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14. ABSTRACT *(Maximum 200 words)*:

This report developed under SBIR contract for topic # A96-025. Fatigue, stress, cognitive overload, and other factors cause errors as human operators perform task operations. The goal of this project was to develop, implement, and test a comprehensive system for measuring and analyzing human performance related data. Applications include basic psychophysiological research, evaluation of computer interfaces, evaluation of other task processes, and real-time performance monitoring. The developed system combines measurement and analysis of psychological, physiological, and performance measures into a single system. The combination and correlation of these three factors provides for a more robust and accurate assessment of total human performance. The development effort built off a strong foundation of prior research and development efforts for networked data collection, physiological monitoring, eye tracking, operator workload modeling, and advanced human-computer interfaces. The developed software system allows for synchronized collection of data from any number of networked devices and provides an array of signal analysis and display tools to support total performance assessment. The Phase II effort developed and implemented the human performance based measurement system and validated operation through a series of performance assessment experiments. The resulting system offers a comprehensive tool set for a wide range of human performance studies and related applications.

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1. Abstract / Executive Summary

Fatigue, stress, cognitive overload, and other factors cause errors as human operators perform task operations. The goal of this project was to develop, implement, and test a comprehensive system for measuring and analyzing human performance related data. Applications include basic psychophysiological research, evaluation of computer interfaces, evaluation of other task processes, and real-time performance monitoring. The developed system combines measurement and analysis of psychological, physiological, and performance measures into a single system. The combination and correlation of these three factors provides for a more robust and accurate assessment of total human performance. The development effort built off a strong foundation of prior research and development efforts for networked data collection, physiological monitoring, eye tracking, operator workload modeling, and advanced human-computer interfaces. The developed software system allows for synchronized collection of data from any number of networked devices and provides an array of signal analysis and display tools to support total performance assessment. The Phase II effort developed and implemented the human performance based measurement system, and validated operation through a series of performance assessment experiments. The resulting system offers a comprehensive set tools for a wide range of human performance studies and related applications.

2. Identification and Significance of Research And Development

Fatigue, stress, cognitive overload, and other factors can cause errors as human operators perform various task operations. It is therefore desirable to know when these conditions occur, and what result they are likely to have on performance. For many applications, it is also desirable to be able to identify individuals who can perform most effectively in critical decision-making operations, even when confronted with an abundance of information.

The overall goal of this project was therefore to develop, implement, and test a methodology and comprehensive system for measuring and analyzing performance related data for human operator tasks.

Initially, we envisioned that this technology would be applied to the task of systematically designing and evaluating interfaces for advanced military computer-based operations. As military computer systems and their corresponding interfaces grow more complex, the operator's (soldier's) task is also becoming more difficult. Interface designs that take into account the operator's cognitive processing can provide a higher level of *cognitive congruence* between the system the operator is using and the operator's existing internal mental models of environment and situation.

As we proceeded through the initial research stages of the effort, it became clear that the proposed system would have significant benefit for virtually any human task environment. We therefore broadened the scope of the development effort to encompass a the complete range of performance assessments, including both physical and mental factors.

Targeted applications include basic research studies that perform fundamental investigations into the nature of human performance. Or, a combination of research and development, such as the evaluation of computer interfaces or task procedures to aid in the design of improved task procedures. The developed system could also be used for real-time performance monitoring and feedback in industrial process or other human task environments.

The fundamental innovation of the developed system for human operator assessment system is the combined measurement and analysis of psychological, physiological, and performance measures in a single, comprehensive, flexible system. The combination and correlation of these three factors within in single, integrated system can provide for more robust and accurate assessment of human performance. Figure 1 illustrates the concept of fusing these three data types to achieve a comprehensive assessment of total human performance.

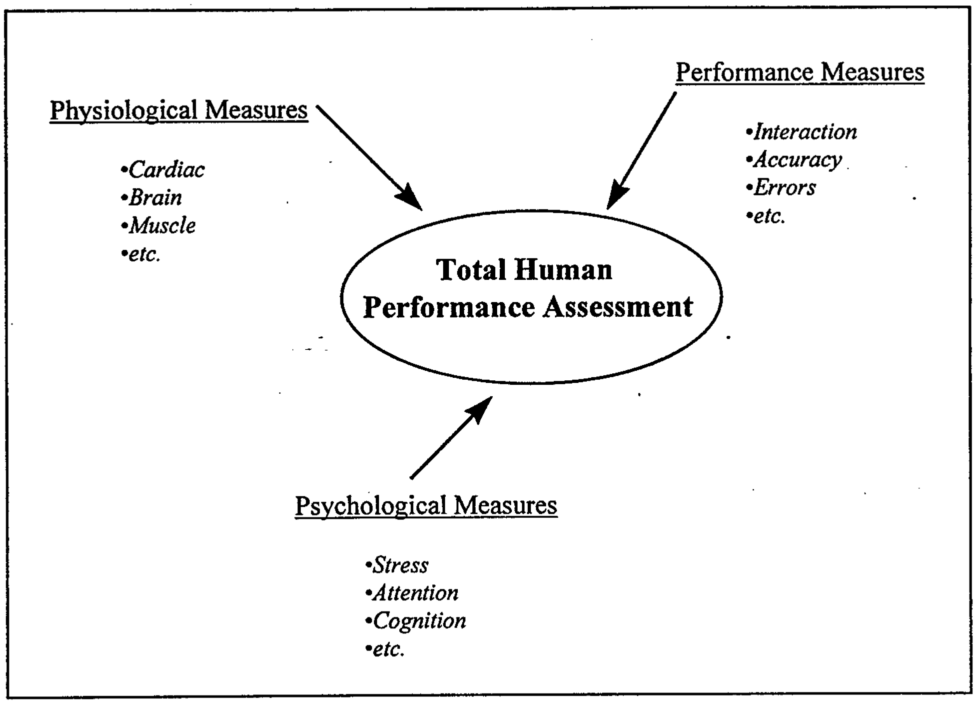


Figure 1: Total Human Performance Assessment through the Fusion of Comprehensive Performance-related Measures

Physiological parameters are fairly easy to measure, and provide valuable information about how a person is reacting to the physical, mental, and other demands of a given task. These measures can provide direct indicators of performance or may be used to help derive other indicators related to performance. For instance, physiological measures can be used to derive indicators of stress, fatigue, attention/alertness, and cognitive workload.

Psychological parameters, while not as directly measured, provide valuable insight into an operator's cognitive processes and perceptions and may allow us to determine what information an operator is considering as decisions are made. Subjective feedback from the human operator is sometimes the best means for acquiring such information. Some psychological measures can also be derived from physiological measures.

Finally, task performance parameters are measures of how an operator performs a specific task and how well the task is performed. These measures allow us to determine methodological factors of performance, and to quantitatively evaluate the effect that task demand has on an operator's performance. A complete assessment of human performance must incorporate measurements from all three of these categories.

Our development of a highly flexible and comprehensive system for human performance assessment has built off the foundation of research and development efforts previously accomplished at Cybernet for networked data collection systems and software, physiological monitoring systems, eye tracking systems, operator workload modeling, and human-computer interface systems. The complete system incorporates measurement of comprehensive performance measures (physiological, psychological, and performance) within a powerful, networked data collection and analysis environment. The data collection and analysis environment (DCAE) software allows for synchronized collection of data from any number of networked devices, and provides an array of signal analysis and display tools. This concept is illustrated in Figure 2.

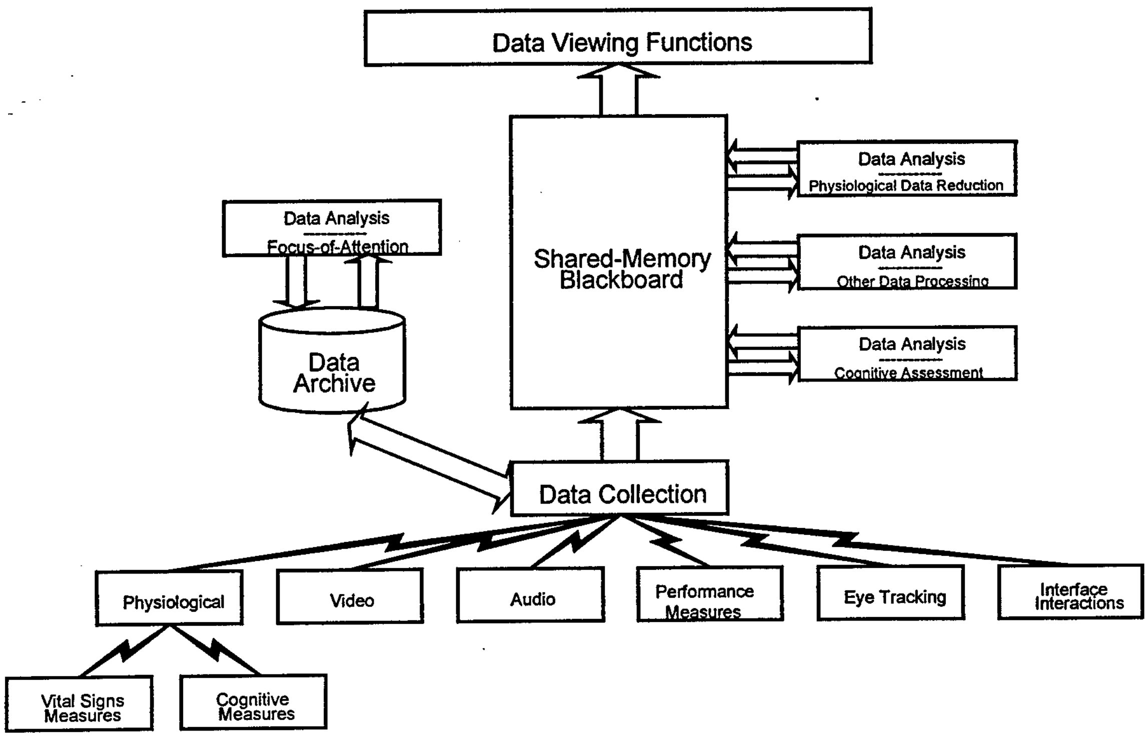


Figure 2: High Level Representation of the Human Performance Measurement System – integrating multiple data measurement systems into a comprehensive, distributed, data collection and analysis architecture

Primary measurement system components of the developed system include the portable physiological measurement system (PPMS), the eye tracking system (ETS), the body tracking system (FireFly) interface, and the video/audio capture mechanism, which are all integrated within the Data Collection and Analysis Environment (DCAE) software system. However, the flexibility and open architecture of this system allows for easy incorporation of additional data collection devices/measures as well as for integration of customized data analysis and evaluation functions.

The Portable Physiological Measurement System (PPMS) is a miniature computing platform that performs multi-channel data collection and provides network interoperability. Programmable signal conditioning features of the PPMS allow for measurement of virtually any signal. The system has a PCMCIA interface providing convenient hardware configuration using PC-cards for data storage (hard drives, FLASH cards), networking (Ethernet, wireless LAN), and other functions. Currently two versions of the physiological measurement system are available: a 16-channel device (shown in Figure 3), and an 8-channel device.

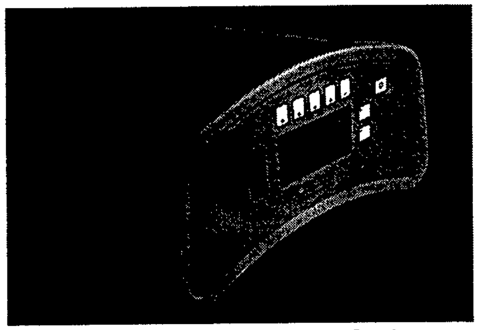


Figure 3: The 16 Channel Physiological Measurement System

The eye tracking system provides for measurement of a user's point of regard (gaze location) and other eye-related parameters, such as pupil size and blink. The eye tracking hardware consists of a head mounted eye tracking device (Figure 4) that captures a video image of the eye as well as a video image of the user's field of view. The specialized software system utilizes a client/server approach, where the user interface application runs on a client PC, and the eye tracking algorithms run on a server PC. This two system approach maximizes performance of the eye tracker. The eye tracking system may be used independently or as part of the HPBMS, where eye tracking results are recorded through the DCAE software.

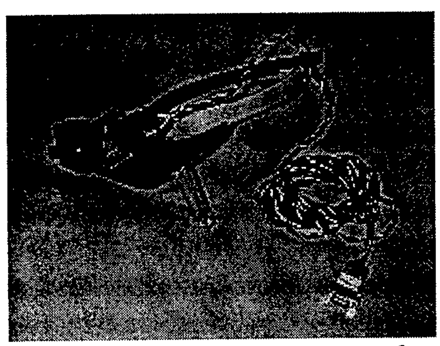


Figure 4: The Head-Mounted Eye Tracking Device

The Firefly optical motion capture system is designed to track the motion of any object (a human body, vehicles, models, etc…), using small infra-red emitting tags placed on the object. Figure 5 illustrates the basic concept. It is ideally suited for the development of computer games, the production of computer animation, as a input device for virtual reality applications, and in providing data for human biomechanic or ergonomic studies.

The Firefly may be used independently or as part of the HPBMS, where position data is recorded through the DCAE software.

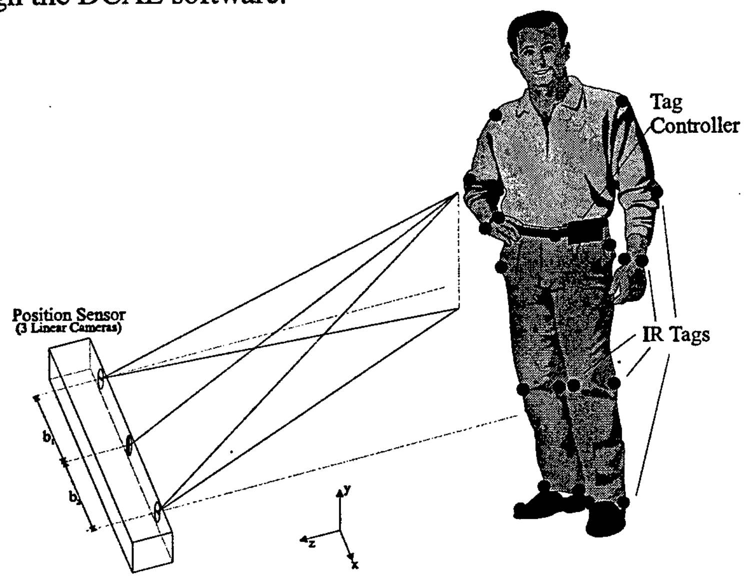


Figure 5: Illustration of the Firefly System Operation

Video and audio signal capture in the HPBMS is performed through the use of a PC-controlled VCR. The VCR can be connected to the serial port of any node within the data collection network. Initiation of video recording and control of synchronized playback is all performed through the DCAE software.

The DCAE software coordinates all data collection and analysis operations within the HPBMS. It allows for collection of data from any of the standard acquisition systems mentioned above, from acquisition systems that supply data through standard serial or TCP/IP protocols, or from custom developed acquisition systems. The system is operable throughout a distributed network of collection nodes, where all data is time and source stamped. Viewing and analysis tools allow for real-time viewing and processing of data being collected on any node within the network. After collection, synchronized playback and processing of all data collected may then be performed. Further details of this comprehensive software system are presented throughout this report.

One particularly unique aspect of the developed human performance based measurement system is the ability to measure and analyze brain activity through the electroencephalogram (EEG) signal. The EEG is a complex signal, representing the summation of all electrical activity of the brain measurable at the given electrode location. Extensive research has been performed, and continues, in the field of EEG signal processing, analysis, and interpretation. There have been many reports of significant changes in the EEG due to varying cognitive demand/workload. In particular, a significant increase in theta wave activity has been demonstrated to occur with increased mental workload (Wilson and Hankins, 1994). Studies have also demonstrated a suppression in alpha wave activity under certain types of cognitive tasks, with different levels of sensitivity in different areas of the brain (Sterman et al., 1993). From these and other studies, it has also been suggested that such measures can provide a means for evaluating the cognitive capacities of different individuals (Veigel and Sterman, 1993). Design and implementation of the HPBMS has therefore had particular focus on the development features related to the measurement, analysis, and display of EEG signals.

3. Physiological Assessment and Human Performance Measurement Taxonomy

3.1 Introduction

Measurement parameters to be made by the Human Performance Based Measurement System (HPBMS) consist of physiological parameters, psychological parameters, and performance parameters. By combining these measurements within a highly flexible and integrated system we achieve a more powerful and robust means of performing performance assessment.

Figure 6: Core Set of Physiological Measurements

Measurement Parameter	Measurement Technique	Sensor
Brain Activity	Electroencephalogram (EEG)	Surface electrodes on scalp (10-20 system)
Heart Rate	Pulse sensor; or computed from electrocardiogram (ECG)	Finger/ear clip (pulse sensor) or surface electrodes on chest (ECG)
Muscle Tension	Electromyogram (EMG)	Surface electrodes over selected muscle (i.e. trapezius)
Respiration Rate	Chest/abdomen belt; or impedance pneumography	Strain gauge or piezo-electric transducer (belt); or surface electrodes on chest (impedance)
Eye Motion	Electrooculogram	Surface electrodes placed adjacent to eye socket
Skin Impedance	Galvanic skin response (GSR)	Surface electrodes on finger
Event-Related or Evoked (stimulated) Brain Response	Event-Related Potentials (ERPs) and Evoked Potentials (EPs) are derived from the EEG	Surface electrodes on scalp (10-20 system). EPs additionally require stimulation method (visual, auditory, or somatosensory)
Cardiac Activity	Electrocardiogram (ECG)	Surface electrodes on chest (ECG)
Blood Pressure	Non-invasive blood pressure measurement	Auto-inflating pressure cuff on arm
Skin Temperature	Thermister	Placed on finger

Physiological parameters include all physiological-based measurements collected from the user, including brain activity (EEG), heart rate, muscle activity, etc. Figure 6 presents the set of core physiological measurements that were targeted for measurement with the developed system. However, given the programmable nature of the system, virtually any physiological measurement may be acquired. The primary means for acquisition of these parameters is through the physiological measurement systems.

