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PEARL II: Portable Laboratory Computer System for Psychophysiological Assessment Using Event Related Brain Potentials[1,2,3,4,5,6]

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HEFFLEY, E., B. FOOTE, T. MU1 AND E. DONCHIN. *PEARL ZZ: Portable laboratory computer system for psychophysiological assessment using event related brain potentials.* NEUROBEHAV **TOXICOL TERATOL** 7(4) 399-. 407, 1985.—The PEARL II portable laboratory computer integrates hardware and software to serve as an on-line, real-time, experimental control and data acquisition system. Although the system can be used in many areas of research, PEARL II development has emphasized investigation of physiological responses from human subjects performing complex experimental tasks. PEARL functions as a "turn-key" system which performs standard neurological tests that would be employed, for example in neurotoxicological assessment. The PEARL system also includes several psychophysiological tests used in human engineering research on performance workload assessment. PEARL can also serve as a tool in basic research on human psychophysiology. The special feature of the PEARL test battery is its suitability for the measurements of event-related brain potentials (ERPs) in these tasks, although other physiological indices such as heart rate may be monitored. In addition, the PEARL system includes a versatile library of laboratory control subroutines that can be used to develop new applications.

Evoked potentials   Event-related potentials   Neurotoxicology   BAEP   PREP   SEP   CNV   P300   Human field testing   Laboratory computer

BACKGROUND

The PEARL system emerged within the context of the research program conducted at the Cognitive Psychophysiological Laboratory (CPL) at the University of Illinois. The CPL has been engaged since 1969 in research with primary focus on development of the theoretical and empirical basis for the use of Event Related Brain Potentials (ERP) as a tool in the study of cognitive function [2,6]. Laboratory work conducted at the CPL and elsewhere has indicated that ERPs could be used in a wide variety of assessment tasks. In particular, ERPs appeared useful in the measurement of mental workload [10], in mental chronometry [12], in the study of preparatory processes [4], in research on

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[1]Development of PEARL has been supported by the Environmental Protection Agency under agreements EPA-R-605628 and EPA-CR-808974 managed by Dr. David Otto, and by the Air Force Aerospace Medical Reasearch Laboratory through USAF Subcontract SRL Order *No. 25390* and Order No. 28727 under a program managed by Colonel Robert O'Donnell. Versions of the LABPAK software were developed at the CPL in connection with projects supported by the [redacted] through contract F49620-79-C-0233 monitored by Dr. Alfred Fregley, and by the Defense Advanced Research Projects Agency through contract N000-14-76-C-0002 monitored by Dr. Craig Fields.

[2]The following members of the CPL Technical Staff also participated in the development of PEARL: Ron Klohr, Wally Meyers, Mike Anderson and Sara Klohr. Dr. Michael Faiman, Department of Computer Science, University of Illinois, provided major direction in the initial development of PEARL. We would also like to thank the many PEARL users who have made valuable contributions to refinements in the ERP test battery. Dr. Theodore Bashore, Medical College of Pennsylvania, and Dr. Sean O'Connor, University of Connecticut Health Center, have been especially helpful.

[3]The versatility of the PEARL system is illustrated by its adaptable acronym. PEARL originally stood for Portable Evoked Average Response Laboratory. EPA knows it as the Portable Environmental Assessment Research Laboratory, while the Air Force calls it the Portable Engineering Assessment Research Laboratory. The CPL, having moved from evoked potentials to event-related potentials, refers to it simply as PEARL.

[4]The PEARL Development Project remains an active program. The CPL can, under certain circumstances, produce PEARL systems at cost for interested scientists. Organizations interested in procuring PEARL systems should contact Earle Heffley.

[5]LSI-11, Q-Bus, and RT11 are registered trademarks of Digital Equipment Corporation.

[6]Organizations that have procured PEARL systems include: the Environmental **Protection Agency,** the Air Force-Aerospace Medical Research Laboratory, the Air Force School of Aerospace Medicine, the University of Connecticut Health Center, Rush-Presbyterian Medical Center, the Medical College of Pennsylvania, the National Institutes of Health, the Technion in Israel, the University of Illinois Aviation Research Laboratory, and the University of Illinois Psychology Clinic. The CPL currently operates ten PEARL systems.

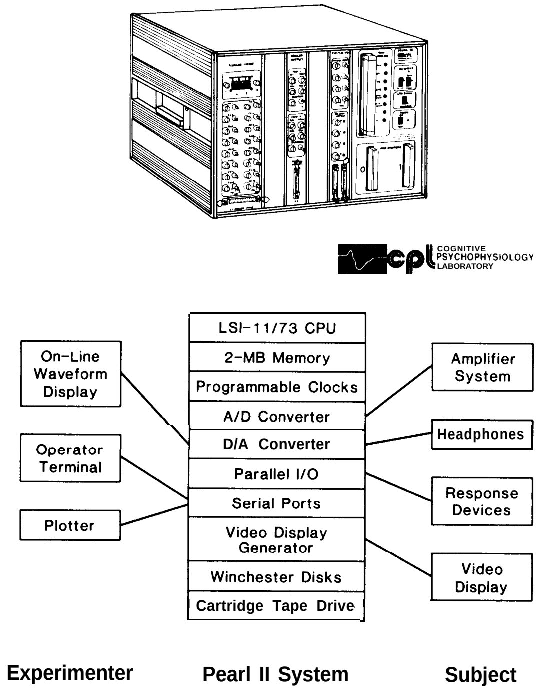

FIG. 1. The PEARL II packaging includes a variety of front panel connectors and switches which determine system inputs (top). A schematic representation of the functional components of the sys- tern is illustrated (bottom).

selective attention [9], and in assessment of neurotoxicity [13,14].

