), *CEAN: Computerized EEG Analysis.* Stuttgart: Fischer, 1975. Pp. 85–97.

DAVIS, J. W., AND AKERS, C. Randomization and tests for randomness. *Journal of Parapsychology,* 1974, 38, 393–407.

DONCHIN, E., AND HEFFLEY, E. Minicomputers in the signal-averaging laboratory. *American Psychologist Special Issue: Instrumentation in Psychology,* 1975, 30, 299–312.

DUMERMUTH, G. Numerical spectral analysis. In M. Matousek, Frequency and Correlation Analysis. Part 5A, *Handbook of Electroencephalography and Neurophysiology,* A. Remond (Ed.). Amsterdam: Elsevier, 1973. Pp. 33–60.

ELUL, R. Gaussian behavior of the electroencephalogram: Changes during performance of mental task. *Science,* 1969, 164, 328–331.

KELLY, E. F. Physiological correlates of psi processes. *Parapsychology Review,* 1977, 8, 1–9.

KELLY, E. F. Converging lines of evidence on mind/brain relations. In B. Shapin and L. Coly (Eds.), *Brain/Mind and Parapsychology.* (Proceedings of the 27th International Conference of the Parapsychology Foundation, Montreal, 1978.) New York: Parapsychology Foundation, 1979. Pp. 1–34.

KELLY, E. F., AND LENZ, J. E. EEG changes correlated with a remote stroboscopic stimulus: A preliminary study. In J. D. Morris, W. G. Roll, and R. L. Morris (Eds.), *Research in Parapsychology 1975.* Metuchen, N.J.: Scarecrow Press, 1976. Pp. 58–63.

KLEIN, F. A waveform analyzer applied to the human EEG. *IEEE Transactions on Biomedical Engineering,* 1976, BME-23, 246–252. (a)

KLEIN, F. A low-powered 4-channel physiological radiotelemetry system for use in surgical patient monitoring. *IEEE Transactions on Biomedical Engineering,* 1976, BME-23, 478–481. (b)

LENZ, J. E., AND KELLY, E. F. Computer-based calibration and system measurement procedures for psychophysiology research. Submitted for publication, 1980.

LURIA, A. R. *The Working Brain: An Introduction to Neuropsychology.* New York: Basic Books, 1973.

MORRISON, D. F. *Multivariate Statistical Methods.* New York: McGraw-Hill, 1967.

NILSSON, N. J. *Learning Machines—Foundations of Trainable Pattern-Classifying Systems.* New York: McGraw-Hill, 1965.

OVERALL, J. E., AND KLETT, C. J. *Applied Multivariate Analysis.* New York: McGraw-Hill, 1972.

PALMER, J. ESP and out-of-body experiences: EEG correlations. In W. G. Roll (Ed.), *Research in Parapsychology 1978.* Metuchen, N.J.: Scarecrow Press, 1979. Pp. 135–138.

SALTZBERG, B. Period analysis. In M. Matousek, Frequency and Correlation Analysis. Part 5A, *Handbook of Electroencephalog-*

raphy and Neurophysiology, A Remond (Ed.). Amsterdam: Elsevier, 1973. Pp. 67–78.

SCHMIDT, H. A quantum mechanical random number generator for psi tests. *Journal of Parapsychology,* 1970, 34, 219–224.

SCHMIDT, H. PK tests with a high-speed random number generator. *Journal of Parapsychology,* 1973, 37, 105–118.

SCHOUTEN, S. A., AND KELLY, E. F. The experiment of Brugmans, Heymans, and Weinberg. *European Journal of Parapsychology,* 1978, 4, 247–290.

SOLFVIN, G. L., ROLL, W. G., AND KELLY, E. F. A psychophysiological study of mediumistic communicators. *Parapsychology Review,* 1977, 8, 21–22.

TIMM, N. H. *Multivariate Analysis: With Applications in Education and Psychology.* Belmont, Calif: Wadsworth, 1975.

VOS, J. E. Between EEG-machine and computer: Data storage and data conversion. In A. Remond (Ed.), *EEG Informatics: A Didactic Review of Methods and Applications of EEG Data Processing.* Amsterdam: Elsevier-North Holland, 1977. P. 143–155.

WALTER, D. O. Digital processing of bioelectrical phenomena. In A. Remond (Ed.), *Handbook of Electroencephalography and Clinical Neurophysiology.* (Vol. 4B). Amsterdam: Elsevier, 1972.

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