Psychological parameters can be derived from physiological measures, assessed through subjective self-reporting evaluation (see Section 3.9), or evaluated by a trained observer. These parameters will therefore be acquired either through the physiological measurement system or through the use of evaluation forms. For enhanced and/or automated analysis the forms may be entered through the computer interface.

Performance parameters include all measurements of the user's interaction and performance achievement for the given task. These measurements will be dependent upon the performance environment, the tasks involved, and the user interface specifics. User interaction includes all measurements of the user's activation and usage of the user interface tools, such as joysticks, steering wheels, keyboards, etc., or physical interaction in a non-computer interface environment. Performance parameters may include measures such as time for completion of a task, accuracy, or number of errors committed. Performance and user interaction parameters can be assessed in real-time through active software running on the user interface platform, through visual monitoring of the procedure, and/or through post-collection review of the experiment, as appropriate.

While the measurement of performance parameters is fairly straightforward, the measurement and analysis of physiological and psychological parameters can be quite complex. The following sections provide a detailed review of psycho-physiological measures and their relevance to performance assessment.

3.2 Electroencephalogram (EEG) Measurement and Analysis

3.2.1 Introduction

The electroencephalogram (EEG) provides the information on brain activity that occurs during mental and physiological functioning, and has been used in the understanding of mental workload, cognitive processing, vigilance, alertness and performance. EEG patterns change as a function of arousal and alertness, and this phenomenon is being used as a method of assessing and monitoring performance. The feasibility and utility of topographic EEG in a multi-task environment makes it possible to associate cognitive changes with increased or decreased performance.

From scalp recording of brain electrical activity it becomes possible to reliably locate regions of brain activated by specific cognitive paradigms or functional activities. EEG scalp recordings are most often recorded utilizing many electrodes in an arranged pattern or montage. A common standard for describing these position is the International 10/20 System.

Figure 7 shows the 10-20 International System of electrode placement. The term 10-20 is used because the electrodes are placed either 10% or 20% of the total distance between a given pair of skull landmarks. The landmarks on the skull have a topographic relationship with the 10-20 system electrodes and areas of the cerebral cortex. The relationship comprises five points that are located on the line that connects the nasion to the inion: Frontal (Fp), Occiptial (O), Parietal (P), Frontal (F), and Central (C).

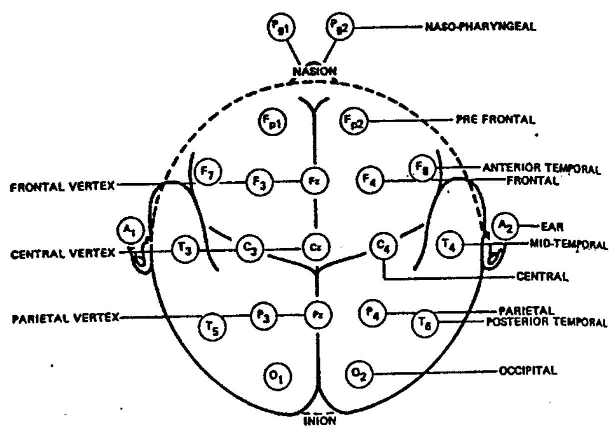


Figure 7: The 10-20 International System of Electrode Placement

The 10/20 system allows the experimenter to associate changes in wave activity with certain regions of the brain. Topographic maps show the spatial distribution and significance of the changes in these waves. Simple linear regression analysis between EEG power spectrum data and task parameters can reveal strong correlations with one another; furthermore, these correlations can be associated with different regions of the brain. These recordings can then be placed onto a paper chart or more commonly digitized into a computer for frequency analysis.

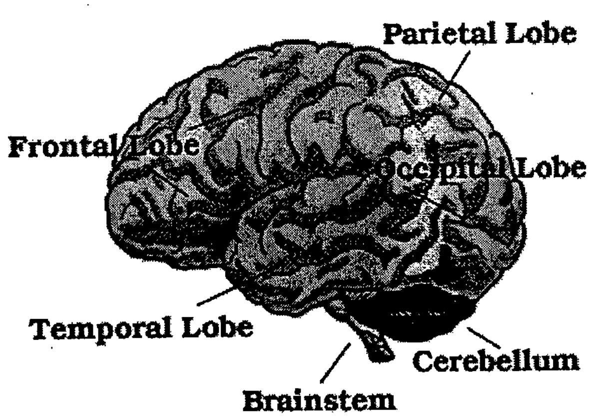


Figure 8: Topographic Relationship Between 10-20 System Electrodes and Areas of the Cerebral Cortex

Figure 8 shows those areas of the cerebral cortex with relation to the 10-20 system of electrode placement.

- The frontal lobe: The frontal lobe is believed to be the cortex of the brain and indeed, it controls motor activity by regulating the contraction of red muscles. However, it is interesting to mention that some sensory data is also processed by this lobe. Thus, "cutting" this lobe (lobotomy) prevents the sensation of pain and also inhibits sexual behavior.

- The parietal lobe: This lobe resides back from the frontal. The parietal lobe processes most of the sensory data that comes from the body.

- The occipital lobe: This lobe is located at the lower back of the cortex. It has one main function: processing all visual data. Therefore it also known as the visual cortex.

- The temporal lobe: This lobe is located at the side of the hemisphere. It has important role in speaking and understanding language, hearing and stability.

3.2.2 EEG Frequency Bands / Waveforms

There are many EEG waveforms that are indicative of both normal and abnormal psychological states. Lindsley (1960) developed a classification system to differentiate these wave forms, as shown in Figure 9.

Figure 9: Description of EEG Waveforms, Scalp Locations and Physiological States

Type of Waves	Frequency range	Amplitude (Volt)	Percent of Time Present	Regional or Diffuse	Region of Prominence	Condition when Present	Normal or Abnormal
Alpha	8-12	5-100	5-100	Diffuse	Occipital or parietal	Awake, relaxed Eyes closed	Normal
Beta	18-30	2-20	5-100	Diffuse	Precentral & frontal	Awake, No movement	Normal
Gamma	30-50	2-10	5-100	Diffuse	Precentral & frontal	Awake	Normal, Sleep deprived
Delta	0.5-4 0.5-4	20-200 20-400	variable variable	Diffuse Both	Variable Variable	Asleep Awake	Normal Abnormal
Theta	5-7	5-100	variable	Regional	Frontal & temporal	Awake, affective or stress stimuli	Normal Abnormal
Kappa	8-12	5-40	variable	Regional	Anterior & temporal	Awake, problem solving	Normal
Lambda	Pos. or neg. spike or sharp waves	5-100	variable	Regional	Parieto-occipital	Visual stimulus or eye opening	Normal
K-Complex	Pos. sharp waves & other slow pos. or neg. waves	20-50 50-100	variable variable	Diffuse Diffuse	Vertex Vertex	Awake, auditory stimulus Asleep, various stimuli	Normal Normal
Sleep spindles	12-14	50-100	variable	Regional	Precentral	Sleep onset	Normal

The EEG itself is made up of waves of different frequencies each relating to different aspects of mental life. EEG is usually described in terms of these waveforms: Gamma (>30 Hz), Beta (13-30 Hz), Alpha (8-13 Hz), Theta (4-8 Hz) and Delta (<4 Hz).

Delta: Delta frequencies are the low frequency waveform. These are less than 4 Hertz and occur during sleep and in some abnormal processes. The presence of delta waves in the awake state is a sign of brain abnormality.

Theta: Theta frequencies are around 7Hz and are believed to reflect activity in the hippocampus and limbic system (a group of structures deep within the brain that are generally believed to play a role in emotions). They have been implicated in drowsiness, anxiety, behavioral activation and behavioral inhibition. The hippocampus anterior portion of the limbic cortex helps to suppress the rage phenomenon. For instance, if these portions of the limbic system are damaged a person or animal becomes far more susceptible to bouts of rage.

Theta rhythm also appears to function normally to mediate and/or motivate adaptive, complex behaviors such as learning and memory. If theta rhythm is not expressed most strongly under unusual emotional circumstances (e.g. stress; or in disease states; e.g. schizophrenia; or drug abuse) there may be an imbalance of three major transmitter systems. Thus, in the waking EEG, theta activity is an indicator of drowsiness or disease. With all this in mind, the technicians observations and notations concerning the subjects behavior are important during performance testing.

Alpha: The most prominent feature of EEG is the posterior dominant rhythm. It is the feature of brain electrical activity that was first described in 1929 by Berger, who named it alpha. This is the 8-13 Hz rhythmic activity that occurs most strongly over the occipital (back of the head), parietal, and frontal cortex.

Contrary to popular belief, alpha is a common state for the brain and occurs whenever a person is alert (it is a marker for alertness or sleep), but not actively processing information. In other words alpha activity is a dominant feature in EEG in the awake, relaxed adult. Alpha has been linked to creativity (creative subjects show alpha activity when listening to and coming to a solution for a creative problem), and mental work.

The alpha rhythm of an awake resting adult is best seen when the person's eyes are closed. Opening the eyes results in an attenuation of the alpha rhythm. Reactivity to eye opening is typically used as evidence that the activity is indeed the alpha or posterior dominant rhythm. Mental effort or focusing ones attention can also attenuate the alpha rhythm. The attenuation is dominant in the central and parietal sites of the brain.

Beta: The brain state that most of the brain is in when we have our eyes open and are listening and thinking is called beta. Beta activity, which consists of frequencies higher than 13Hz and up to 30 Hz, is also dominant during states of concentration and attention activity.

Beta tracings are best seen from the anterior regions, it is commonly present in the posterior regions as well, albeit masked by alpha rhythm.

nGamma: The highest frequency is called gamma and contains waves of 35Hz and up. In contemporary research there is a great deal of speculation that this wave might reflect the mechanism of consciousness.

3.2.3 Topographic Representation

Topographic display and analysis of EEG data has experienced a rapid escalation in utilization over the past several years due to the advanced tools and techniques that have been developed. The rationale for topography is that the traditional EEG tracings contain information which under normal circumstances is not easily appreciated by the naked eye. There is too much data and it is in a form unsuited for visual analysis.

The first step for topographic representation is typically to return to the time domain after a frequency analysis is made, and then make an estimate of generators in one period of the sine wave representing one Fourier component (Weinberg, et al., 1989). In this instance:

- The first stage is to record the distribution of the electrical fields over the head.

- The second stage is to do a Fourier analysis of the recorded data for each position. The Fourier analysis is used to extract a single frequency from the EEG and plotted in the time domain for different locations over the head

- The third stage is to select a particular frequency, or frequency band, of interest, e.g., 8Hz and do the inverse computation for that frequency.

- The next stage is to select a method to achieve spatial resolution of the EEG signals. Spatial resolution is the ability of a method to distinguish separate signal sources that are positioned close to one another. This is primarily achieved by increasing signal-to-noise, and image resolution through interpolation.

One method for spatial resolution is the Laplacian Derivation; this method involves the computation of the 2nd derivative in space of the potential field at each electrode position. It converts the potential at an electrode to a quantity that is proportional to the current that enters and exits the scalp at that site.

Deblurring is another approach for spatial resolution of EEG signals, using a realistic biophysical model of the passive conductive properties of the subject's head, to estimate the electrical potential distribution. The following steps are followed in this method:

1. measure the size and shape of the head
1. measure local scalp and skull thickness
1. estimate local skull conductivity
1. use a mathematical model to correct EEG signals for distortion

Common mathematical models include the finite element model, spherical model or the boundary integral model of the cortex, cerebrospinal fluid, skull, and the scalp, to estimate potentials that would be recorded on the surface of the brain.

Topographical changes in the EEG data as a function of mental task difficulty were studied by Fisher and Wilson (1995). Their objective was to determine the parameters of EEG associated with task difficulty. 19 scalp electrodes were used to record the EEG data, and analysis was done in a frequency range of up to 32 Hz. The data was transformed into spectral measures averaged for the entire task spanning a duration of 3 minutes, with the tasks being considered as entities. Mental workload was assumed to be a function of three factors:

1. energy expenditure
1. amount of the available processing resources used
1. the build up or consumption of resources

Topological evaluation was done by correlating the full cross-spectral matrix for the set of signals from the 19 scalp electrodes. Data was displayed as topological brain maps (Duffy,1986). Results showed a reduction in the parietal and occipital alpha power during the visual scanning task, and an association of theta activity to attention. Retinal involvement of oculo-motor control was attributed to the observations recorded with the visual scanning task.

3.2.4 EEG Experiment Design

The most important criteria in the collection of EEG data is a well controlled experimental design, which can minimize the effects of demographic (age, gender, handedness) and behavioral variations on the data.

Two types of experiments can be used, namely, those where the subject's attentional state is not controlled, and others where it is. In the second type of experiments, the subject's attention is controlled by instructing him/her to perform simple goal-directed tasks. Additional factors that will be controlled in these experiments are expectancy, stimulus properties, cognitive and response requirements, task difficulty, learning, and subject arousal. Constancy of subject arousal level is monitored by behavioral criteria such as accuracy of response, and the response-reaction time. The effects of fatigue and practice on EEG data are minimized by manipulating the task difficulty over time.

Another important issue in experiment design is sample size. Due to lack of knowledge on the nature of data, a statistical power analysis cannot be performed easily, and instead, simple rules have to be followed in determining sample size. The number of persons to record data from, is usually chosen by practical considerations, with a minimum of seven subjects, meeting the minimum requirements of the simplest statistical tests.

With regard to the number of data samples to be collected per subject, common sense "rules of thumb" are followed. Sufficient data is gathered so that there are at least 10 data observations for each independent EEG or ERP variable under each category of the experiment.

The third factor in experiment design is the length of the EEG sample, or the number of trials to include in each average ERP. In the case of EEG signals, it has been demonstrated that 30 second to 2 minute samples are sufficient to characterize the intra-subject variability of the background EEG. With respect to ERP signals, the number of trials must be sufficient to distinguish the Event Related Potential from the unrelated background EEG.

3.2.5 Data Collection

The first step in the recording of EEG data is to determine the optimal number of electrodes to use and their position on the scalp. With respect to the number of electrodes used for the collection of EEG signals, any number from 1 to 256 can be used. The greater the number of electrodes, the greater is the spatial accuracy and source localization of the signals. Generally 21 (19 + 2) electrodes are used in the International 10-20 format. Ideally it is preferred that 64 to 512 electrodes be used, with 256 being the optimal number.

The locations for placement of the scalp electrodes has been standardized since 1958 (Jasper, 1958) through a system called the International 10-20 system. This system uses four reference points: the inion (small bump at the back of the head), the nasion (small cavity at the base of the nose), and the right and left preauricular (mastoid) points (tiny cavities above and behind each ear), and 19 active sites. For standard EEGs, the linked mastoid references are commonly used. The organization of electrode placement on the scalp is illustrated in Figure 10.

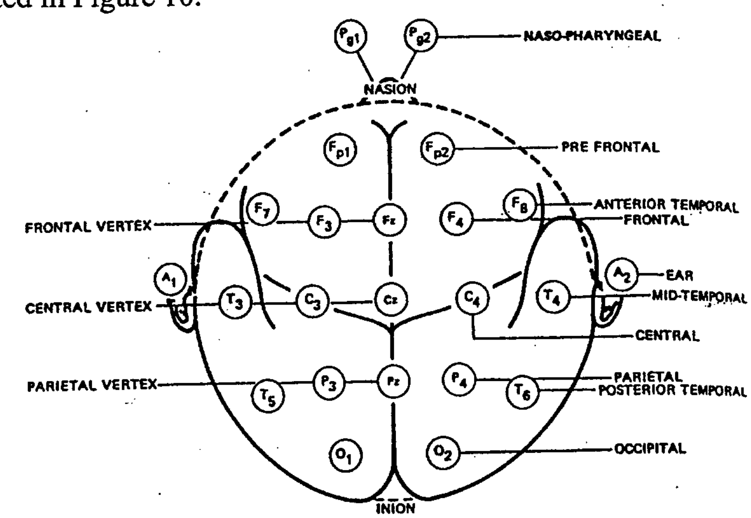


Figure 10: Electrode Locations in the International 10-20 System

Electrodes are placed on the scalp at points that are 10 and 20 percent of the distance from the lines of the nasion to the inion, and from the left to the right mastoid points. The capital letters F, T, P, O and C marking each electrode location refer to the frontal, temporal, parietal, and occipital lobes and the central sulcus respectively. Odd numbered channels represent locations on the left and even numbers the locations on the right side of the brain. The full 10-20 montage involves all 19 electrodes additionally supplemented with two leads to record eye movements (EOG), making it a total of 21 channels to record. Eye movements are recorded since they produce artifacts in the EEG recordings. Other artifacts are caused by eye blinks, head movements and muscle activity especially of the temporalis and the masseter.