While many significant results emerged from ERP laboratories, it was difficult to evaluate the degree to which the procedures could be applied in the working environment of the clinician, the human factor specialist, and the toxicologist. Until a few years ago, the equipment available for research in these environments was costly and bulky. Moreover, users were forced to choose between systems that were preprogrammed for a specific purpose and systems that were quite general yet difficult to program. The problem became particularly acute for the CPL in two of its research programs. The Air Force was interested in evaluating the ERP as a work-load metric within the context of actual, or simulated, aviation. The Environmental Protection Agency was interested in conducting assessments of cognitive and neural function in field sites outside the laboratory. The success of both projects was contingent on the availability of a portable, flexible, replica of the rather sophisticated laboratory developed at the CPL [5]. The PEARL system was developed in response to this need.

In 1977, we began development of the PEARL I laboratory computer system, which was designed to support ERP research both in the laboratory and at field testing sites. The PEARL project became a major hardware and software development effort because the commercial marketplace did not offer a laboratory system that could satisfy the needs of a broad basic research program in psychophysiology. Existing systems could not satisfy two important requirements: First, they did not provide for the execution of a large repertoire of experimental paradigms. In general, commercial systems of the time allowed the user control over relatively few experimental parameters within a very small number of stimulus/response contingencies. Second, commercial equipment lacked adequate capability for the acquisition and retention of massive amounts of data. Most research applications demand that digital records of all raw data be stored for future analysis, which allows for removal of physiological artifacts and for thorough examination of the effects of experimental variables. Thus, PEARL was designed as a programmable, general purpose, laboratory computer system with the power to perform properly managed storage of relatively large volumes of physiological data concurrently with control of complex experimental paradigms.

The development of PEARL I was supported by the Health Effects Research Laboratory (HERL) Environmental Protection Agency, which was interested in using ERPs in field testing situations to assess the consequences of exposure to toxic substances. Scientists from the CPL and from HERL developed specifications for a basic hardware package which was designed to prove the feasibility of developing a portable laboratory computer system for ERP research. The technical staff of the CPL and members of the University of Illinois Computer Science Department collaborated in the design of PEARL I, which was successfully built and tested. One design criterion emphasized in PEARL I was portability and the system could indeed be stored in a large suitcase which could be carried by one person. However, this design limited the scope of the system and only relatively simple programs were developed for recording brainstem auditory evoked responses to clicks and for recording P300 potentials to infrequent tones which deviate from regularly presented standard tones (auditory oddball). The success of the initial PEARL project led to a cooperative agreement between the CPL and the EPA to develop an advanced version of the system (PEARL II).

The Air Force Aerospace Medical Research Laboratory (AFAMRL) also became interested in the PEARL project as a means to bring ERPs into their research program on human performance in complex man-machine systems, particularly in aircraft simulators. As noted above, the CPL had been investigating for several years applications of the endogenous ERPs in engineering psychology, and therefore collaboration with AFAMRL provided an excellent opportunity to expand these research efforts into more complex man-machine environments. With the added support of the Air Force, the PEARL project was enlarged to include development of production-quality laboratory interface hardware and to include a major software engineering effort designed to yield an extensive battery of psychophysiological tests. The result of this effort is the PEARL II system for research on ERPs in neurology, neurotoxicology, human engineering, psychopathology, and basic cognitive psychophysiology.

PEARL PROJECT GOALS

A set of eight project goals were established based upon discussions with collaborators in the PEARL project and upon consideration of our experience with larger minicomputers in ERP laboratories.

Goal I: Support for Common ERP Tests

Scientists associated with the PEARL project were interested in a variety of experimental tests, ranging from sensory evoked responses generated by simple stimuli to endogenous event-related potentials recorded in complex manual tracking and monitoring tasks. Because research applications for a given test vary considerably, we sought to offer many variations of each task through parameters that could be easily changed by the user. The need for flexibility in the test battery motivated selection and development of hardware capable of supporting a wide range of data collection rates and processing requirements.

Goal 2: Portability

All research organizations involved in the development of PEARL were interested in a portable system. We sought to design a system that could be packaged in a small number of packing cases, which could be transported in a van or by a commercial air carrier.

Goal 3: Suitability for Computer-Naive Users

Given the variety of tests in the battery and the variations of each particular test, design of a user-friendly system was important. We decided upon a menu-driven battery with a scheme for parameter selection that included levels of protection, legal range specification, and on-line help.

Goal 4: Support for Basic Research

Basic research in ERPs frequently entails extensive reprocessing of individual data records stored for each stimulus presentation. Many commercially available ERP computer systems do not offer this capability. In order to support off-line data analysis, a database management approach was specified that would allow storage and retrieval of single trial ERP records along with meaningful identification information and other dependent variables, such as subject responses.

Goal 5: System Completeness

Most investigators associated with the PEARL project wanted a complete package that would include hardware and software necessary to control experiments, acquire and analyze data and generate numerical and graphic reports. It was vital that scientists be able to execute their experimental plans without having to engage in extensive software or hardware development after delivery of the system. The frustration of watching months, sometimes years, pass between the delivery of equipment and the initiation of serious research is painfully common, particularly given the difficulty finding and retaining staff qualified to develop complex real-time programs. Thus, PEARL has been designed as a system that enables an investigator to begin research with basic ERP tests the moment the system is delivered.