An important challenge in the use of multiple electrodes is to determine the accurate spatial positions of these electrodes. Determining the position of the electrodes on the scalp helps in the correlation of the EEG signals with the underlying brain anatomy. One method developed by Gevins (1992) uses a flexible grid of electrical field sources or nodes in close proximity to the head, and measures the potential induced in each electrode when each node in the grid is activated. He suggested the use of resonant circuits or switch points as nodes, which formed a grid on a flexible cap. The relative position of each node is calculated by interpolation from the pattern of induced voltages.

EEG data can be recorded in two ways namely as analog data, or as directly digitized data. The advantages of direct digitization of EEG signals over analog recording are several, the most important of which is the avoidance of noise patterns that resemble brain waves (e.g. theta band activity).

Signal conditioning is an essential process in the recording of EEG data. Linear-phase filters with high attenuation outside their passband (for example, 24 dB or more attenuation per octave outside their passband) are used. There are several cutoff values for EEG signal conditioning, the most common bandpass being 0.5 to 70 Hz for EEG studies. The bandpass values of the ERP signals are as follows:

1. Brain Stem ERP: 50 - 150 Hz to 3000 Hz
2. Exogenous ERPs including pattern shift visual ERP: 1 to 100 - 300 Hz
3. Endogenous ERP studies: DC 0.01 to 16 Hz

Sampling rate for digitization needs to be at least twice the highest frequency at which the filtered potentials have negligible power. This frequency is also called the *Nyquist* frequency.

The conversion of EEG signals to a digital representation is usually done with 12 bits of accuracy, between plus and minus 2048, or 4096 levels of quantization. In order to represent the EEG with maximal accuracy, the amplitude of the largest waveform that needs to be recorded without distortion should span most of the numerical range of the A/D converter. It is also essential not to exceed this numerical range in order to avoid saturation of the A/D converter's range. It is advisable to save some spare A/D range to allow for changes in the DC level of the signal.

For example if abnormal adult delta band EEG activity has to be recorded, the full A/D range should correspond to plus or minus 500 μV (600 μV for the EEG and 400 μV for the spare A/D range). If the full scale input range of the converter is plus or minus 5 V, each microvolt of EEG will correspond to 0.01 V at the A/D converter. Each microvolt will be represented by 4 quantization levels when a 12 bit digitization is used. Optimization of the range of the A/D converter can be achieved by adjusting the sensitivity of the EEG amplifiers with a well chosen test signal, and monitoring the voltage at the input to the A/D converter.

Another factor that requires consideration is the finite amount of time required to digitize the signal, resulting in a time difference between sampling the first and last channel. An unwanted difference in sampling time can systematically distort the precise measurements of interchannel phase and time delay. This can be remedied in two ways, namely, using a "sample and hold" A/D converter which stores the voltage of all the channels at the same instant, or following the time consuming procedure of numerically interpolating the digitized values to compensate for the systematic time shift during the digitization.

3.2.6 Data Preparation

There are several steps involved in data preparation prior to analysis of the digitized EEG signals. These include:

1. Topographic representation
2. Digital filtering
3. Numerical calibration
4. Artifact rejection
5. Creation of data sets.

<u>Topographic representation</u>
Topographic representation was previously discussed in Section 3.2.3.

<u>Digital Filtering</u>
Digital filtering is a process by which unwanted frequency components are removed, or frequency bands of interest are isolated from a signal. For example, contamination of the EEG signal by the 50 Hz or 60 Hz power lines, as well as their harmonic frequencies can be removed. There are simple software programs that apply a series of weighting and summing arithmetic operations according to precise formulas (Oppenheim and Schafer 1975; Rabiner and Gold 1975; Peled and Liu 1976; Oppenheim et al. 1983). Programs for designing digital filters with user-specified bandpass and stopband parameters are available from IEEE (1979). In general, non-phase-shifting filters (non-recursive filters) are used in order to measure the timing relationships between channels.

<u>Numerical Calibration</u>
Numerical calibration is a procedure to determine the gain correction factor that has to be applied to each sample of the digitized data. This is done by passing a calibration signal through the amplifiers, filters, and the A/D converter. Single frequency sine waves, square waves, and swept-frequency sine waves are commonly used as calibration signals. The choice of the signal depends on the purpose of the analysis. Sine waves resemble

ongoing brain wave activity and can pass through a recording system without distortion. Square waves contain abrupt transitions that mimic the effects of paroxysmal events, while swept frequency waves provide gain calibration at the high and low cutoff frequencies in passband amplifiers and filters. It is standard practice to record a calibration signal at the beginning of every recording session, and to apply the correction factor to each channel of data to compensate for inter-channel differences in gain.

When a new system is first installed, it is good practice to perform a sweep of the entire frequency range of the recording system's passband to determine if different gain factors need to be applied for the different frequencies. Very long recordings should also be made to determine the magnitude of temporal variations. If it is found that the signal is significantly attenuated or amplifies at the edges of the desired passband, it is often simpler to record with a broader bandwidth, and digitize at a higher rate, than to perform frequency specific calibration corrections.

A second type of calibration correction is performed for significant phase differences between channels, a procedure that is advisable when studying inter-channel time delays. These differences are measured by sending the same signal through all the amplifiers, and computing the correction coefficients based on any cross-spectral phase differences.

Another type of calibration signal is a zero level input obtained by shorting all the input channels to ground, prior to the A/D converter, which allows the measurement of noise and the DC offset of the amplification and recording system due to thermal noise in the amplifiers, loose or dirty electrical connections, and ambient electrical or magnetic fields.

Artifact Rejection

Removal of artifacts from EEG data is an essential step prior to data analysis. Traditionally visual inspection of data has been used for artifact removal, a procedure that is prone to subjective bias. There are several sources of artifacts in the recorded EEG signals. Drowsiness of the subject during the experimental session can cause an artifact that can be confused with a pathological slowing of the EEG. The three major classes of artifacts include:

1. Head and body movements, perspiration, and low frequency instrument artifacts (under 1 Hz),
2. Eye movements (under 3 Hz in the frontal channels), and
3. High frequency artifacts including gross muscle potentials from scalp and tongue muscles (34 - 50 Hz).

In most instances the best method for removing artifacts is by visual inspection. However for the purpose of removing eye movement potentials (EOG), subtraction of a weighted and simultaneously recorded EOG signal from each channel of EEG, is currently followed. One of the more popular artifact rejection algorithms is short-time spectral subtraction developed by Whitton et al. (1978). In this method, the differences in the spectral signatures of eye movement and brain signals are used to create filters, which then remove eye movement contaminants from each trial.

A recent adaptive interference canceler for EEG movement and eye artifact has been developed by Gevins et al. (1996). A sketch of the system is illustrated in Figure 11. The head and body movement reference signal is provided by an accelerometer or motion detector, and the spatial averages of the EEG channels. Eye motion sensors are used as a reference for eye movement artifacts. A composite reference signal consists of the head, body, and eye movement reference signals. The contaminated EEG is the primary input to the adaptive movement and eye artifact canceler, in which an adaptive filter estimates the contaminants in the measured EEG data, and subtracts them from the primary signal to obtain the corrected EEG data. This methodlogy is discussed in detail in Appendix B.

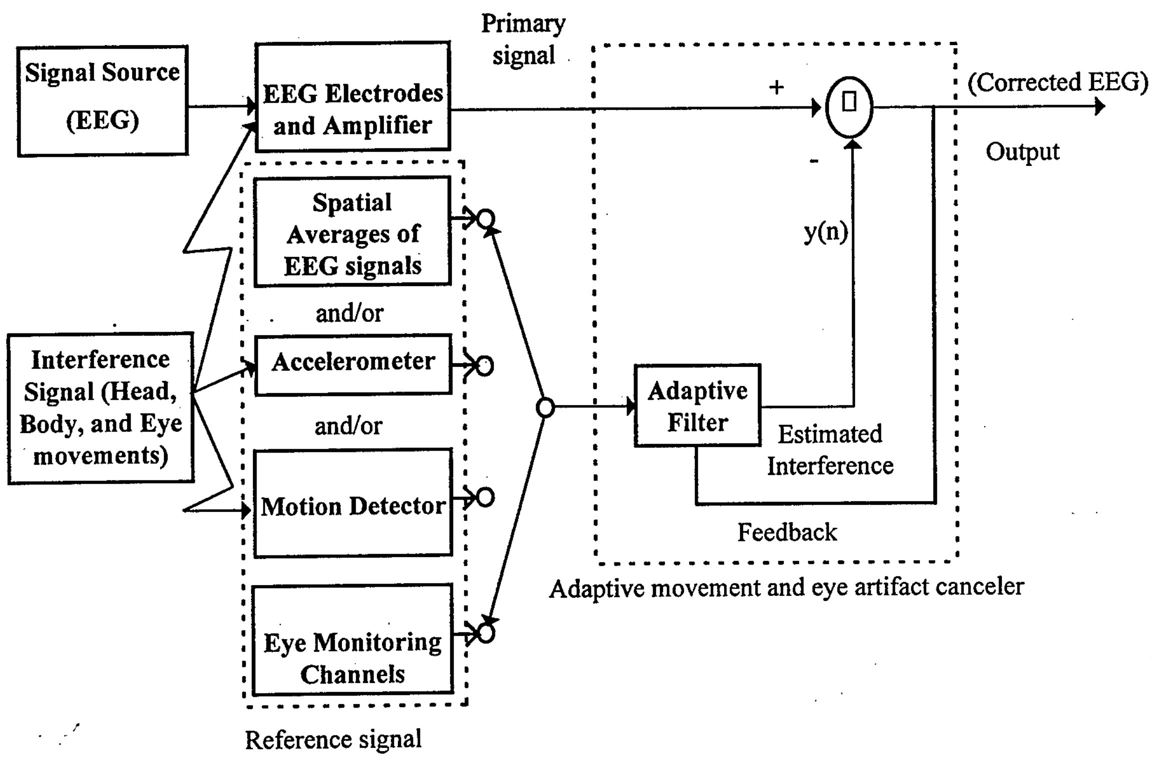


Figure 11: Adaptive Interference Canceler (Gevins et al., 1996)

<u>Data Set Formation</u>

The final step in data preparation is to look for outliers, and to check that the data meet the *a priori* specifications for experiment control. This process involves observation of behavioral measures of the subject, such as reaction time or response accuracy, for each observation or trial. If the behavioral data is significantly out-of-range, the EEG and ERP data collected during this segment can be discarded.

3.2.7 Primary Analysis

Following the preliminary data preparation steps of signal conditioning, digitization, artifact rejection, and formation of data sets, primary analysis is done to extract meaningful information from the data. The major objects of primary analysis include the analysis of background EEG, event-related signals, and/or spatial processes.

Background EEG can be analyzed in two ways namely, frequency analysis and non-stationary analysis. The most common method of characterizing the frequency content of background EEG is by the use of Fourier analysis, which results in the power and phase spectra of the EEG data. The power spectrum results from taking the sum of the energy of the sine and cosine waves at each frequency, while the phase spectrum is the inverse tangent of their ratio.

The results of spectral analysis are often grouped into traditional frequency bands, namely, delta (less than 4 Hz), alpha (8 - 13 Hz), beta (14 - 30 Hz), and gamma activity (above 30 Hz). However, the use of these traditional frequency bands has to be based on the types of experiments that are conducted. For example, in the case of EEG recorded from children, the delta and theta bands may have to be divided into additional bands. Also other measures derived from the spectrum, such as the peak frequency in each band may be more sensitive to specific experimental manipulations than the energy in a band.

The most popular method of performing frequency analysis is the application of the Fast Fourier Transform (FFT) algorithm directly to short segments of digitized data, usually 1 to 4 seconds long. These digitized time series segments have to be prepared for the FFT by first removing any non zero mean and trend in the segment, and then smoothing the abrupt discontinuity at the edges of the segment to avoid spurious spectral components. A detailed description of the method of performing spectral analysis is provided in the following section.

From a mathematical/statistical point of view, the EEG represents a set of continuous voltage/time graphs and can therefore be considered as a multivariate time series. Like many other biophysical phenomena, the EEG shows more or less irregular patterns and, therefore can only be described by average properties. Since EEG belongs to a category of random data that cannot be described in explicit mathematical relations, it is described in statistical terms.

The analytical approach is to define a random process $x(t)$ generating "realizations", which may be thought of as random functions, having statistical features as close as possible to those of the observed data. A random (or stochastic) process represents the collection of all possible sample functions which the random phenomenon might have produced. Such a collection is called an ensemble. A sample record of EEG data may be regarded as a single realization of a random process, and thus statistical testing of this process becomes possible.

Appendix C addresses, in greater detail, the methodologies involved in the primary analysis of EEG.

3.2.8 Feature Extraction and Data Standardization

Following Fourier transformation of the EEG data (or other primary analysis technique), further condensation, parameter extraction, synopsis and statistical treatment of the EEG data are necessary. There are several techniques to perform the post processing of spectral data, and these are listed as follows:

Parameter Extraction

- Band power, band coherence
- Power of white, pink and colored noise components
- Baseline slope and intercept
- Spectral quotients
- Peak parameters: peak frequency, peak power (area of the peak), relative spectral peak power (RSPP)
    - half power bandwidth, peak width (distance between the peak footpoints),
    - skewness (asymmetry coefficient), kurtosis (peak shape)

Statistical Treatment / Pattern Recognition

- Simple treatment
    - Mean and standard deviation of spectral parameters
    - Average spectra with range of variance
    - Product moment correlation of power spectra
    - Analysis of variance
- Multivariate analysis
    - Principle component and factor analysis
    - Multidimensional scaling
    - Multivariate analysis of variance
    - Discriminant analysis
    - Cluster analysis
    - Non-linear pattern classification

Condensation and Visual Presentation

- Sequential spectral or coherence displays
- Compressed spectral arrays
- Contour plots
- Topographic parameter display
- 3-Dimensional scalp maps
- Chernoff faces

Methodologies for parameter extraction are discussed in detail in Appendix D, while statistical pattern recognition techniques are discussed in Appendix E.

Key Issues in using Pattern Recognition (PR) Algorithms

Several important issues constitute the key to effective use of PR algorithms. These include having sufficient sample of data, choosing good features and good combinations of feature subsets, standardizing features, validating and assessing the significance of a classification equation, and interpreting results.

Sample size: The sample size required to achieve a given level of significance in distinguishing between conditions generally has an inverse relationship with the degree of difference between conditions. As differences between conditions increase, smaller sample sizes are sufficient to obtain a given significance level. However, it is also possible that increasing the sample size will decrease the differences between conditions because of the individual differences in the group of persons tested. This indicates that the smaller sample is insufficient to characterize within-condition variability. Since these factors cannot be estimated *a priori*, a reasonable procedure is to measure the approximate magnitude of separation between conditions on several small groups of persons. If the separation varies greatly between the groups, a larger sample must be used. Cohen (1969) has shown that with this information, an estimate of the minimal necessary sample size can be made using a table for statistical power analysis.

Parametric studies for variable subset selection: Feature selection is problematic since it is not clear which ones are the best, or how to combine them to produce the highest discrimination between the conditions of an experiment. A reasonable procedure is to perform a series of parametric studies on a small but representative data set. In each study a different type of feature is input to a classifier-directed feature extraction algorithm, and the one with the best performance is selected. Exhaustive searches can then be performed to find the best subset of the best feature type.

Standardization of features: A simple but effective method of amplitude standardization can be obtained by transforming the voltage of each channel of each participant's data into a standard score; the mean is subtracted and the result is divided by the standard deviation of all observations from all conditions for the participant. A method of temporal standardization for the ERPs can be achieved by applying PCA to the averaged time series pooled across channels and conditions, either for each person separately, or for all participants. Alternatively, analysis windows can be centered on each person's ERP peaks. PCA can also be similarly applied to EEG spectra to define common frequency bands.

Validation and assessing significance: Validation is an important step in checking the validity of the equations produced by the PR algorithm. This check reduces the possibility of a type I (false positive) error due to insufficient data samples, or to violations of the statistical distribution assumptions of the analyses. The most convincing analyses is obtained with a completely independent data sample drawn from a new set of controls. However because of the expense and the difficulty in collecting data, validation is often performed using a portion of the database, half or one third. This allows for testing of the PR equation generated from the rest of the data. This process can be performed by different shuffling of the training and the validation data sets. Then the average classification accuracy obtained on the validation data sets can be used for assessing the significance of the results.

There are several methods for assessing the significance of the validation classification accuracy. These procedures can be used alone or in combination. One such method involves determining the accuracy of the PR equation on randomized data, i.e. data whose identity by experimental condition has intentionally been randomly scrambled. The same observations which were used to develop the PR equation are randomly arranged, a new PR equation is computed, and the significance of a similarly randomly ordered validation data set is then measured. This procedure is repeated a number of times using data from different electrodes, or different temporal epochs, resulting in an estimate of the mean and the variance of the significance level of classification of randomized data. It is then a simple matter to compare the results obtained with the correctly arranged data with those obtained with the random data to assess the former's actual significance.