Goal 6: Design Which Facilitates Test Development

In the hardware domain, specification of laboratory interface devices was guided by the particular needs of ERP research. The experience gained in more than a decade of research at the CPL was crucial in this case, with the result based on extensive practical experience. Our approach was to maintain interaction between scientists, engineers, and programmers during all phases of the project.

Minimizing processor overhead and maintaining precise timing of events during acquisition of a relatively large volume of data were crucial objectives in the design of the system. Many commercially available packages are unsuitable because they are not designed for the relatively unique requirements of the ERP research laboratory. Therefore, we sought to develop a software subroutine library (LABPAK) that would take full advantage of the hardware capabilities in the most efficient manner possible. Thus, development of a specialized, but flexible, programming foundation was a primary goal.

Goal 7: Standardized Hardware and Software

The core of the PEARL system was to be based upon standardized hardware and software development tools procured from a commercial vendor. This choice was made for two reasons. First, it was necessary to select components that would continue to be supported by the vendor for many years, given the common mortality of product lines in the computer business. For this reason, the Digital Equipment Corporation (DEC) LSI-11 processor and RT11 Operating System were selected as the foundation for the PEARL system (Note 5). Second, if users are to be able to develop their own test battery items, then a standard language processor is a requirement. RT1 l/FORTRAN was specified as the development system because the compiler generates efficient, reliable code and because most scientists are familiar with FORTRAN. Therefore, development of new testing paradigms was to be supported by a standardized software development environment (RT1 l/FORTRAN) in conjunction with the LABPAK library of FORTRAN-callable subroutines for flexible control of the specialized laboratory interface devices.

Goal 8: Modularity and Adaptability

Our approach was to develop a system that could grow to meet expanding needs in psychophysiological research by taking advantage of new computer hardware products. We also sought to configure the system so that additional interface modules could be added to increase data collection capabilities. Although PEARL was developed specifically for ERP research, the system is based upon a common microcomputer and it includes general-purpose laboratory interfaces and software.

ORGANIZATION OF PEARL DEVELOPMENT PROGRAM

The PEARL Development Program is an ongoing research project at the CPL, which has a technical staff dedicated to the project. The initial goals of the project have been satisfied and approximately twenty PEARL II systems are currently in operation. Through interactions with scientists at the several organizations utilizing PEARL systems, new ideas have been generated for ERP applications and for test battery development. In addition, the hardware configuration has evolved to take advantage of new products from the computer industry. Thus, the program continues to be a vital research and development effort.

Organizations that procure PEARL systems agree to become “user-testers” and to furnish feedback to the CPL on the operation of the system. This arrangement is designed to enhance the scientific value of the PEARL software available to participating institutions. Over the past eight years, the CPL has built more than twenty PEARL systems, including many that have been delivered to other laboratories (Note 6).

PEARL HARDWARE DESCRIPTION

PEARL II is a computer system based on a Digital Equipment LSI- 11 microprocessor. The hardware configuration includes digital input/output, programmable clocks, an analog-to-digital converter, digital-to-analog converters, a digital magnetic cartridge tape drive, and removable hard disk drives. The processor is connected to memory and peripherals via the standard DEC Q-Bus. Special purpose laboratory peripheral devices, packaging, software, and documentation have all been developed at the CPL. A special feature of the system is the modular front panel which features a flexible scheme for making connections and selecting signal paths (see Fig. 1, top)... A block diagram of the PEARL II system appears in the lower portion of Fig. 1.

The current PEARL II system includes an LSI-1 1/73 processor, 2 megabytes (MB) of memory, six serial I/O ports, six programmable clocks, parallel input/output (I/O), a 16-channel analog-to-digital (AID) converter, two dual-channel digital-to-analog (D/A) converters, two removable 10-MB Winchester disk drives, a 1/4-inch cartridge tape drive for data storage, power supplies, packaging, and software. The original PEARL II system utilized an LSI-11/23 processor, 256 kilobytes (KB) of memory, and dual DECtape-II units in place of the Winchester drives.

System Core

The PEARL II system is based on an LSI-11 processor and Q-Bus from Digital Equipment Corporation. The LSI-11 processor was selected because an extensive array of peripheral devices exists, a well-developed real-time operating system is available, and many scientists and programmers are familiar with DEC's PDP-11 series of computers. Another consideration was DEC's apparent commitment to support and expand this product line. This strategy has enabled us to take advantage of many new products in the Q-Bus family. For example, the central processor used in PEARL has been upgraded over the years as new versions have become available (from the LSI- 1 1/2, to the LSI- 1 1/23, and recently to the LSI- 1 1/73). Several laboratory interface modules, custom-designed by the CPL, were added to the core system. These modules are described in the following paragraphs.

Programmable Clocks

The PEARL clock module contains six individually programmable clocks capable of supporting the timing of complex testing paradigms. The availability of six hardware clocks permits timing of multiple intervals with a minimum of system overhead.