Interpreting results: Neurophysiological interpretation of the PR equations and their coefficients requires that the features not be randomly combined. The use of spatiotemporal constraints can greatly facilitate an anatomical interpretation of the results. When this is done, separate equations are derived for each electrode, and possibly for each time interval when analyzing ERPs. Comparison of the relative significance of the equations can reveal information about the topography and the timing of the effects under consideration. When standardized features are used, (mean = 0, and variance = 1), equations with many terms can be reduced by extracting the largest terms and then reducing the equations to the minimal number of terms required to produce a significant classification.

3.2.9 Estimation of Event-related Signals

There are several ways of estimating an event-related signal. These include averaging, Wiener filtering, latency correction, time-varying filtering, pre- to post-stimulus transformation, and Wigner distribution.

Averaging: This is a technique that is useful for the analysis of event-related activity. In this method, a number of brief EEG time series which are time registered to an expected or actual stimulus or response are averaged. Some of the inherent disadvantages to the averaging technique are that the event-related signal may not occur at the same time, may not have exactly the same shape, or may not be present to the exact degree in each trial.

Wiener filtering: This method also known as the minimum mean square error (MMSE) filtering, is a controversial approach to improving event-related signal estimation (McGillem et al., 1981). It works on the principle of using a custom designed digital filter which selectively enhances the event-related signal components and suppresses the unrelated noise. In order to implement the MMSE filters, it is necessary to have an estimate of the signal or its spectrum, and/or of the noise. This is a problem since the actual signal is unknown. This is overcome by first estimating the spectrum of the signal plus noise followed by the spectrum of the noise alone. The spectrum of the noise alone is estimated by subtracting the power spectrum of the average (signal + 1/N times noise) from the average of the set of single-trial power spectra (signal plus noise). The noise can also be estimated by averaging the residuals resulting from subtraction of the average ERP from each trial, or by averaging with the polarity reversed on alternate trials. Wiener filtering is not a commonly used method due to mixed success of the results.

Latency correction: This is another method for estimating event-related signals that can occur at different times on different trials. This procedure adjusts the temporal position of each trial to best align it with a peak in the average ERP. This is done by shifting the entire time series of each trial or segments of it by the lag number of the maximum correlation of the time series with the average. The main drawback of this procedure is that it requires the event-related signal to be large so that individual trials do not line up with the background EEG signals. An essential accompaniment to the latency correction procedure is reliability testing for the signal-to-noise ratio, as well as for the accuracy of the time-shift estimates.

Time-varying filtering: This is a technique to deal with time-varying ERP. The averaged ERP time series is decomposed by a bank of octave-band digital filters with time-varying gain coefficients, and the event-related signal is estimated by summing the weighted filter outputs. A more recent approach by Yu and McGillem (1983) is the application of a time-varying MMSE filter to each trial. This approach is based on an explicit model of the ERP as a random process with varying amplitude and timing, and which is contaminated by random noise.

Pre- to post-stimulus transformation: This model proposed by Basar (1980) assumes that the event-related signal is a nonlinear transformation of the brain state existing prior to the time of stimulation. Several preliminary applications of this concept to practical signal processing algorithms have resulted in encouraging results (Rauner et al. 1983).

Wigner distribution: More recently, the Wigner distribution has been applied by Morgan and Gevins (1986), which allows the visualization of both the time and the frequency aspects of a set of data. With this method, it is possible to view the spectral patterns of rapidly changing event-related processes within small frequency regions. These above mentioned methods are some of the ways in which event-related signals can be estimated and analyzed.

3.2.10 Spatial Analysis

Spatial analysis is an important aspect of EEG research since the spatial patterning of scalp-recorded brain signals is complex, reflecting the activity of several anatomically and functionally differentiated underlying neural systems. The separation between electrodes required to avoid spatial aliasing can be determined by measuring the spatial spectrum from closely spaced electrodes. The average inter-electrode distance while using 60 electrodes is 3.25 cm, while with 120 electrodes is 2.3 cm.

The first step of spatial analysis has been to examine the differences in EEG or ERP voltage or the EEG spectral intensity between the various electrodes. Over-the-head spatial displays represent an important development that allowed visualization of the EEG and ERP potential distribution in two dimensions. Maps of this type consist of a series of contour lines representing the peaks and valleys of potential, very similar to the topographic geophysical maps. The three major issues associated with topographic maps include: 1) Manner of projecting the three-dimensional head onto a two-dimensional representation, 2) Choice of reference electrode, and 3) Type and the amount of interpolation. In general, the contours are drawn on a sketch of a top, side, or back view of the head using orthographic projection and interpolating the voltage values at several points between the actual recorded electrodes.

An important factor that affects the topographic voltage distribution is the choice of the different reference electrodes. The solution to the reference problem of spatial maps is to convert the measurements into quantities that are independent of the reference, for example, to gradients by taking the first derivative of the field (Remond 1968), to current densities by applying the Laplacian operator, or to measures of the extrema of field power (Lehmann 1971). Recently color computer graphics have become very popular for displaying the scalp voltage distribution of 16 or more channel ERPs or EEG spectral intensities.

While valuable information can be obtained by viewing over-the-head displays, statistical methods are necessary to quantitatively compare the data. There are several approaches to this problem. The maps can be reduced to a few features, such as the location, orientation and magnitude of an equivalent current dipole which could produce the observed field, or to the location and magnitude of the maximal and minimal values of the field power. Another approach to objectifying the interpretation of the maps is to statistically compare them. Multivariate statistical analysis is used by several systems such as the BEAM system by Duffy et al. (1981), the Brain State Analyzer by John et al. (1977), and the Neurocognitive Pattern Analysis developed at the EEG Systems Laboratory. The BEAM system works by reference to normative values derived from control populations for each electrode, while the Brain State Analyzer has an additional component of comparing serial recordings from the same patient. The Neurocognitive Pattern Analyzer compares between experimental conditions for each electrode or group of electrodes for one or more people.

The reduction of spatial smearing of brain potentials due to the effects of volume conduction is highly desirable, since the hypothetical point source of current on the surface of the cortex becomes spread over an area of approximately 2.5 cm when transmitted to the scalp (Doyle and Gevins 1986). This is achieved by the use of a Laplacian operator montage that requires the computation of the curvature of the potential field at each electrode. This amounts to adding together bipolar EEG channels surrounding a particular electrode after they have been weighted by the actual inter-electrode distances. This transformation has an additional advantage of removing dependence of the measures on the reference electrodes by converting the scalp voltage distribution into measures of the flow of current entering and exiting from the head at each electrode. However, this Laplacian montage (LM) or current source density (CSD) works best when many channels are recorded since it is not possible to accurately compute the LM for channels on the periphery. For example, with 19 channels of EEG, only 9 LM channels can be computed, while for 63 channels, 43 LM channels can be computed.

Another promising method is the use of mathematical transformations such as spatial deconvolution, which can greatly reduce the spatial smearing of scalp recorded potentials, making it appear as if the signals were recorded on the cortical surface.

While the observation and the analysis of spatial patterns is straight forward, the basic but more difficult problem is to determine the source in the brain of the patterns observed on the scalp. For this purpose, *a priori* models of the character and the number of sources have been proposed. The most commonly used model assumes that the scalp field distribution arises from an equivalent current dipole source, that can be represented by six parameters, three for position and three for the magnitude along each axis. This model does not however represent the true state of affairs in the brain since there are multiple simultaneously active sources. This problem is dealt with by using magnetic encephalography (MEG) in association with the EEG measurements.

3.3 Eye Movement / Position

3.3.1 Electro-Oculogram (EOG)

The EOG is a measure of the potential difference that exists between the cornea and the retina, called the resting or standard potential of the eye. The cornea is approximately 6 mV positive with respect to the retina, which changes with changing retinal illumination. The standing potential of the eye is generated mainly by the transepithelial potential across the pigmented epithelium of the retina.

Thus sensors placed on the right and left external canthi of the eyes (i.e., the outside or lateral location, just next to each eye) will pick up the change in orientation of the +/- dipole of each eye. Similarly, sensors placed above and below the eye will provide corresponding EOG information about up and down movement of the eyeball. In summary, sensors on the sides of the eyes provide information about lateral movement (X-axis) and sensors placed above and below the eyes provide information about up and down movement (Y-axis). In combination, then, the two electrode pairs provide information about where the eyeball is oriented in an X-Y coordinate system, and hence the direction of gaze (Figure 12).

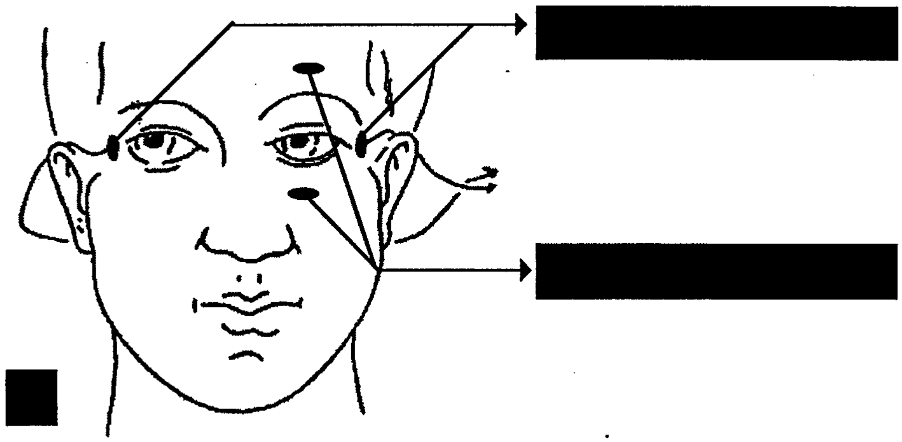


Figure 12: Typical Placement of EOG Sensors for Lateral & Vertical Eye Movements
(From McGuigan, 1979).

Several studies have been performed to demonstrate that eye behavior changes with alterations in workload, task difficulty, fatigue, and the nature of the visual display. Brown and Huffman (1972) have demonstrated that lateral eye movements are significantly affected in driving tasks. They found that the highest amount of visual activity is present in residential driving, followed respectively by business district, expressway, and rural driving. They also discovered that lateral eye movements are lower in night driving as compared to daylight driving.

Synchronization of the horizontal and vertical eye movements can provide the point of gaze of the eyeballs, and this information can be overlaid across the visual display that the subject views. Such processing can provide secondary visual measurements such as point of fixation, duration of fixation, saccade velocity, and the patterns of visual scanning across a display.

Itoh et al. (1990) have examined the characteristics of pilot scanning behavior to compare use of CRT displays versus electromechanical displays in the cockpit. They observed that the altitude indicator is the most frequently gazed at instrument within the cockpit. Studies can also be done to observe and compare the changes in behavior in normal versus emergency situations, so as to understand how attention changes, what instruments are viewed, for how long, and in what order.

Visual scanning behavior has also been used as a way of comparing the skill levels of novices and experts. It has been found by Summala et al. (1996) that novices are much more affected by loading tasks than experts are, and rely on foveal or central vision. Experts on the other hand, learn to use and depend upon peripheral vision, and are able to use this information effectively and fast. With increasing task load, the scanning behavior increases in novices, while the average dwell time or the duration of fixation increases in experts (Tole et al., 1982). These results imply that monitoring eye movements can be used as an indirect but effective method of evaluating and assessing improvements in subjects who have undergone vigilance training for target search and identification tasks.

3.3.2 Blink Measurement

Several blink related variables such as blink rate, blink amplitude, inter blink interval, and blink closure duration, have been used as indicators of human attention, workload, vigilance, and fatigue.

Both eye blink rate and eye blink duration are useful measures of workload level. Research has shown that:

1. As cognitive workload level increases, eye blink rate decreases.
2. As cognitive workload level increases, eye blink duration decreases.

It appears that as the subject is forced to concentrate harder, they focus their visual attention along with their mental attention, and the eyes remain open more as a result of this increased intensity and focus.

Hancock et al. (1990) have demonstrated the relationship between blink rate and increased workload in a driving task in curved versus straight road driving. Eye blink rate is lower in visually demanding and high workload tasks. Wilson and Fisher (1991) have demonstrated this effect in pilots under different flight segments, and used blink rate to classify mission segments using discriminant analysis.

Blink characteristics in conjunction with eye movement recordings, could therefore be used as a powerful tool for estimating cognitive workload and operator stress and performance in specialized tasks and environments.

Several studies have also demonstrated that blink rate is a reliable measure of fatigue associated with the time-on-task (TOT). Cabon et al. (1993) have shown that the onset of drowsiness in a vigilance type task is marked by a strong increase in blink rate followed by a complete disappearance of eye blinks.

Morris and Miller (1996) have tested specific components of the eye and eyelid movements as predictors of performance decrements resulting from fatigue in sleep deprived pilots. The variables that they measured included blink rate and duration, long closure rate (LCR), blink amplitude (BL), saccade rate and velocity, and the peak saccade velocity. Their results show that subjective reports of fatigue are strongly correlated with increased error, and that blink rate is the best predictor of error performance, followed by blink amplitude and long closure rate.

As an alternative to the EOG or Video image tracking methods for measuring eye movement, the blinkometer device (Figure 13) may be used to strictly measure eye blinks. Manufactured by IM Systems, located in Baltimore, MD, the $800 device consists of a sensor that mounts near the eye and a pager-sized data-collection unit that can be read by the lab computer. IM Systems' owner, biomedical researcher David T. Krausman, says IM plans to sell a $100 version that sounds an alarm when blinking patterns indicate that its wearer is about to fall asleep. This device is expected to find applications ranging from truck drivers to machine tool operators.

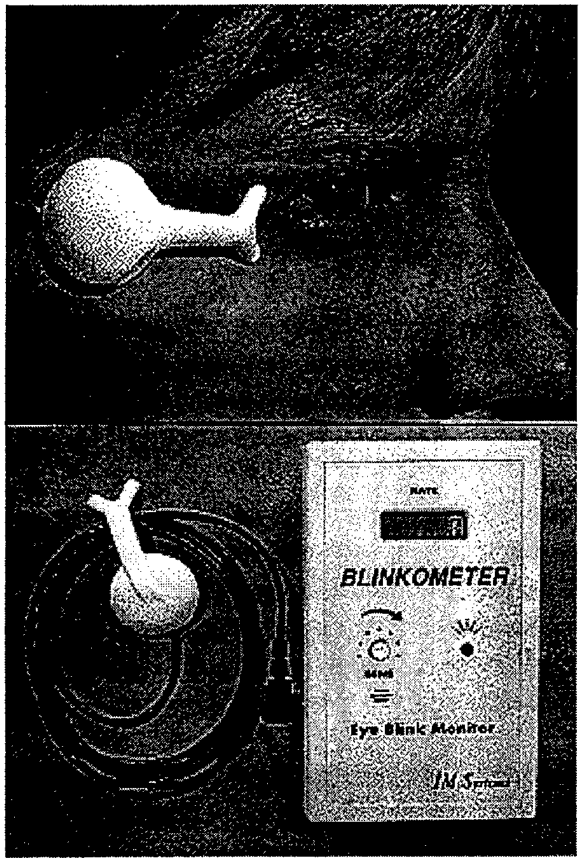


Figure 13: Blinkometer

3.3.3 Infra-red & Video Imaging Based Eye Tracking

The EOG measurement discussed previously is often very convenient and effective when measuring eye motion, but is typically not very effective at determining absolute eye position and gaze location (i.e. what the person is looking at), due to electrode drift over time. Eye position and gaze location can be more effectively determined using infra-red (IR) sensing and/or video imaging techniques that measure and track features of the eye.

IR sensing techniques utilize one or more infra-red point sources to create reflections on the eye; these reflections are then measured using discrete IR sensors. As the eye moves, features of the eyeball change the reflection characteristics that are measured by the IR sensors. Calibration and mapping algorithms can therefore be applied to determine the position of the eye based on the infra-red measurements.

Several research and commercial eye tracking devices have used this type of approach. It provides for a relatively low-cost and light-weight implementation, with a high sampling rate. As a disadvantage, it has some performance limitations, particularly with regards to vertical dimension tracking, and it may be difficult to setup and align the components.

Alternately, a video image of the eye may be used to measure and track eye position. In this case, eye position is determined using image processing algorithms performed on the captured image of the eye. These algorithms may track infra-red reflections (as done in the previous method), or detect pupil location (using infra-red illumination for creating pupil-iris contrast), or both. Calibration methods are then used to map pupil center and/or IR reflection locations to a gaze position.

Video based eye trackers limit gaze determination to much slower sampling rates than can be achieved using the discrete IR sensing eye trackers; this is due to the time involved in image capture and processing. However, video eye trackers generally provide better consistency and accuracy.

With both methods the eye tracking system may be either head-mounted, or remote from the subject, each offering different advantages and disadvantages. Remote systems can present little or no obstruction to the subject's field of view, but require keeping head position within a very limited space. Head-mounted systems allow for free head motion, but require some obstruction of the subject's field of view and may present additional challenges when determining gaze (due to head motion).

Several available infra-red sensing (infra-red oculography) and video imaging eye trackers are reviewed in Figure 14. Cybernet has also developed our own custom eye tracking systems based on video imaging.

Besides the significance of motion, blink, and gaze measurements already discussed, pupillary responses – namely the size of the pupil – have also been used as an indicator of attention, workload, and fatigue. Peavler (1974) has demonstrated that information overload can result in the dilatation of the pupil due to the mental processing effort and the involvement of task related anxiety. Geacintov and Peavler (1974) have used pupillography in industrial fatigue assessment and shown that pupil constriction occurs with fatigue. Pupil size can be readily measured using video based eye trackers that already use pupil detection methods to determine gaze location.

Figure 14: Summary of Several Eye Trackers

Company	Product Name	Method	Mounting	Features	Precision	Range	Sampling Rate
AmTech GmbH	ET4	CCD Line Scan Camera	Table	Measures eye position and pupil diameter	Position: 2 arcmin horizontal, 5 arcmin vertical. Pupil diameter: 0.01mm	+/-40 degs horizontal, +/-8 degs vertical	50 to 500 Hz
Applied Science Laboratories (ASL)	Model 210	Infra-red oculography	Head	Measures eye position	0.25 degs	+/-15 degs horizontal and vertical	1,000 Hz
	Model 1050	Video imaging	Table	Measures pupil size	<5% CV	2.0 - 10.0 mm	
	Model 4000SU / 4000CU	Video imaging: Pupil - corneal reflex	Table	Measures point of gaze and pupil size	0.5 degs	50 degs horizontal, 40 degs vertical	50 / 60 Hz
DBA Systems Inc.	626 PC Eye Tracker	Video imaging: pupil - corneal reflex	Table or Floor	Measures point of regard, blink, and pupil diameter	< 0.5 degs	80 degs	50 / 60 Hz
LC Technologies	Eyegaze system	Video imaging: pupil - corneal reflex	Table	Measures eye position	<0.5 degs	80 degs	25 / 30 Hz or 50 / 60 Hz
Microguide, Inc.	Microguide	Infrared oculography: limbus tracking	Head	Measures eye position	0.1 deg	+/-30 degs horizontal, +/-20 degrees vertical	0-250 Hz
NAC	EMR-7	Infrared oculography	Head	Measures eye position	>0.2 degs	40 degs circle	30Hz
SensoMotoric Instruments GmbH (SMI)	Eyelink	Video imaging	Head	Measures eye position and pupil size	Position: 15 sec of arc. Pupil diameter: 0.01 mm	30 degs horizontal, 20 degs vertical	250 Hz

3.4 Dermal (Skin) Measurements

The human electrodermal system consists of the eccrine sweat glands concentrated in the digits and the palms of the hands. It is innervated by two systems, namely the sympathetic innervation from the autonomic nervous system, and the basal ganglia-limbic-cortical control circuitry. Electrodermal activity or EDA is considered one of the most sensitive indicators of psychological activity. EDA has been measured in a variety of environmental settings like work-sites, traffic jams and classrooms, using ambulatory recording techniques (Turpin, 1985).

Sweat gland activity is responsible for EDA that is recorded as changes in electrical resistance of the skin. It is hypothesized that the increase in sympathetic nervous system activity causes an increased hydration of the eccrine sweat glands and therefore the surface of the skin. This leads to a drop in skin resistance, and subsequently an increase in skin conductance that is recorded as EDA. EDA is therefore an indicator of "psychological sweating" as opposed to the "thermoregulatory sweating", and occurs when there is information processing and cognitive activity in the human.

3.4.1 Skin Resistance, Skin Conductance & Spontaneous Fluctuations

Electrodermal activity can be measured either as an endosomatic or as an exosomatic activity. Endosomatic activity refers to the actions potentials generated in the sympathetic nerves under the skin. A technique of microneurography developed by Wallin and Fagius (1986), has been used to directly measure the sympathetic activity using microelectrodes inserted into the nerve. These potentials can be uniphasic or biphasic, depending on the number of deflections observed in the recording. Recordings have shown a positive correlation between the bursts in sympathetic activity and the amplitude change in the skin resistance measured. Exosomatic electrodermal activity is measured directly from the surface of the skin. A small current is passed across two electrodes placed on the skin and the change in skin resistance is recorded as a function of increased sweat gland activity.

EDA can record two types of activity namely the slow tonic responses occurring in minutes, and the fast phasic responses occurring within seconds following the stimulus. Phasic changes that occur in the absence of stimuli are known as spontaneous fluctuations. An example of a recording of an electrodermal response to stimuli is shown in Figure 15.

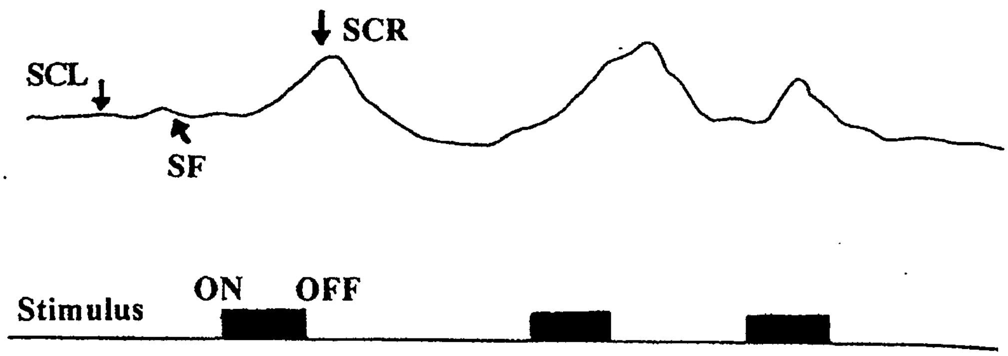


Figure 15: Types of Electrodermal Measures

The three basic modes of EDA activity are closely intercorrelated, but represent different physiological processes. Tonic activity is believed to reflect vigilance, sustained attention, and heightened arousal over time (Kilpatrick, 1972). Phasic responses reflect both the cognitive and emotional demands of a stimulus, especially one that is unexpected or of particular significance to the subject. Barry and Sokolov (1993) have found that the levels of both tonic and phasic responses of skin conductance decreases as a function of the visual stimulus trials. Spontaneous fluctuations show high sensitivity to arousal and anxiety by increasing in their frequency of occurrence (Lader, 1967).

Another measure of electrodermal activity is recovery rate, that is defined as the time taken by electrodermal activity to return to the prestimulus baseline after the response peak. In reality, it is measured as time taken by the recording to return to halfway of the baseline (rec t/2). It has been shown by Edelberg (1970) that a slow recovery correlates with emotionality, while a rapid recovery correlates with attention and goal-directed behavior.

3.4.1.1 Recording and Scoring of Electrodermal Activity

The commonly used terminology on EDA is shown in Figure 16. Tonic changes are expressed as skin resistance levels or skin conductance levels, while phasic responses are labeled as skin resistance responses and skin conductance responses.

Figure 16: Recording Parameters for Tonic and Phasic Electrodermal Activity

Response Type	Resistance	Conductance
Tonic level	Skin resistance level (SRL, KΩ)	Skin conductance level (SCL, μS)
Phasic response (elicited or spontaneous)	Skin resistance response (SRR, KΩ) Spontaneous skin resistance fluctuations (SF, Fluctuations per minute)	Skin conductance response (SCR, μS) Spontaneous skin conductance fluctuations (SF, Fluctuations per minute)

The normal range for tonic changes in skin conductance is 1-30 $\mu S/cm^2$, where μS stands for microsiemens. The normal range of the amplitude of the phasic SCR is 0.05 to 5 μS. An important measure in electrodermal activity is the smallest accepted phasic response, which is set to 0.05 μS, but can be as low as 0.01 μS or lower, if computerized scoring programs are used.

Strict guidelines have been laid out for recording of electrodermal activity by Fowles et al. in 1981. In particular, the sodium chloride (NaCl) concentration used in the electrode paste should not exceed 0.05 molar concentration, which is the upper limit of the NaCl concentration of the skin surface due to sweating. It is recommended that a non polarizable silver/silver chloride electrode be used together with an electrode paste of 0.05 molar NaCl, made from a mix of unibase paste and 3% saline solution. Electrodermal responses can be elicited from several sites such as the volar or dorsal aspect of the hand, the plantar aspect of the foot, the ankle, the forehead, or the abductor hallucis muscle. Care should be taken not to clean the electrode site with alcohol or abrasive cleaning paste since this can disrupt the functioning of the sweat glands.

Phasic responses of EDA can be scored in several ways, some of which are illustrated in Figure 17.

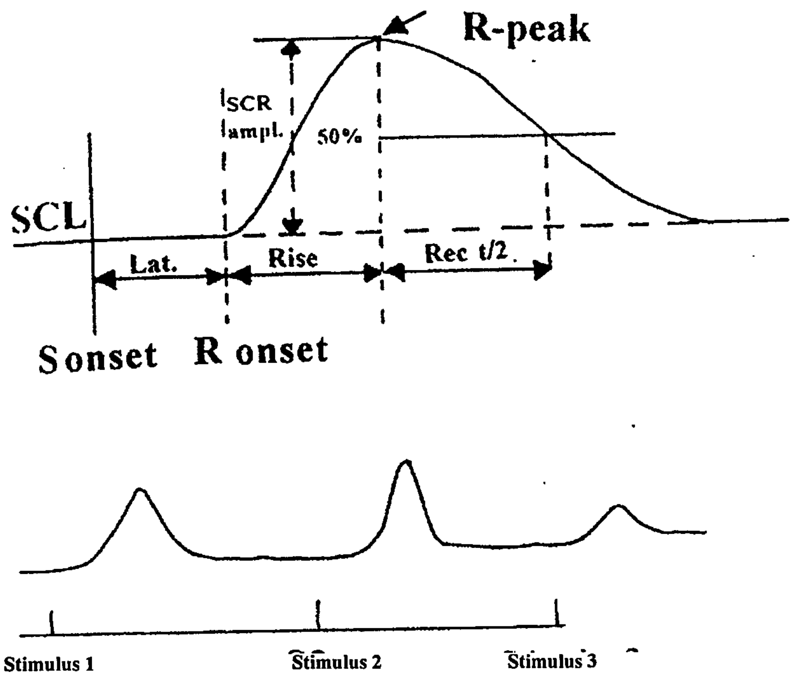


Figure 17: Parameters of a Phasic Electrodermal Response

A response is measured from a deflection point to the response peak. Averaging responses across trials including "zero responses", estimates the *stimulus response magnitude*, while averaging without the "zero responses" estimates the *mean response amplitude*. *Response frequency* is the number of responses per unit time, and response probability is the number of identifiable responses in proportion to the number of trials. *Recovery rate* is measured as the time it takes for the recording to return from the peak value to half the displacement from the baseline and is called the *rec t/2*, indicating the time to 50% recovery. Another way of representing recovery time can be *rec t/4* which refers to the time to 25% recovery. *Rise time* is the time to reach the peak (maximum amplitude) from the onset of the stimuli and its value ranges between 1 and 4 seconds. *Latency* refers to the time of onset of a stimulus to the initiation of a response, with a value of 1-2 seconds for skin conductance responses.

In certain instances, multiple responses may occur within the scoring "window". It has been observed by Lockhart (1966) that in experiments with two stimuli and long interstimulus intervals between the two stimuli, three distinct responses are present as shown in Figure 18. They have been named as the first anticipatory response (FAR), the second anticipatory response (SAR), and the third omission response (TOR). The FAR has been attributed to perceptual and attentional processes like the orienting response, the SAR reflects a conditioned response, in anticipation of the strong unconditioned stimulus (UCS), and the TOR reflects learning, referring to the omission on test trials with the UCS.

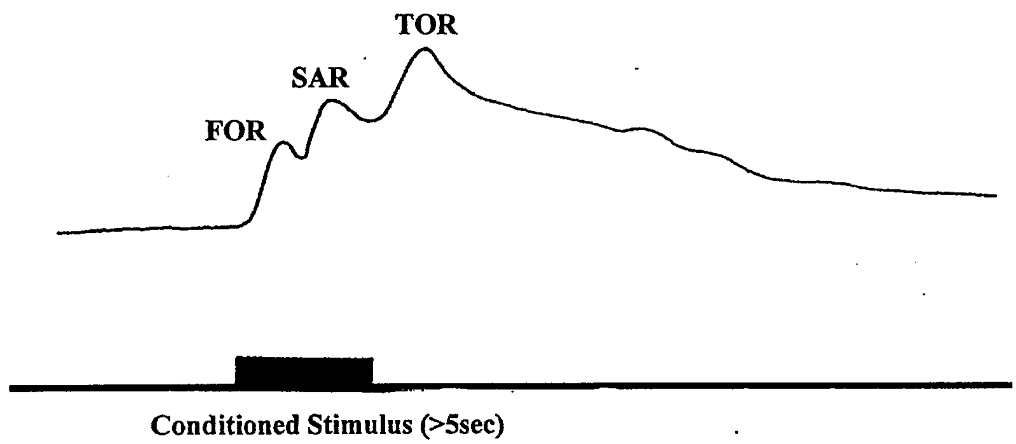


Figure 18: Example of FOR, SAR, and TOR in an Experiment Using a Conditional Stimulus

3.4.1.2 Cognitive Implications of EDA

The mechanisms of control of electrodermal phenomena from the highest centers are yet to be completely understood. It has been observed that areas in the cortex like the lateral frontal cortex and the dorsolateral cortex have direct influence on the electrodermal response. Neuroanatomical correlates of electrodermal responses have shown that cortical area activity is critical in the elicitation of skin conductance response (Tranel and Damasio, 1994). From a functional view point, the central nervous system control of EDA can be examined as three separate systems, namely the locomotor, orienting-activating and the thermoregulatory systems.

Furedy (1993) has succinctly discussed the notion of electrodermal activity as a tool to differentiate psychological processes in humans. He emphasizes the physiological differentiation between the sympathetic and the parasympathetic nervous system that may be relevant in drawing the psychological distinction between stimuli that result in an increase in stress from those that result merely in an increase in attention. An example to illustrate this importance of such a distinction, is the need to differential the indicators of susceptibility to cardiac arrest from those stress indicators due to increased attention. Since electrodermal activity is known to predominantly reflect sympathetic nervous system activity, an increase in electrodermal level can be reasonably used as an index of stress. In contrast, preparation for a stressful task where more attentional resources are demanded than the development of stress per say, will cause an acceleration in heart rate without a change in the electrodermal level. Another example is the electrodermal differentiation-of-deception (DDP) where falsely or deceptively answered questions cause a larger skin conductance response than honestly answered questions (Vincent and Furedy, 1992), and this principle has been used for many years on polygraphy.

The potential advantage of investigating the psyche using the low technology tool of electrodermal activity cannot be sufficiently emphasized. It has been observed that involuntary physiological changes detected through electrodermal activity can be used to explore the emotional and cognitive aspects of the psyche more easily and effectively than methods of greater technical sophistication.

3.4.1.3 Commercial Application: MindDrive™ Technology

One such commercial tool using the concept of electrodermal activity is a computer game called MindDrive™. It works on the principle that differing mental activities like remembering, relaxing, analyzing, positive and negative thoughts and left and right brain activity, all generate different bioelectric patterns that are measured through the skin. Users can volitionally control cursor movement by getting into an "excitatory" state or into a "relaxed" state of mind. This concept is illustrated in Figure 19.

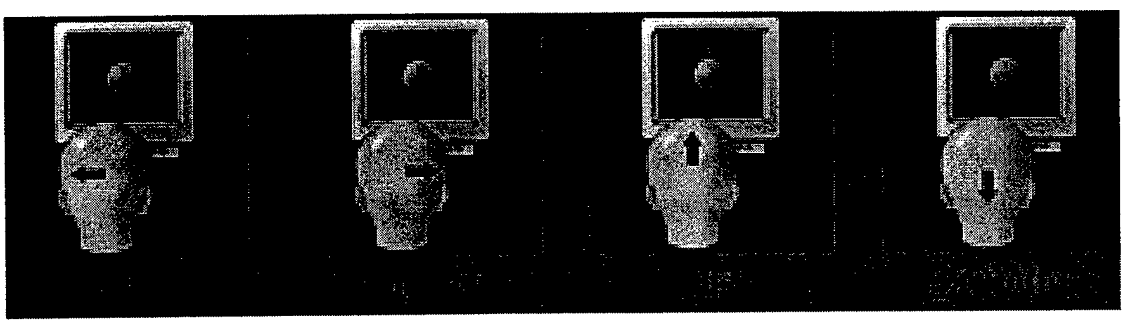


Figure 19: Cursor Control Using Thought Processes in MindDrive

The sensor that is used is a finger sensor which measures heart rate, temperature, blood pulse volume, and Composite Neural Activity (CNA) which is composed of a set of multiple bioelectric signals. The MindDrive technology automatically and continuously analyzes the following components of CNA in the following manner:

1. Amplitude (output and strength of the signals)
2. Velocity (speed or rate at which the signals change)
3. Attenuation (size of the changes)
4. Delta or asymmetry of the CNA signals, as compared to each other
5. Combination of both the phasic (rate of change) and tonic (absolute measurement) signals.

A picture of the finger sensor is shown in Figure 20.

Figure 20: Finger Sensor Used in MindDrive

The two major obstacles that have prevented the use of electrodermal signals to control devices and computers are:

1. The 2.5 to 3.5 second delay between a human thought and the traditional measurement of the thought response at the skin.
1. Inability to differentiate the changes generated by cognitive volitional thoughts from those resulting out of the influence of the autonomic nervous system on CNA, heart beat, blood pulse volume, and temperature.

It is claimed that the MindDrive technology is able to decipher the differences between a physiological signal generated by volitional thought (transmitted though the central nervous system) and one that has been changed by the autonomic nervous system. This difference is recognized through a filtering process of the changes generated by the autonomic nervous system, so that only the signals generated by cognitive/volitional thoughts remain. This system was tested at Cybernet Systems Corporation and it was found that subjects could control the cursor to a certain degree. A representation of this system is shown in Figure 21.