Analog-to-Digital Converter

The PEARL II A/D system consists of a 16-channel analog multiplexer, a 12-bit A/D converter, and a direct memory access Q-Bus interface. The system samples up to 16 independent channels of electrophysiological signals at rates up to 90K samples per second. The number of channels, total number of points, and sampling rate are all selected under program control. The modular construction of PEARL allows for the inclusion of additional A/D subsystems, which increase the number of channels in groups of 16.

Digital-to Analog Converters

The D/A system consists of four independent channels which are grouped into two pairs. In most applications, one pair will be devoted to driving an on-line display of waveforms on an oscilloscope for inspection by the system operator. The second pair of D/A channels is available for a variety of purposes, including presentation of auditory stimuli through headphones, generation of simple visual stimuli on a CRT, or driving other external devices that require analog input.

Maxi-Cartridge System

The maxi-cartridge system is one of PEARL's most important features because it allows a large quantity of data to be rapidly stored on a very compact magnetic cartridge tape. The tape system utilizes a 1/4-inch cartridge tape drive and formatter from Digi-Data Corporation. The cartridge system provides laboratory functions similar to industry standard digital tape drives on larger systems. Digitized data are rapidly transferred to tape from computer memory during experimental sessions. The data along with identification codes supplied by the program are recorded serially on tape for later retrieval and analysis. The total unformatted capacity of a single extended-length cartridge tape is approximately 17 million bytes, or 4-MB per each of the four tracks.

Digital Input and Output

A parallel I/O board provides 16 bits of input and 16 bits of output under program control. This interface enables PEARL II to interact with other digital devices and to sense signals from apparatus such as manual response units operated by the subject. The digital I/O unit includes a DEC DRV11 module with additional circuitry for response sensing developed by the CPL.

Other System Components

A complete PEARL laboratory package typically includes a Matrox video display generator, a graphics terminal, and a plotter. The display processor is used to produce visual stimuli such as checkerboard patterns for visual evoked potentials or words for cognitive ERP experiments. The graphics terminal presents on-line subject performance data to the experimenter and is also used for examination of ERP waveforms after each session. Hardcopy records of the waveforms can be made on the plotter. PEARL includes a four-line serial interface unit for system connections to units such as plotters, line printers, modems, voice synthesis modules, and other computer systems. The following devices have been connected to PEARL systems in one or more laboratories: counters for integrating multiple unit activity, a vector display generator, an additional video display generator, an array processor, and nine-track magnetic tape drives.

PEARL SOFTWARE OVERVIEW

A major goal of the PEARL project was development of a package of programs to support ERP tests, with each program allowing selection of the common versions of each test through parameter specification. This approach overcomes limitations in test flexibility and in program maintenance which follow from the manner in which laboratory research software is traditionally developed. In a typical research environment, programs are usually developed for the purpose of conducting some specific study and are rarely generalized beyond the needs of the study at hand. Consequently, recurring software development efforts are required each-time the experimental plan is-altered. Often, the result is a collection of programs -that are difficult to maintain because the software has been rewritten by several authors, with reasons

TABLE 1

PEARL ERP TEST BATTERY

1. Brainstem Auditory Evoked Potential (BAEP)
   Application: Basic neurological assessment of brainstem auditory pathways
   Major Variables: Stimulus intensity, duration, and rate.
2. Pattern Reversal Evoked Potential (PREP)
   Application: Basic neurological assessment of visual pathways
   Major variables: Checkerboard contrast, check size, and reversal rate.
3. Auditory Oddball
   Application: Cognitive abilities to classify auditory stimuli into sets defined by experimenter instructions. Often used as a secondary task to measure mental workload.
   Major variabiles: Stimulus discriminability, relative probability, interstimulus interval, and type of response.
4. Visual Oddball
   Application: Cognitive abilities to classify visual stimuli into sets defined by experimenter instructions.
   Major variables: Task (word classification, brightness judgment, color discrimination), relative probability, set size, interstimulus interval, and type of response.
5. Visual Monitoring
   Application: Cognitive abilities to process displays of varying levels of complexity.
   Major variabilies: Number of display elements, relative probability of significant events, interstimulus interval, and type of response.
6. Sternberg Memory Task
   Application: Short-term memory search task. Sometimes used as a secondary task to assess memory workload.
   Major variables: Set size, display size, masking, type of response, and presentation rate.
7. Jex Critical Tracking Task
   Application: Test of ability to perform a complex manual tracking task with visual display.
   Major variables: Target forcing function characteristics, response dynamics, and other difficulty manipulations.
8. Slow Potentials
   Application: Assessment of slow cognitive ERPs and motor potentials.
   Major variables: Task (simple reaction time, choice reaction time), foreperiod duration, stimulus probability, type of stimulus classification, and response type.
9. General Purpose Averager
   Application: Used in conjunction with triggers to enable ERPs to be recorded in response to externally-generated stimuli. Also, can be used to trigger external devices (somatosensory stimulators, for example).
   Major variables: Internal/external trigger, stimulus timing, event classification, and response type.

behind coding strategies obscured by successive strata of modification. In application areas where the nature of the research demands that large volumes of complex data be manipulated, the absence of a focused approach to research programming can lead to a geometric explosion of effort over time.

In the PEARL II Project, we have attempted to obviate the reprogramming cycle by raising to the level of preprogrammed parameter selection the manner in which ERP investigators can make substantial changes in a research design. Thus, the investigator specifies a particular version of a test by editing tables of experimental options, labels, and parameters, rather than by programming in a computer language. It is possible, by giving greater initial attention than is customary to the design of a experiment control/data acquisition program, to produce a program that is capable of running a large number of related research paradigms. Many tasks that previously required new programming become mere special cases of the' "battery style" programs.