Figure 21: User Controlling a Game Through MindDrive Technology

Electrodermal activity shows promising value in application for the assessment of cognitive human performance.

3.4.2 Sweat Rate

Eccrine sweat glands are controlled by the sympathetic nervous system, and primarily responsible for electrodermal activity. These are distributed all over the human body, but occurring with a greater density in the palms of the hands and the soles of the feet. The density in these regions ranges around 1000 glands/cm^2, as compared to 100-200 glands/ cm^2. Besides the influence of the sympathetic branch of the autonomic nervous system, sweat glands are also influenced by circulating epinephrine, indicating a hormonal influence on electrodermal response.

An important factor in determining the magnitude of the electrodermal response is the amount of perspiration or the level of hydration of the sweat gland. A simple and accurate test to measure sweating is the use of the palmar sweat index (PSI) developed by Sutarman and Thomson (1952). The PSI has been shown to correlate significantly with both the spontaneous fluctuations as well as the skin conductance responses. The PSI is a count of the active glands in a specific area of the skin. A plastic impression of a patch of skin on a fingertip is made after the presentation of a stimulus, or over time, and the number of "sweat dots" is a measure of the electrodermal activity to a psychologically relevant event. The palmar sweat index is a sensitive measure of both anxiety and arousal, and can be used with ease in situations where conventional recordings are difficult to perform.

3.5 Cardiovascular Measurements

Another organ that comes under the influence of the autonomic nervous system is the heart. Two specialized regions in the heart, namely the sino-atrial node and the atrio-ventricular node, are responsible for regulating the heart beat, with the sino-atrial node being the pacemaker. Both the SA and AV nodes are innervated by the vagus nerve from the parasympathetic nervous system. This has an inhibitory effect on the heart, and decreases the heart rate. On the other hand, the sympathetic nervous system has an excitatory effect on the heart causing an increase in the frequency.

3.5.1 Heart Rate, Stroke Volume, and Inter-beat Interval

Important concepts of heart physiology are the heart rate, stroke volume and interbeat interval. Heart rate is the number of times the heart beats per minute (bpm). Stroke volume is the amount of blood ejected at each beat of the heart. Both these parameters are related to a third parameter, cardiac output which is the quantity of blood pumped by the ventricle per minute in the following manner.

$$\text{Cardiac Output (liters)} = \text{Stroke Volume (liters/bpm)} \times \text{Heart Rate (bpm)}$$

The heart rate can also be expressed as another parameter, namely the inter-beat interval. This is the time between two heart beats in milliseconds and is determined from the ECG recording. The heart rate is related to the inter-beat interval by the following relationship.

$$\text{Heart Rate (bpm)} = (60 \times 10^3) / \text{Inter -beat Interval (msec)}$$

All the above parameters are regulated both by nervous system control as well as hormonal control.

Heart rate activity can be recorded using the electro-cardiograph. This records the electrical currents generated by the action potentials of the cardiac muscle cells through electrodes placed on the skin. A typical ECG recording is shown in Figure 22. The ECG recording consists of a P wave, a QRS complex and a T wave.

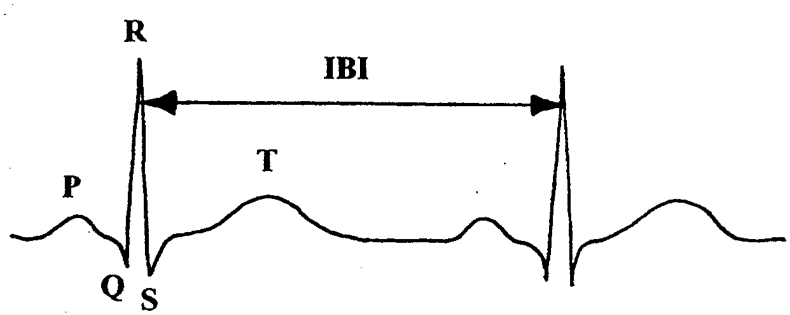


Figure 22: Typical Electrocardiogram Recording

The heart rate or the frequency with which the heart beats can be determined using the time in milliseconds between two consecutive R waves,.also called the inter-beat interval. There is a reciprocal relationship between the heart rate and the inter-beat interval. In psychophysiological research, measurement of the changes in heart rate as a function of stimulus presentation are based on identifying successive R waves in the ECG. Choice of using the heart rate versus the inter-beat interval (or heart period) is dependent on the type of study performed. In many cases the inter-beat interval is used as the dependent measure. Figure 23 shows the appearance of an inter-beat interval plot.

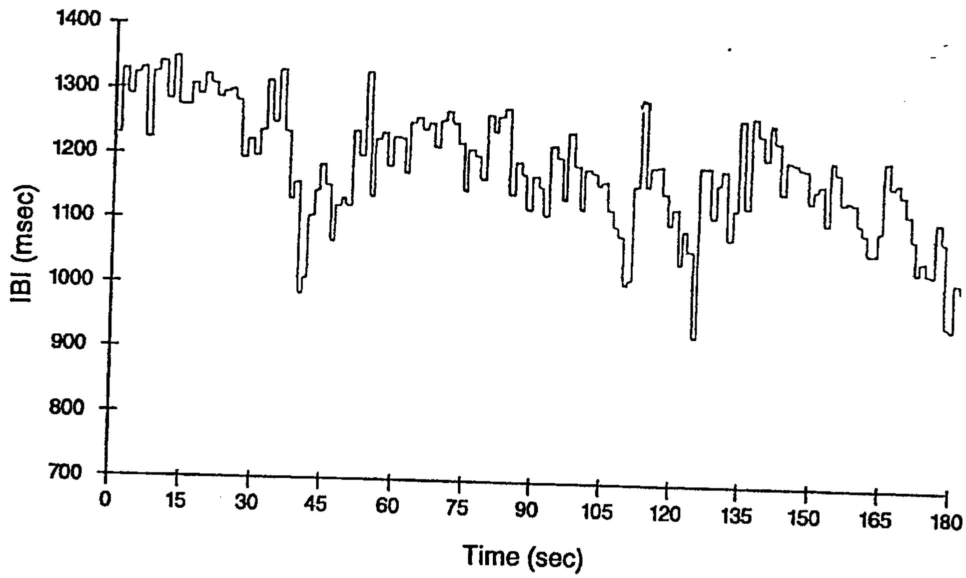


Figure 23: Inter-beat Interval Plot Showing the Beat-to-Beat Fluctuation

Heart rate was one of the earliest physiological parameters used to monitor the state of the human operator, with both physical and mental activity being known to increase the heart rate. Many studies have observed systematic relations between cognitive demands and heart rate in different environments (Kramer, 1991; Roscoe, 1992; Wilson and Eggemier, 1991). Several studies have also looked at heart rate characteristics during aircraft piloting: flying combat missions (Lewis et al., 1967), flying surface attack training missions (Wilson, 1993), flying aircraft test missions (Roscoe, 1980), gradient of landing approach (Roscoe, 1975), pilot versus copilot flying (Hart and Hansen, 1987; Kakimoto et al., 1988, Roscoe, 1978), and high speed low level flight (Lidderdale, 1987). All these studies have shown that with an increase in task difficulty, there is an increase in heart rate. Rokicki (1987) and Roscoe and Ellis (1990) have used heart rate as a debriefing tool for aircraft test and evaluation, as well as in the certification of commercial aircraft (Roscoe, 1987; Speyer et. al., 1988; Wainwright, 1988).

All the above studies have demonstrated an increase in heart rate with mental workload. A study by Wilson and Fisher (1991) used cardiac variables and eye-blink to classify flight segments in pilots and systems officers for air-to-ground training and weapon sessions. Similar results have been reported in studies relating to automobile driving (Helander, 1975), boat driving (Johnson, 1980) and in radar operation (O'Hanlon and Beatty, 1977).

Changes in heart rate as a function of attention and vigilance has also been observed in several psychophysiological studies. Studies on heart activity following a stimulus have shown an initial cardiac deceleration that is sometimes followed by an acceleration, and a second deceleration. Cardiovascular psychophysiology has been explained in terms of information processing using the heart rate curve. A typical triphasic heart rate curve is illustrated in Figure 24. An initial deceleration D1 is associated with the cognitive processes of focusing attention and orienting to the stimulus. The acceleration A has been attributed to the emotional aspects of the stimulus, or to the internal cognitive processing. The second deceleration D2 is attributed to the anticipation of the next stimulus.

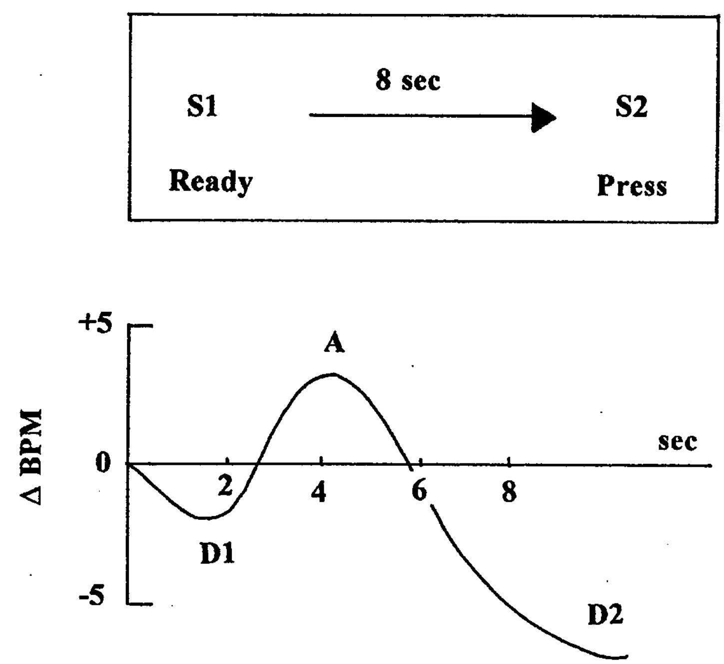


Figure 24: A Typical Tri-phasic Heart Rate Curve Shown Against Stimulus Presentation

Venables (1991) proposed that the deceleration of the heart rate is coupled to an "open attentional stance", and cardiac acceleration to a "closed attentional stance", both of which are related to sensory intake and environmental rejection respectively.

3.5.2 Heart Rate Variability

Heart rate variability has also been used as a measure for evaluating task load. Many studies reported a decrease in heart rate with increasing task demands.

Heart rate power spectrum analysis (HRPSA) is a relatively new technique, based on analysis of the R-to-R interval, to determine the heart rate variability or oscillations. Heart rate oscillations have been shown to fall into three spectral peak categories: a high frequency component peaking around 0.2 to 0.4 Hz, a mid frequency component peaking around 0.05 to 0.10 Hz, and a low frequency component peaking at 0.04 Hz. The high frequency component has been found to be sensitive to vagal influences, the mid frequency to be a quantitative measure of the sympathetic nervous system (Pagani et al., 1986), and the low frequency component being an indicator of both sympathetic and parasympathetic activity. Figure 25 illustrates the different frequent components in a heart rate power spectrum analysis.

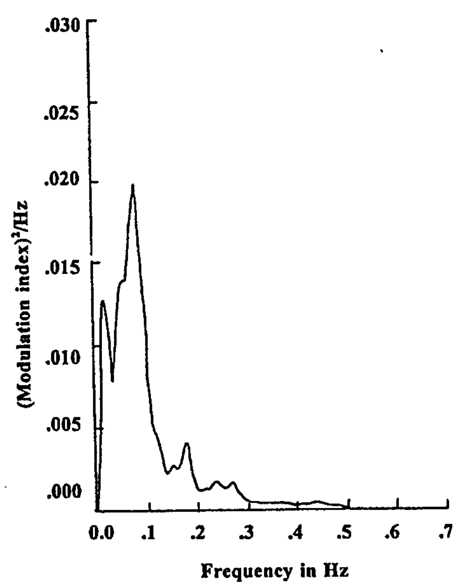


Figure 25: Power Density Spectrum of Heart Rate with Peaks in Low, Middle and High Frequency Ranges

HRPSA can display the variability in the heart rate signal as a power density spectrum with Fourier analysis. Specifically it has been observed that the mid frequency band, namely the 0.10 Hz component, is sensitive to the amount of mental effort required by a task (Mulder, 1992), and that a reduction in the 0.10 Hz component is an evidence of resource limited tasks. However increased task difficulty in data-limited tasks are not associated with a reduction in the 0.10 Hz component.

Opmeer and Krol (1973) have reported that the heart rate variability and respiration are sensitive to simulated flight task demands. Itoh et al., (1989) found the heart rate variability in the 0.10 Hz band to decrease during take off and landing when compared to the flight cruise segments. Transient air craft difficulties have been found to produce a decreased 0.10 Hz activity. Wilson (1993) found a decrease in the mid and high frequent band activity during high demand segments of air-to-ground missions and during a ground based tracking task. However neither band could distinguish between flight segments or between the tracking tasks.

Egelund (1982) reported changes in heart rate variability as a function of driving conditions and driver fatigue. Jorna and Mulder (1983) found differences in heart rate variability between novice and expert underwater divers. It is believed that the high frequency band reflects respiratory activity and provides an index on the influence on the heart by the parasympathetic nervous system. This band width has been found to be sensitive to manipulations of cognitive workload (Porges and Byrne, 1992).

3.5.3 T wave Characteristics and Chaos Theory in Heart Function

The T wave amplitude of the ECG recording was initially suggested to be an index of sympathetic activity (Heslegrave and Furedy, 1980), but this assumption was questioned leading to the non use of this index. Instead, a different measure called the T-alterans was proposed and is used to analyze the repetitive pattern of T wave amplitude (Verrier and Nearing, 1994). The T wave alterans has been suggested to be an important index of vulnerability to cardiac failure.

The most recent trend in heart physiology is the application of non linear dynamics and chaos theory to analyze heart rate and frequency (Goldberger, 1991). This method has been championed for the detection of imminent cardiovascular dysfunction, especially arrhythmias. It has been observed that the heart rate of a patient before sudden death due to cardiac arrhythmia is periodic and non chaotic, whereas the variability of the normal heart follows algorithms predicted from fractal and chaos theory.

The importance of chaos theory and non linear dynamics of the heart rate on human performance and operator state, and their relevance to psychophysiology, has yet to be understood.

3.5.4 Blood Pressure, Pulse Transit Time, and Pulse Wave Velocity

The flow of blood through a vessel is determined by the pressure exerted by the flow divided by the resistance of the vessel to the passing blood. The arterial pressure is determined by the product of cardiac output and the total peripheral resistance. The arterial pressure refers to both the systolic and the diastolic pressures, which are the highest and the lowest pressures in the cardiac cycle. The systolic varies between 120 and 140 mm Hg and the diastolic varies between 80 and 90 mm Hg. The mean arterial pressure (MAP) is an important measure of the functional status of the cardiovascular system, and is defined as the difference between the diastolic and systolic pressures plus 1/3 of the diastolic pressure. With relation to mental activity, studies have observed that shifts in the EEG in the frontal cortex area were smaller when baroreceptor stimulation occurred than when baroreceptor inhibition occurred.

Pulse Transit Time (PTT) and the carotid dP/dt are two measures of the of the rate of change in blood pressure when the blood is ejected from the left ventricle. Both these methods measure the time it takes for the pulse from the peak of the R wave to reach a certain point at a distance from the heart. Carotid dP/dt is a measure of the relative change in pressure (dP) in relation to a change in time (dt). Pulse transit time is measured in present times using impedance techniques while carotid dP/dt is measured using a piezo-sensitive device that is present in a neck collar that the subject wears.

Pulse wave velocity is a measure of the speed of the wave traveling along a viscoelastic wall of a blood filled vessel using a photo-plethysmographic sensor (Jennings and Choi, 1983). It is closely related to the pulse transit time. Both the pulse transit time and the pulse wave velocity are considered as the index of sympathetic influences on the heart. Increase in the sympathetic influence on the heart will result in increased contractility and stroke volume, resulting in a decreased time for the pulse to reach the sensing device on the carotid artery. Pulse transit time has been demonstrated to covary with the systolic blood pressure under different stressful conditions (Obrist et al., 1979).

3.5.5 Peripheral Pulse Volume

The volume of the blood flowing through blood vessels in the periphery can be measured to understand the cardiovascular state. Both phasic and tonic changes can be measured in the peripheral blood flow as pulse volume or pulse amplitude and as blood volume respectively. Phasic changes are the beat-to-beat fluctuations that occur for each stroke of the heart. Tonic changes occur over longer periods of time. Figure 26 shows the changes observed in blood volume, pulse amplitude and blood flow measured from a digit during the presentations of three auditory stimuli. The increase in pulse amplitude indexed by the vasodilatation of the peripheral blood vessels, is caused by the sympathetic nervous system. A decrease in pulse amplitude is caused by increased sympathetic activity that results in vasoconstriction of the peripheral blood vessels.