Additional benefits accrue from the battery approach to laboratory software development. The presence of a significant degree of flexibility facilitates exploratory approaches to experimentation, similar to the range of investigation that many statistical packages give in data analysis. With the impediment of having to be concerned with new program development frequently eliminated, the researcher can be in a position to try out research directions that might otherwise have seemed too cumbersome to undertake. Another benefit of the battery approach is that by concentrating effort on a single general purpose program, rather than on an increasingly diffuse collection of programs, greater attention can be given to error checking and debugging. Also, new features added to a general program are instantly available to all the applications that utilize it.

The generalized software battery approach certainly does not satisfy all needs. Often, the best way to realized a new research idea will be to produce a custom computer program to conduct it. Research, by its nature, will always defy attempts to anticipate and to package solutions for the questions it might pose. However, for relatively mature, stable lines of research, the battery scheme can prove quite fruitful. For new directions, the existence of well-conceived programs for similar experiments can provide a valuable model. Further, the subroutine libraries and data management schemes underlying existing battery programs facilitate generation of programs for new experiments. The PEARL II LABPAK programming environment was designed to support development of programs for any sort of experimentation that might be executed with the PEARL hardware.

Within this context, it is useful to distinguish between two modes of operation of the PEARL system. In the *applications* mode, the user loads standard test battery programs by selecting the appropriate item from a menu of tests. The PEARL software battery includes flexible programs for visual oddball [3], auditory oddball [7], visual Sternberg task [17], visual monitoring [8], dual-task critical (Jex) tracking [11], warned oddball [15], brainstem auditory potentials [19], visual pattern reversal potentials [16], and heart rate monitoring [18]. Each program includes a parameter section that gives the operator considerable control over the manner in which the test is conducted. A brief summary of these tests may be found in Table 1.

In the *development* mode, the user interacts with DEC's RT11 operating system to develop applications programs which are then linked with PEARL device driver modules stored in a standard system library file. The software for the PEARL II system has been designed so that scientists or technicians with modest programming skills can develop applications programs in a high-level programming language. The laboratory support package supplied with PEARL (LABPAK) provides the programmer with a means to control all PEARL II laboratory devices (clocks, A/D converter, digital I/O, D/A converters, and cassette tape system) with standard subroutine calls from a FORTRAN program.

```
                         V I S U A L    O D D B A L L

Page Name:   User ID Directory                                 Page 1 of 39

Page ---->  : Data Parameters            Page ----> : Trial Parameters
Page ---->  : Block Parameters           Page ----> : Data Control
Page ---->  : Movement Rejection         Page ----> : Clipping Control
Page ---->  : External Triggering        Page ----> : Stimulus Generation
Page ---->  : Warning Control            Page ----> : Warning Words
Page ---->  : Digital Outputs            Page ----> : D/A Tone Control
Page ---->  : Fiatrox Control            Page ----> : Box Control
Page ---->  : Word Parameters

                 Type H for Help, Q to Quit this Section

ID Name    Type      Value    Units    Access      Low    High
-------    Direct    -----    -----    Constant    ---    ----

Data Parameters -- Basic Data Collection Parameters.
       This page contains the IDs controlling basic digitizing parameters
       such as epoch, number of points, and channel collected, etc.
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                         V I S U A L    O D D B A L L

Page Name:  Data Parameters                                    Page 4 of 39

Calc Epoch  =   NO    [Y/N]           Epoch     =   2000  MilliSec
Calc Rate   =   NO    [Y/N]           A/D Rate  =   5000  MicroSec
Calc Pnpts  =   Yes   [Y/N]           Points    =    401  #
Start Chan  =     1   [1-16]          Channels  =      5  [1-16]
Bytes Used  =  4010   Bytes           A/D Gain  =      1  [0-3]
Bytes Free  = 21590   Bytes

                 Type H for Help, Q to Quit this Section

ID Name    Type       Value    Units    Access     Low    High
Points     Integer      401    #        X1-1---    1      12800

Points -- Number of Digitizer Sweeps per Trial.
       "Points" is the number of Digitizer Sweeps per Trial the Analog
       Input System will make. Thus, "Points" Points will be recorded
       for each active channel.
```

FIG. 2. Menus are used to select and review parameters for each test. The first page in the parameter section contains a directory of groups of similar parameters (top). The operator can set parameters according to the specific plan for the experiment (bottom). The parameter menus are associated with an underlying data management scheme that provides range checking, protection, and user help.

THE BATTERY USER INTERFACE

Particular attention has been paid in the PEARL software package to the user/operator interface to the battery items. Such an emphasis seems appropriate for a number of reasons. First, an enhanced user interface can lead to an expansion in the number of investigators utilizing particular tests by reducing the level of computer expertise needed to execute the research. Second, a consistent, simple interaction scheme makes a software package easier for a novice user to learn. Third, as the number of parameters increase, a more powerful user interface is required to deal with the complexity associated with a flexible program.

The battery presents a menu driven user interface to the operator. The initial battery menu gives a list of the items in the battery. The novice user selects items with a cursor controlled by standard arrow keys on the terminal keyboard. After the user becomes familiar with the menus, the cursor-controlled menu selection process may be circumvented with a more efficient parallel, single keystroke *synonym* mechanism.