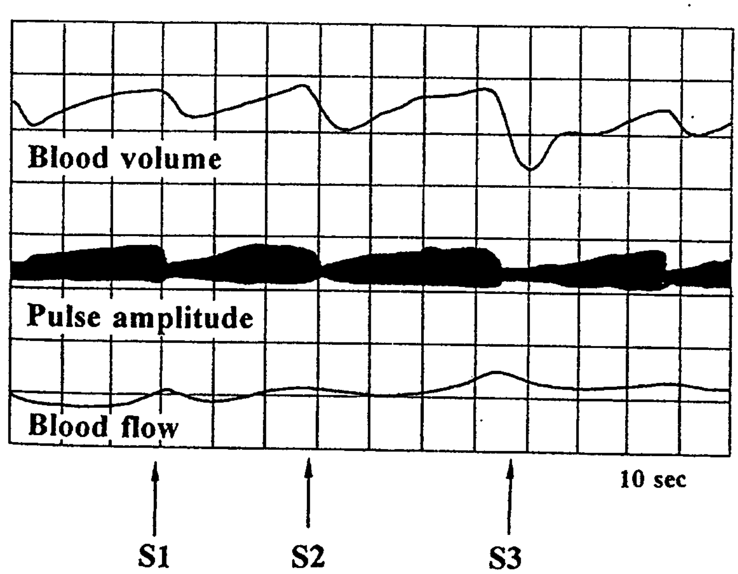


Figure 26: Changes in Blood Volume, Pulse Amplitude and Blood Flow During Stimulus Presentations

Some studies have been performed to demonstrate the relationship between vascular parameters and human behavior. Sokolov (1963) used plethysmographic recordings of the fingers and forehead to distinguish between orienting (OR) and defensive responses (DR) to sensory stimuli. He found that at the fingers, both the OR and the DR result in vasoconstriction due to sympathetic activity, while at the forehead OR results in vasodilatation and DR in vasoconstriction, since there is both a sympathetic and parasympathetic influence.

There are several methods for measuring vasoconstriction and vasodilatation, by measuring the changes in the peripheral blood volume. A standard method is by the use of plethysmographs, which record the change in blood flow. There are several types of plethysmography depending on the type of sensor used. Photoplethysmography utilizes a light emitting diode with a sensor on either side of, for example, the thumb. The amount of light reflected to the sensor device is dependent on the amount of blood flowing in the peripheral vessel. For example, as more blood flows, less light gets reflected.

Other types of plethysmography are impedance plethysmography and Doppler flowmetry. Impedance plethysmography measures the changes in blood volume by measuring the changes in electrical resistance. Doppler flowmetry on the other hand, measures blood flow velocity by acoustical monitoring.

3.6 Respiratory Measurements

Respiratory psychophysiology has had little impact on main stream psychophysiology in the last decades. However respiration measurements have found a place in several types of studies such as:

1. To evaluate the effects of work demands,
1. To evaluate the effects of environmental stressors such as G forces and vestibular stimulation,
1. To detect hyperventilation due to over-reactivity caused due to danger or threat, and
1. To obtain an approximation of energy expenditure.

One reason for the poor popularity of respiration is the complex nature of breathing patterns which vary both in time and volume. Noninvasive measurement techniques only provide an assessment of respiratory rate and not of volume. Respiratory rate is quite insensitive to workload and stress, and does not provide meaningful information. It is currently accepted that respiratory measures can be useful only when both volume and time parameters are simultaneously measured.

3.6.1 Breathing Rate and Breathing Volume

The respiratory cycle is composed of several parameters. These are the duration of inspiration (T_i), duration of expiration (T_e), total cycle duration (T_{tot}), respiratory rate (inverse of T_{tot}), and tidal volume (VT) which is the volume displaced in one breath. Figure 27 shows the components of a single ventilatory cycle.

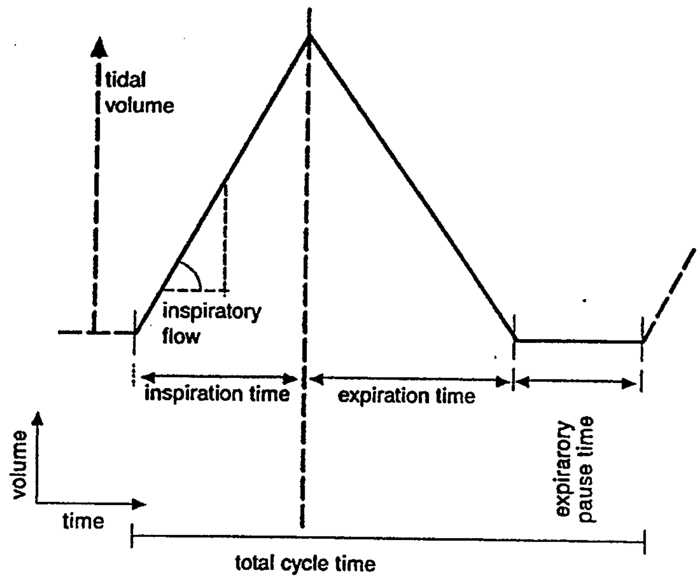


Figure 27: Decomposition of Minute Ventilation into Components of Central Respiratory Regulation

Two fundamental mechanisms control the breathing cycle. These are the *drive mechanism* regulated by chemoreceptors which controls the firing rate of the inspiratory neurons, and the *timing mechanism* regulated by the central rhythm generator, which switches these neuron between the on and off positions. These mechanisms can further be described by combination parameters such as the inspiratory flow rate (VT/ T_i) for the drive mechanism, and the duty cycle time (T_i/T_{tot}) for the timing mechanism. Another parameter called the minute volume, which is the total volume ventilated per minute, is equal to the product of the inspiratory flow rate and the duty cycle time.

Respiratory time and volume parameters can be measured non-invasively using the technique of inductive plethysmography. This method uses techniques to measure the motion of the rib cage and the abdomen, and does not interfere with normal breathing. Respiratory volume changes are measured based on a model that describes the chest wall as a system moving with 2 degrees of freedom. After proper calibration of the system, measurement of the changes in the rib cage and chest wall circumference can provide reasonably accurate measurements of volume and time components.

Innumerable studies have been done in the past to assess the changes in respiration with performance of effort demanding tasks and stressors. With mild mental effort and stress, an increase in respiratory rate, decrease in tidal volume and an increase in minute volume have been observed (Turner and Carroll, 1985; Wientjes, 1992). However with extreme workload demands (Allen and Crowell, 1989) and with painful passive coping stress (Allen, Sherwood and Obrist, 1986), an increase in tidal volume has been observed. The use of respiratory rate as a measure has been questioned since increase in respiratory rate with workload is confounded with other factors like vocalization, motor activity, aversiveness, etc.

It is currently believed that the drive mechanism is sensitive to work demands. Inspiratory flow rate was found to discriminate reliably between task demands in the performance of a memory comparison task (Wientjes, 1992), implying that a greater workload is associated with a stronger inspiratory drive. However the timing mechanism was not seen to be influenced by workload.

3.6.2 End-tidal pCO_2 and Transcutaneous pCO_2

Since respiratory changes are also influenced by changes in metabolic processes, it can also be important to measure indices of the metabolic process. One such index is the end-tidal pCO_2. This is measured using the capnograph which is attached to the subject's face-mask. A reduction in the end-tidal pCO_2 is indicative of hyperventilation which is ventilation in excess of the metabolic requirements. Since the use of a face-mask is relatively cumbersome, newer techniques such as transcutaneous pCO_2 measurement methods have become available. This method uses a heated electrochemical sensor that measures the arterial pCO_2 through the skin. The output voltage is proportional to the logarithm of the CO_2 concentration of the skin. The sensor is heated to about 45 degrees Celsius which causes a vasodilatation of the capillaries under the skin, and arterialization of the capillary blood. Therefore the CO_2 concentration in the skin tissue is assumed to be representative of the arterial pCO_2. The main disadvantage of this method is the time lag of the response of the sensor to the change in arterial pCO_2. The transcutaneous measurement of pCO_2 has been used in studies involving ambulatory monitoring (Pilsbury and Hibbert, 1987).

Few studies have used the end-tidal pCO_2 levels in assessing its change with mental load. It has been demonstrated that in active coping, where the subject is actively involved in performing a demanding mental task, there is no associated hyperventilation or hypocapnia. It is therefore believed that the ventilatory changes observed in these tasks are mainly due to the changes in metabolic activity brought about by motor activity.

Hyperventilation can also be brought on by certain aversive conditions such as pain and cold pressor tasks. This can have an important effect on the subjective and objective state of the human, both due to the manifestation of adverse somatic reactions and a reduction in myocardial and cerebral perfusion and therefore oxygen delivery. The latter can lead to a decrement in cognitive functioning (Grossman and Wientjes, 1989).

Some applied studies have used respiratory measures to characterize human performance and operator state, as in the study by Harding (1987) with jet fighter pilots in different flight segments. Results indicated that respiratory rate, peak inspiratory flow, and minute volume were increased during all phases of the regular flight, but particularly elevated during highly demanding maneuvering phases. It has been suggested that stress in flight can cause a significant reduction in pCO_2 leading to detrimental effects in psychomotor performance (Gibson, 1978 & 1979). Another field of application of respiratory measures has been the area of vestibular stimulation. A study by Bles et al. (1988) has found high correlation between the degree of motion sickness, stress anxiety and end-tidal pCO_2 decrease in subjects onboard a mine-hunter. It has therefore been suggested that hyperventilation be used as an index to study the response to an aversive stimuli.

In summary, the sensitivity of respiratory measures is highly dependent on the choice of the parameters. The use of time parameters alone, like respiratory rate, are insufficient to detect changes with task demands. There is a need to use parameters dependent on driving mechanisms, and those influenced by chemoreceptor activity.

3.7 Musculo-Skeletal Measurements

3.7.1 Electromyography

The electromyogram (EMG) is a recording of the action potentials generated when the fibers of a muscle contract. The amplitude and frequency of the EMG signal in most situations has a positive linear relationship to the strength of the muscle contraction. The most direct means of communication between the "inner" and "outer" environment of an individual can be thought of as being done by the efferent motor system. Muscle tensions occur in response to physical motor demands, and are also intimately linked to emotional and cognitive activity. The recording of muscle activity is therefore relevant in many situations, the most important related to the current discussion being anxiety and stress response.

3.7.1.1 Techniques for EMG Recording and Analysis

There are two fundamental ways of recording EMG signals: by the use of indwelling electrodes within the muscles, or through surface electromyography, with electrodes placed on the skin. The latter technique is more commonly used, and can give an accurate picture of muscle activity of superficial muscles. Electrode placement is determined through an anatomical analysis of the muscle of interest. The best placement site of an electrode is over the muscle belly, near the motor point.

Pairs of silver/silver chloride electrodes are commonly used, about 4 to 7 mm in diameter and spaced at a distance of 10-20 mm apart. The skin is carefully abraded and prepared using alcohol and fine sand paper. The active surface electrodes are placed longitudinally over the muscle belly, with their axes parallel to the muscle fibers. Electrode resistance is recommended to be below 5-7 k Ohm. A third grounding electrode is placed over any bony prominence. Figure 28 shows examples of electrode placements for the trapezium and the forearm flexor muscle.

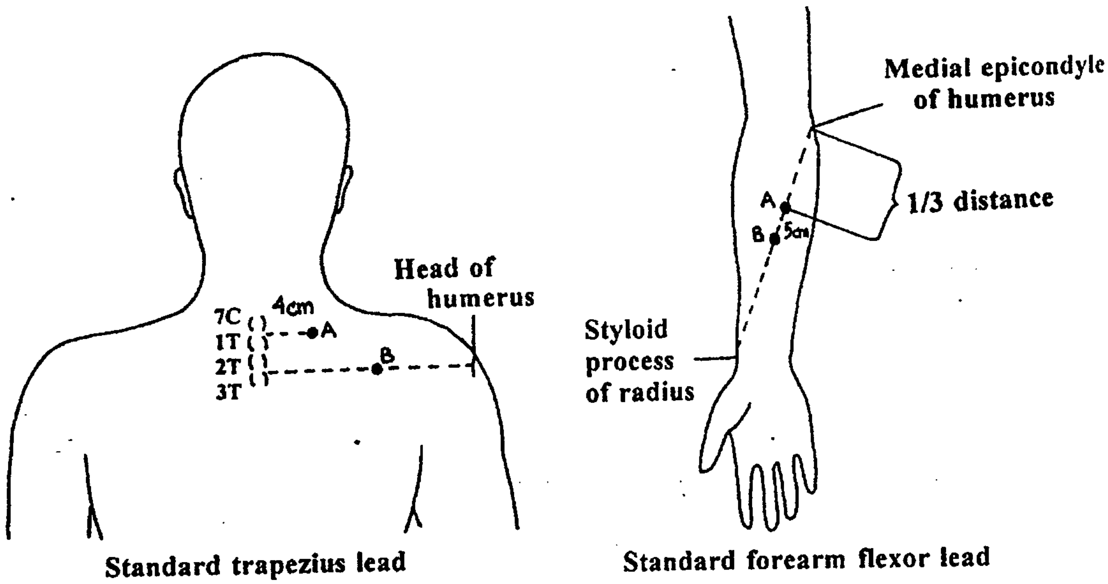


Figure 28: Typical Electrode Locations for EMG Recording from the Trapezium and a Forearm Flexor

The EMG signals are amplified using a multi-channel system and band-passed filtered with the upper filter frequency set to about 1 kHz and the lower to 10 Hz. The EMG signal ranges in amplitude between 100 to 1000 μV, but may be as low as between 2-4 μV under conditions of deep sleep.

Common techniques for quantifying an EMG signal are rectifying and signal integration. After signal amplification, the signals are full-wave rectified, and then integrated with a time constant ranging between 0.5 to 2 seconds. A variant of signal integration is *criterion integration*. In this procedure, the integrated voltage is compared to a preset voltage level called the "criterion". Whenever the integrated voltage reaches the criterion level, the computer marks a spike on the screen. The number of "marked" spikes from the recorded data can help estimate the EMG activity during the recording session. Examples of raw and processed EMG data are shown in Figure 29.

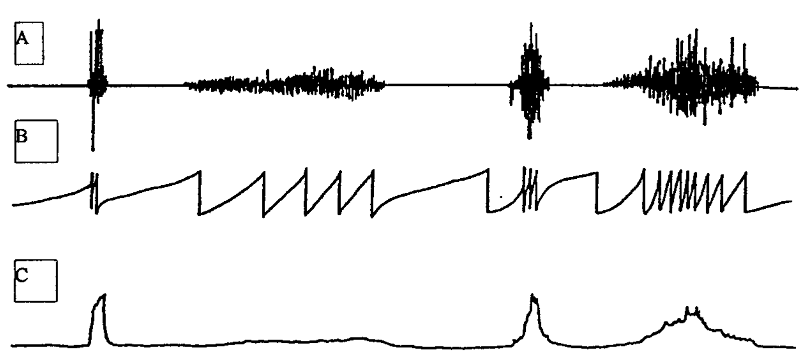


Figure 29: Raw (A), Criterion-Integrated (B), and Regular Integrated (C) EMG Signal

The power frequency spectrum of EMG signals is also frequently used to quantify the muscular events occurring with fatigue. The fast Fourier transformation (FFT) is used to convert the recorded time domain data into the frequency based data. Each time domain is divided into 10-20 segments, and FFT is done for each of the individual segments. From this, the additional parameter of EMG, namely the mean power frequency, is obtained.

3.7.1.2 Use of EMG in Human Performance/State Identification

It is now well understood that EMG amplitude is a consistent and sensitive measure of motor unit recruitment. Many studies have demonstrated the relationship between the force generated by a muscle and the mean signal recorded during isometric exercise (Lippold, 1952) or with contractions with constant velocity (Bigland and Lippold, 1954). Linear relations between the contraction strength and the integrated EMG signal have also been established. Many analysis models have been proposed that have an ability to predict the potential muscle capability of an individual, and thus help in optimal placement of individuals in suitable jobs. The frequency components of EMG have been observed to decrease with fatigue (Piper, 1912), and the power frequency spectrum analysis has been used as an accurate method to detect muscular fatigue.

Psychophysiological studies of muscle activity have a long history. Involuntary muscle tension has been observed following stimulus presentation in a two-stimulus reaction time paradigm (Jennings et al., 1970). EMG measures have also been used frequently in studies of motor preparation, which requires subjects to wait before responding. Peripheral measures such as the EMG have been used by Brunia (1993) in comparison with central measures like event related potentials. It has also been demonstrated by McGuigan (1978) that there are specific changes in the musculature of the speech muscles and the writing-arm muscles during "silent" language processing, both writing and verbalization.

One significant work on the relationship of EMG to mentation, is the study by Caccioppo and Petty (1981). They observed that mental processes are accompanied by muscle activity in focal sites, especially at sites in the musculature required for "acting out" one's thoughts. They maintain that the amplitude of somatic responses observed through EMG, decreases as the distance of measurements from these focal sites increases.

Measurement of muscle activity can provide additional information on subject readiness or stress, as well as the levels of fatigue. Some of the commonly used sites have been the frontalis, temporalis, masseter, and the trapezius muscles. Monitoring of muscle activity at these sites, and the special data processing techniques that are currently available, can provide a real time indicator of the stress and fatigue level in the human operator.

3.7.2 Actimetry / Motion Measurement

Though motor activity may not be considered a psychophysiological measure, activity monitoring is an essential since it can affect physiological measures. Actimetry has been particularly used in studies on vigilance, work shifts, and jet lag. The two common techniques in actimetry are ambulatory actimetry using a wrist actimeter, and video actimetry using video recordings. The former measures motor activity when the subject is free to move around in a physically large area, while the latter is the preferred technique when subject behavior and activity is restricted to a confined setting.