Each battery item presents the user with a main menu of its own. While there are item specific variations, the following options will typically be available:

Inspect or Alter Parameters
Run a Block of Trials
Manipulate Tape
Display Data
Exit this Battery Item

Parameter Specification

The first item on the menu allows the user to inspect or edit the table of option, text, and numeric parameters that configure each battery item to perform the specific task from among the domain of experiments it is capable of executing. This table is called the parameter dictionary. The parameter dictionary is organized into functionally related pages, that in turn are composed of individual parameters. A parameter directory appears as the initial menu in the parameter section; as illustrated in Fig. 2a. The directory menu leads to the next level of menus, which contain the individual parameter table entries, as displayed in Fig. 2b.

Parameter pages display groups of parameters using sym-

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B L O C K   P R E V I E W   I N F O R M A T I O N

Epoch Length:  2000 Milliseconds. Baseline:  95 Milliseconds.
5 Channels, 401 Points/Chan Digitized every 5000 Microseconds.
4010 out of an available 25600 Bytes/Trial will be Used.

Stimuli are Program Generated.
Trials:   96, 9 Category A Trials (9%), and 87 Category B Trials (91%).
Anticipated Block Duration: 12:48.
SOA will vary between 7200 and 8800 Milliseconds.

Visual Stimuli will be presented on the Matrox Display.

Catogory A Stimuli on Output Bit 0, Category B Stimuli on Bit 1.

Q to Quit, RETURN to Continue
```

V I S U A L   O D D B A L L

Trial	Stimulus	Response	RT	Resp. Code	SOA	G/T A	G/T B	EOG	EMG	PEAK
1	Potato	Category-B	511	Correct	8729	0/ 0	1/ 1	541	0	595
2	Mouse	Category-A	560	Correct	7716	1/ 1	1/ 1	320	0	630
3	Tomato	Category-B	495	Correct	8183	1/ 1	2/ 2	693	0	520
4	Bear	Category-B	598	Incorrect	7423	1/ 2	2/ 2	250	0	575
5	Horse	Category-A	576	Correct	7969	2/ 3	2/ 2	810	0	460
6	Birch	Category-B	554	Correct	7557	2/ 3	3/ 3	442	0	485
7	Maple	Category-B	521	Correct	8144	2/ 3	4/ 4	568	0	455
8	Radish	Category-B	509	Correct	8293	2/ 3	5/ 5	955	0	470
	Tulip	Category-B	517	Correct	7625	2/ 3	6/ 6	678	0	510
10	Rose	Category-B	490	Correct	7971	2/ 3	7/ 7	342	0	490
11	Violet	Category-A	588	Incorrect	8658	2/ 3	7/ 8	511	0	585
12	Giraffe	Category-A	567	Correct	8234	3/ 4	7/ 8	280	0	530
13	Monkey	Category-A	539	Correct	7871	4/ 5	7/ 8	535	0	495
14	Daisy	Category-B	543	Correct	7214	4/ 5	8/ 9	489	0	505
15	Lemur	Category-A	592	Correct	8603	5/ 6	8/ 9	306	0	550

PAUSED -- A or B for Sample Stimulus, RETURN to Continue

FIG. 3. The Block Preview allows the operator to review the characteristics of the experiment before beginning each session (top). During execution of the experiment, the investigator receives an on-line summary for each trial, including: stimulus, response, reaction-time, response code, stimulus onset asynchrony, good/total trials for each category, electro-ocular activity, electro-myogenic activity, and an estimate of the peak latency for the ERP component of interest (bottom).

bolic names, together with their current values, legal ranges, units, and access information. Some parameter values are designated as being for inspection only, while others can be changed by the operator. Those variables that are deemed accessible to the operator can be easily modified by first selecting a parameter, then entering a new value. Numeric parameters can be specified as a function of other parameters in combination with numeric constants. A calculator routine built into the battery user interface evaluates such expressions and places the result in the parameter dictionary as the new value for the edited parameter. Another significant feature of the user interface is the parameter description feature. A single keystroke provides additional descriptive information for any parameter to the user, as illustrated at the bottom of the screens depicted in Fig. 2. A help screen describing general parameter section facilities is also available.

Parameter tables are stored twice. First, after the user completes editing the table for a particular experiment, the parameter table is written to a disk file. This file can be read for future experimental sessions that will use the same set of parameters. Second, the parameter table, including symbolic names for all parameters, is written to the data storage tape at the beginning of each session. Thus, there is a complete record of all parameters attached to the data file for each session.

Run Section

After parameters have been adjusted according to the plan for the particular experimental session, the operator enters the Run section from the main menu. Initiation of the experiment is preceded by a capsule summary which previews the session, as illustrated in Fig. 3a. The Block Preview gives the operator a chance to recheck the experiment specification before data collection begins. If the operator elects to continue, presentation of stimuli and collection of data commence at this point.

During data collection, the operator is presented with extensive information as to the progress of the experiment. With the slow-wave ERP items, for example, a table appears on the operator's terminal giving values for such experimental trial variables as stimulus type, subject response time, estimated P300 peak, and ocular artifact activity, as in

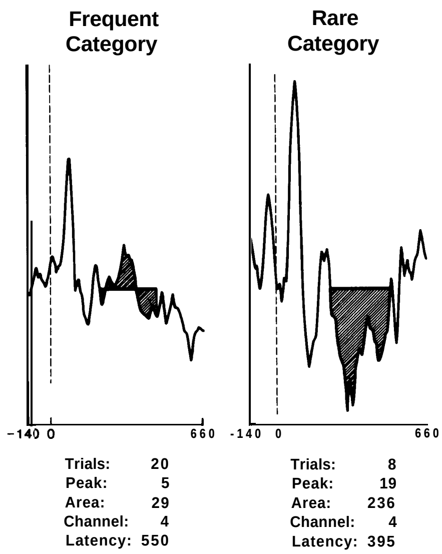

FIG. 4. The PEARL II display sections produce hardcopy plots of average waveforms for each stimulus category, along with the number of trials in the average, the electrode channel selected, and ERP component measurements determined by latecy and polarity parameters selected by the operator. Peak amplitude, component area, and peak latency are displayed.

Fig. 3b. In addition, a running average for any of the recorded leads can be displayed using the D/A system and an oscilloscope. This on-line display is especially useful for monitoring the integrity of the electrophysiological data path.

Display Section

Each battery item contains a Display section which offers waveform displays appropriate to the particular class of ERPs recorded in the experiment. In most cases, two types of waveform displays are offered: Distribution displays overplot waveforms for different electrode recording sites and Measurement displays present waveforms for assessment of basic experimental effects. The Measurement sections allow the experimenter to inspect and score waveform characteristics, including the peak amplitude, peak latency, and area of ERP components. The displays can be dumped to a plotter for hardcopy records (see Fig. 4).

PEARL II LABPAK LIBRARY

The PEARL II LABPAK Library is a collection of device interface and utility subroutines that allow access to the unique capabilities of the PEARL II hardware. The routines may be called from the FORTRAN level, so that all user program development can be done in a relatively high-level language. The core of the PEARL II LABPAK library has descended directly from the CPL's original LABPAK library, described in Donchin and Heffley [5].

The guiding philosophy behind LABPAK has been to employ fast, carefully coded assembly language subroutines for those functions where real-time or space constraints make using a high-level language impractical, while retaining the convenience of high-level language programming elsewhere. This approach, which is now widespread in the realm of research programming, allows complex application programs to be developed quickly and permits programs to be modified much more readily than would be the case if pure assembly language were used. The use of assembly language in the LABPAK subroutines in tandem with a high-level language processor (FORTRAN) that generates relatively efficient code at the applications level allows the PEARL programming package to fulfull real-time constraints that cannot be satisfied by lab-BASIC processors or pure high-level language implementations.

Program design is further facilitated by the ease with which PEARL II LABPAK routines allow the programmer access to the full power of the PEARL II peripheral devices. The PEARL devices are designed to perform their functions with a minimum of program intervention. For example, the LABPAK A/D routines allow the programmer to schedule with a single call a series of digitizer sweeps, with a specified number of channels, sweep interval, and total number of scans. The PEARL A/D system then conducts data collection in parallel with other system actions, freeing the processor for other functions. When a full bufferload of data have been collected, the program is notified via a designated flag variable. The PEARL II A/D, D/A, programmable clock and magtape systems may all be operated in this fashion.

LABPAK also contains a number of utility routines. Subroutines have been developed to perform certain operations that might be too slow if they were coded in FORTRAN. Examples of these sorts of operations are block data moves, running average calculation, and display device updates. Recent additions to the PEARL II LABPAK library are subroutines that allow LABPAK programs to access, with performance adequate for real-time applications, memory above the standard 56-KB boundary. These subroutines facilitate development of programs for experiments that require acquisition of large numbers of data points for each trial.

An unusual feature of the PEARL II LABPAK library is its built-in debug trace feature. The programmer may, should the necessity arise, specify that system generate a trace message and optional pause upon the entry to each LABPAK subroutine called from an application program. The programmer need do nothing special to generate programs with this ability; it is included with each program when it is linked with the LABPAK library. The user types a single-line RT11 command to enable the debug trace feature. LABPAK also augments the runtime error checking ability of RT11/Fortran by attempting to detect inadvertent changes to pure code or data. This is done using a checksum scheme.

While FORTRAN remains the primary language for the PEARL battery, the project has employed a FORTRAN preprocessor called FLECS [1] for program development. Standard RT1 l/FORTRAN lacks a number of features that are available in newer programming languages that make development of large applications program much more efficient. FLECS ameliorates many of the shortcomings of FORTRAN by providing features such as modem control structures and variable scope rules. The FLECS preprocessor accepts an input syntax that more closely resembles the C programming language than FORTRAN. The FLECS output is then converted into machine code by the standard FORTRAN processor.

SUMMARY AND EVALUATION OF PEARL PROJECT

The PEARL Project has several aspects. Successes and setbacks have been experienced in each domain, with many lessons learned.

As a Research Tool

The PEARL program may be viewed as an attempt to generate a research tool, specifically a portable experiment control/data acquisition system for ERP research. In this sense, the project has clearly been successful in that more than twenty fully-functional systems have been built and installed in various scientific research facilities, including a mobile van operated by the EPA. The CPL now relies on PEARL exclusively for all its laboratory systems. Although the system has not achieved miniaturization, developments such as removable Winchester disk drives have made the system more truly portable.

Computer Software Engineering

The PEARL Project had its roots in a collaboration between Psychologists and Computer Scientists. It remains a study in the application of ideas from computer science to practical programming problems. The PEARL Battery continues to explore the benefits of attempting to apply ideas such as integrated data management, good user interface design, and more extensive use of graphical presentations to psychophysiological research.

One lesson learned from the project relates to overconfiguring software relative to existing hardware. As the PEARL Battery development progressed, the capacity of existing microcomputer hardware was exceeded by the demands of the elaborate software package deemed necessary to satisfy project goals. Rather than abandon goals that had solid merit, an implicit decision was made to program beyond the abilities of the current hardward. Fortunately, microcomputer hardware and software systems (the LSI-1 1/RT11 family in this case) have now grown to the point where the PEARL Battery operates rapidly and efficiently. Had the project goals been set aside temporarily so that the PEARL Battery could be written to operate entirely within the bounds of microcomputer hardware from 5-10 years ago, we would now have a mass of software with an internal structure that would be totally inadequate to the full objectives of the PEARL Project. The practicality of rewriting a major software package is perhaps much less certain than the development of computer systems with faster processors and greater storage capacity.

Conclusion

As scientific research in psychology, physiology, medicine, and human engineering becomes more sophisticated, experimental plans will surely require more complex computer hardware and software for their execution. Further, research objectives in many disciplines call for studies involving greater numbers of subjects, which imposes additional requirements.

The "battery" approach to laboratory systems design offers considerable promise toward meeting the demands of these growing research programs. Good user interfaces and comprehensive data management facilities will be the hallmark of successful laboratory applications systems. In our experience with the PEARL project, we have learned the value of a highly interactive core development group composed of scientists, computer programmers, and engineers. Further, positive and open collaboration with other laboratories is vital in the development of general research tools.

REFERENCES

1. Beyer, T. *FLECS User Manual.* Eugene, OR: University of Oregon, 1975.
2. Donchin, E. Event-related brain potentials: A tool in the study of human information processing. In: *Event-Related Brain Potentials in Man,* edited by H. Begleiter. New York: Plenum Press, 1979, pp. 13-75.
3. Donchin, E. Surprise! ... Surprise? *Psychophysiology* 18: 493-513, 1981.
4. Donchin, E., M. G. H. Coles and G. Gratton. Cognitive psychophysiology and preparatory processes: A case study. In: *Preparatory States and Processes,* edited by S. N. Kornblum and J. Requin. Hillsdale, NJ: Erlbaum, 1984, pp. 155-178.
5. Donchin, E. and E. Heffley. Minicomputers in the signal-averaging laboratory. *Am Psycho1 30: 299-312, 1975.*
6. Donchin, E., W. Ritter and W. C. McCallum. Cognitive Psychophysiology: The endogenous components of the ERP. In: *Event-related Brain Potentials in Man, edited* by E. Callaway, I? Tueting and S. H. Koslow. New York: Academic Press, 1978, pp. 349-441.
7. Duncan-Johnson, C. C. and E. Donchin. On quantifying surprise: The variation in event-related potentials with subjective probability. *Psychophysiology* 14: 456-467, 1977.
8. Heffley, E. Event-related brain potentials in visual monitoring tasks: Selective attention, display format, and event frequency. Paper presented at the Annual Meeting of the Eastern Psychological Association, 198 1.
9. Hillyard, S. A., T. W. Picton and D. Regan. Sensation, perception and attention: Analysis using ERPs. In: *Event-Related Brain Potentials in Man,* edited by E. Callaway, I? Tueting and S. H. Koslow. New York: Academic Press, 1978, pp. 223–347.
10. Isreal, J. B., G. L. Chesney, C. D. Wickens and E. Donchin. P300 and tracking difficulty: Evidence for multiple resources in dual-task performance. *Psychophysiology* 17: *259-273,* 1980.
11. Jex, H. R., J. P. McDonnell and A. V. Phatak. A "Critical" tracking task for manual control research. *IEEE Trans Human Factors Elect* HFE-7: 138-144, 1966.
12. Kutas, M., G. McCarthy and E. Donchin. Augmenting mental chronometry: The P300 as a measure of stimulus evaluation time. *Science* 197: 792-795, 1977.
13. Otto, D. (ed.) *Multidisciplinary Perspectives in Event-Related Brain Potential Research.* EPA-60019-77-043. U.S. Government Printing Office, Washington, DC, 1978.
14. Otto, D., S. Bauman and G. Robinson. This volume.
15. Otto, D., V. Benignus, K. Muller and C. Barton. Effects of age and body lead burden on CNS function in young children: I. Slow cortical potentials. *Electroencephalogr Clin Neurophysiol 52: 229-239, 1981.*
16. Regan, D. *Evoked Potentials in Psychology, Sensory Physiology and Clinical Medicine.* London: Chapman & Hall, 1972.
17. Sternberg, S. Memory scanning: mental processes revealed by reaction time experiments. *Am Scientist 57: 421-457, 1969.*
18. Singleton, W. T., J. G. Fox and D. Whitfield (eds.) *Measurement of Man at Work: An Aparaisal of Physiological and Psychological Criteria in Man-Machine Systems.* London: Taylor and Francis Ltd., 1969.
19. Stockard, J. J., J. E. Stockard and F. W. Sharbrough. Brainstem auditory evoked potentials in neurology: Methodology, interpretation, clinical application. In: *Electrophysiologic Approaches to Neurologic Diagnosis,* edited by M. J. Aminoff. New York: ChurchillLivingstone, 1979, pp. 370-413.