The recording system consists of a watch-like unit that can be worn around the wrist, leg, or the body after suitable adjustments as shown in Figure 30. A three axis accelerometer sensor, a preamplifier and a filter are incorporated into this system, which is interfaced to a microprocessor. There is provision for standard analyses through software that allows sleep state scoring, basic statistics and several forms of data display.

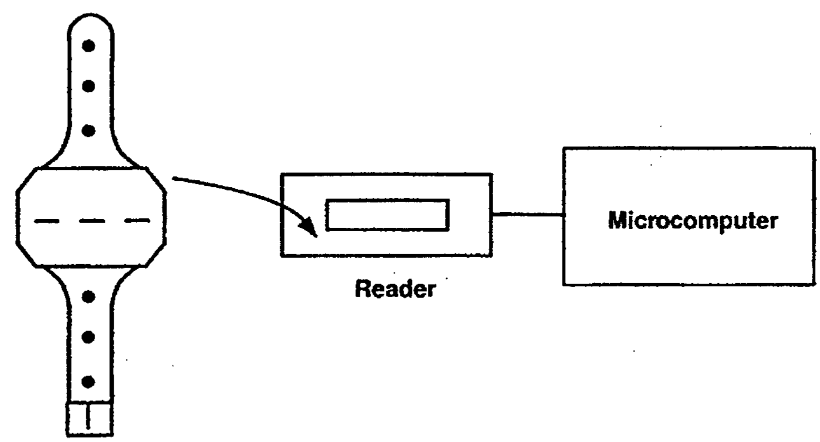


Figure 30: Ambulatory Monitoring Actigraph

The unit can be programmed for an epoch interval, the start delay, an event marker, sensitivity parameters, and filter cutoff frequencies, as well as detection thresholds and gain. The human operator wears the unit during the complete experimental period. Movements of the wrist are recorded whenever the energy exceeds a programmed threshold. There is also provision for the subject to record the times at which interesting events occur, by pressing a button.

Other techniques in actigraphy have used sensors made of strain gages that are fixed to the skin using adhesive. Video display sensors along with video cameras have also been used as recording devices, with CCD cameras for night-time recording.

3.7.2.1 Use of Actimetry in Human Performance/State Identification

Actimetry recordings have been used in a study of a French air force crew during an exercise operation for readiness (Le Menn et al. 1988) in a confined environment over a period of ten days. This was done to assess the response capability of the crew at the end of the test period and to test the efficiency of the shelters. Results from this study indicated that subjects were more active during the day than the night, and that the greatest activity was observed during the first and the last three days than the middle four days.

Actigraphy can provide an additional perspective to the changes in psychophysiological parameters which may be related to the changing aspects of the activity that the subject is involved in. Patterson et al. (1993) conducted a study to evaluate the reliability and validity of the wrist actigraph, where subjects performed various sedentary and physical activities. They found that the actigraph reliably differentiated between the various types of activities, both physical and sedentary. They also found that the oxygen update and the heart rate were closely correlated with the actimeter data.

3.8 Endocrine Measurements

As mentioned before, many endocrine systems respond to stress and their function is closely related to the autonomic nervous system activity. It is also known that a subject's level of control over a situation influences the stress reactions manifested. From an application view point, a subject who is able to regulate stimulus input is better suited for maintaining psychological arousal and involvement at an optimal level in a variety of situations than one without this ability. Studies have shown that the plasma level concentrations of certain hormones are influenced by operationally stressful environments. The plasma level at an initial phase of a task situation may vary from that at a later stage, when coping strategies have been established (Frankenhauser, 1978).

3.8.1 Hormone Performance Markers

The three important hormonal indicators of stress are cortisol, prolactin and testosterone, all of which are sensitive to stress and high workload. Noninvasive techniques are available for measuring hormonal level using saliva and urine. It is, however, important to minimize stress due to the sample collection process by debriefing subjects before the testing, and by using the least invasive method of collection.

Cortisol is a steroid hormone that has major effects on carbohydrate metabolism, salt and water balance and the inflammation response. Its level in blood can be regarded as the anticipatory stress experienced by a subject. Johansson et al. (1990) have reported changes in prolactin level prior to and following psychological stress in both men and women. Prolactin has been found to be particularly sensitive to stress anticipation and anxiety. Testosterone is a sex hormone produced by the testes, ovaries, and the adrenal cortex. Stressful conditions have a suppressive effect on testosterone secretion.

Salivary analysis has been proven useful to determine the level of cortisol and testosterone. Secretion from salivary glands varies in composition from time to time, especially as a function of experimental condition and the intensity of individual stimulation. The resting or the baseline secretion is the continuous secretion that takes place in the absence of obvious stimulation. Saliva can be collected using a dental roll placed in the mouth after thorough rinsing. After the dental roll is saturated, it is removed and centrifuged to obtain the saliva for analysis by radio-immunoassay. A disadvantage of the dental roll procedure is that the cotton interferes with the identification of several hormones, particularly testosterone. The Oral-Diffusion-Sink (ODS) device is the other alternative, which can be used for the in situ collection of an ultrafiltrate of saliva and is a variation on an earlier design developed for time-integrated measurement of corticosteroids in interstitial fluid. It is worn in the mouth and continuously accumulates the compounds of interest as they diffuse into the device along a concentration gradient. This method can be used for testing for cortisol.

Additional information that needs to be recorded during the collection of saliva is the time of day and date of collection, physiological and psychological state of the subject, and the circumstances under which the sampling is done. There are several commercially available kits for radio-immunoassay of cortisol, prolactin and testosterone. Analysis of the levels of these hormones is one way of determining the impact of stressors on the subjects, as well as the influences of the environment.

Considerable insight into the adaptive, psychological and biological reactions that allow subjects to cope with work-related, environmental, and other stressors can be obtained using hormonal analysis. Biological fluid analysis however does require assistance from individuals with significant biochemical training since it is easy to obtain incorrect results due to use of faulty procedures.

3.9 Subjective Evaluation

There are two general approaches that can be applied to the assessment of cognitive/mental workload: objective measures and subjective evaluation. Objective measures are based purely on measurable parameters and experimental methods; this includes the array of psycho-physiological measurements previously discussed. The subjective approach, on the other hand, gathers data from the subject about the task experience through ratings, rankings, questionnaires etc.

Subjective evaluation methods are mostly used by practicing ergonomists, and involve self-reporting by the task performers or product users. Examples include: ranking and rating methods, questionnaires, interviews and checklists which involve asking the subject how he/she feels about the workload level of the task. Recently, a growing interest in the nature and capabilities of human performance has begun to suggest that supplementing objective measures with subjective evaluation can provide a better evaluation of human performance (Jex, 1988).

Subjective rating is actually one of the easiest ways to estimate the mental workload of a person. The subjective assessment involves asking the subject what he or she feels about the load of the task. The subject is usually given instructions for how to rate loads, as well as definitions of the various rating scales, and an example rating scale and/or interview/questionnaire. The subject then rates the load with reference to predetermined levels (i.e. high/low, good/poor, no effort/enormous effort) determined by the researchers.

Figure 31, below, lists several subjective evaluation methods that can be used to assess operator workload in various human-machine environments.

Figure 31: Subjective Evaluation Methods

Method	Technique	Outcome Measures
NASA Bipolar[1]	Rating	Overall workload, performance, frustration, task difficulty, fatigue
Multidimensional bipolar rating scale[2]	Rating	Overall workload, frustration level, stress, performance, fatigue
NASA-TLX[3]	Rating	Overall index of mental demand, physical demand, temporal demand, performance, effort, frustration
SWAT[4,5]	Rating	time load, mental load, stress load
MCH[6]	Rating	task difficulty
McDonnell Rating Scale[7]	Rating	control difficulty, attentional demand
Bedford Workload Scale	Rating	overall workload, task difficulty, perceived exertion
Borg Scale[8]	Rating	perceived exertion

* NASA-TLX= NASA-Task Load Index; SWAT= Subjective Workload Assessment Technique; MCH= Modified Cooper-Harper.

1 American National Standard. (1992). *Guide to Human Performance Measurements*. BSR/AIAA, G-035-1992)

2 Hauser, J.R., Childress, M.E., and Hart, S.G. (1982). *Rating consistency and component salience in subjective workload estimation.* Paper presented at the 18th Annual Conference on Manual Control, Dayton, Ohio

3 Hart, S.G. and Staveland, L.E. (1988). *Development of a NASA-TLX (Task Load Index): results of empirical and theoretical research.* In Human Mental Workload, edited by P.A. Hancock and M. Meshkati (Amsterdam: North-Holland).

4 Reid, G.B. and Nygren. T.E. (1988). *The subjective workload assessment technique: a scaling procedure for measuring mental workload.* In Human Mental Workload, edited by P.A. Hancock and M. Meshkati (Amsterdam: North-Holland).

5 Reid, G.B., Singledecker, C.A., Nygren, T.E. and Eggemeier, F.T. (1982) *Development of multidimensional subjective measures of workload.* Proc. of the Human Factors Society, p. 403-406

6 Wierwille, W.W. and Casali, J.G. (1983). *A validated rating scale for global mental workload applications.* Proc. Of the Human Factors Society, pp.129-133

7 McDonnell, J.D. (1968). *Pilot Rating Techniques for the Estimation and Evaluation of Handling Quantities.* AFFDL-TR-68-76

8 Borg, G.A.V. (1982). *Psychological bases of perceived exertion.* Medicine and Science in Sports and Exercise, **4**, 377-381

The NASA bipolar and multidimensional bipolar rating scales can be used to examine differences in individual subjective responses and associations between subjective and objective measures. The multidimensional scale utilizes several bipolar scales: overall workload, frustration level, stress, performance and fatigue.

The NASA-TLX is one of the most widely used methods for assessing mental workload. Developed by NASA, this technique measures six workload-related factors scales: mental demand, physical demand, temporal demand, performance, effort and frustration. What can be determined from the NASA-TLX scale are the following: differences in subjective and objective responses and their respective magnitudes and individual information about the task. Figure 32 and Figure 33 illustrate the NASA-TLX workload assessment methodology.

SWAT was first developed by the Armstrong Medical Research Laboratory (AARML) for the purpose of assessing pilot workload. SWAT measures mental workload by measuring how hard one has to work on a certain task. The three key measures for SWAT are: time load, mental effort load, and psychological stress load.

MCH was first developed to assess flight characteristics and to evaluate the "flyability" of aircraft. This scale, which is a modified version of the Cooper-Harper scale, is considered a sequential rating process. The controllability and then the performance are assessed. Any modifications needed with respect to pilot workload optimization are made to achieve the desired performance.

The McDonnell rating scale, similar to the Cooper-Harper scale, rates aircraft handling properties. Ratings are "linearized" so that statistical techniques can be applied to all rankings.

The Bedford rating scale and the Borg scales measure perceived exertion. These two scales give a cross comparison to the physical measures and allow the investigator to explore how the job feels to the employee – or, in other, words the relationship between the physical stimuli and the perception of their intensity.

RATING SCALE DEFINITIONS		
Title	**Endpoints**	**Descriptions**
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
PERFORMANCE	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
FRUSTRATION LEVEL	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Figure 32: Rating Scale Definitions: NASA-TLX Method for Subjective Workload Assessment

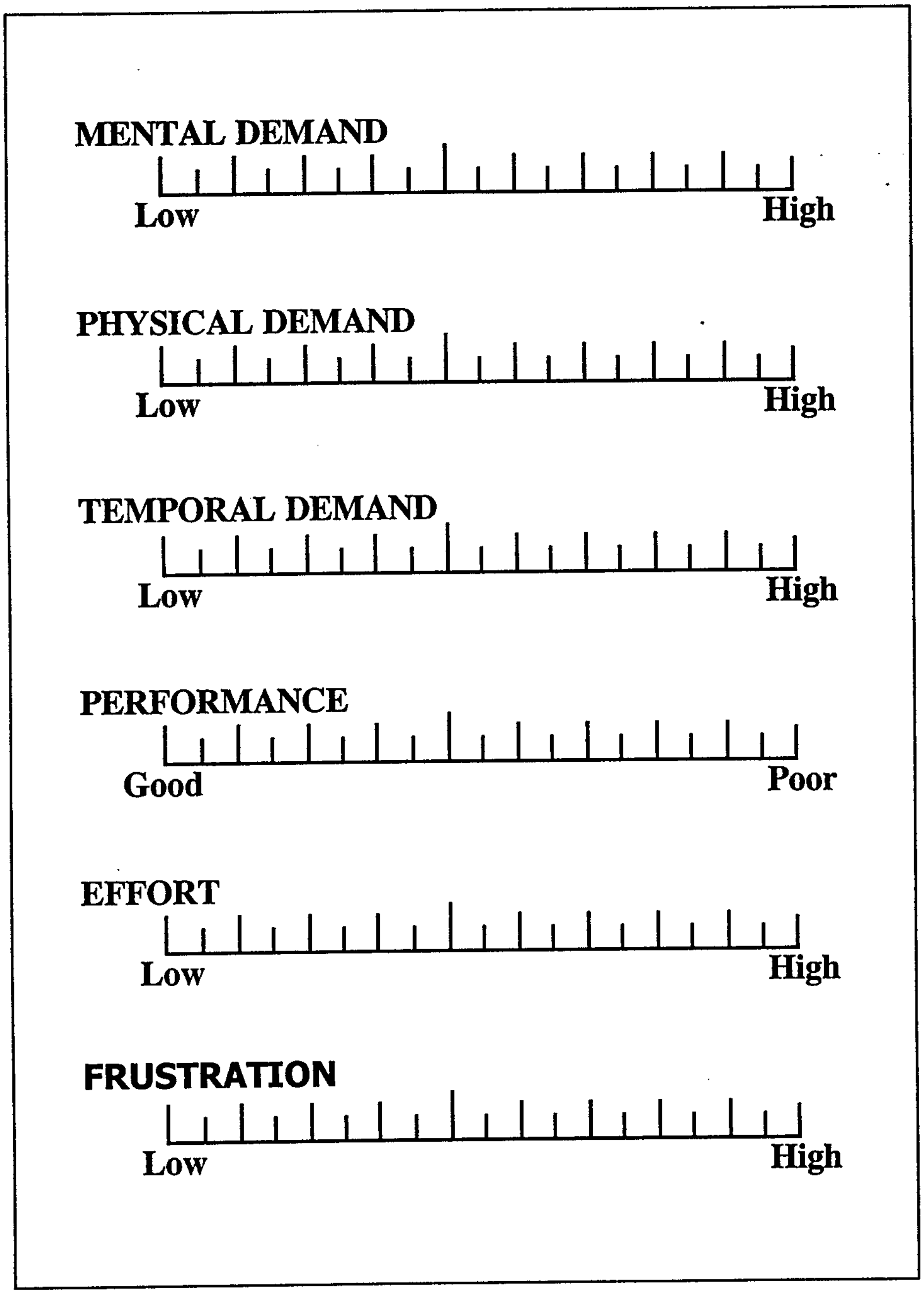


Figure 33: Sample Rating Sheet: NASA-TLX Method for Subjective Workload Assessment

3.10 Processing and Analysis of Measured Data

The nature of the psycho-physiological parameters that can be measured were discussed in detail in the previous sections. Here we present a brief review of the types of analyses that can be performed on these data in order to derive indicators human performance.

Electrocardiogram (ECG)

Rate detection algorithms can be applied to the ECG in order to determine heart rate parameters. Basic Heart Rate (HR) is computed as beats per minute, and is generally averaged over a period of time (i.e. 1 minute). Inter-Beat Interval (IBI) is a measure of instantaneous heart rate that is computed at each beat. Variations in HR/IBI can then be examined for patterns indicative of stress level and workload. An advanced method for examining heart rate variability is the Heart Rate Power Spectral Analysis (HRPSA), which provides a frequency domain view of the variability.

Electromyogram (EMG)

EMG is generally processed by performing a power calculation (sometimes within a specific frequency band) over successive windows/epochs to provide a measure of muscle tension. Values may be normalized against full scale power (i.e. when muscle tension is at maximum) in order to provide a more quantitative assessment. Muscle tension variations can then be examined for patterns indicative of stress level and workload.

Respiration

A rate detection algorithm can be applied to the respiration signal in order to determine respiration rate. In addition, other respiratory parameters may also be estimated from the respiration signal, including: tidal volume, inspiration time, expiration time, and expiratory pause time. It may prove useful to combine these respiration parameters into a single measure of respiration regularity or other indicator. Variations in respiration rate and other respiration measures can then be examined for patterns indicative of stress level and workload.

Galvanic Skin Response (GSR)

The GSR is a direct measure of skin impedance and needs no specific processing. Skin impedance variations can be directly examined for patterns indicative of stress level and workload.

Electro-oculogram (EOG)

The EOG is generally processed to determine absolute eye position, specific eye motion characteristics (such as REM activity), and blink detection. Eye position can be determined from calibrated levels of the absolute DC voltage value, and may be used to confirm/correlate eye tracker measurements (if also performed). Specific eye motions can be determined by examining power in specific frequency ranges, for instance: saccades, accomodations, or REM activity. Blink detection can be determined by identification of its distinctive waveform shape and then used along with a rate determination algorithm to produce blink rate. Once eye position, eye motion, and/or blink rate are determined, they can then be examined for patterns indicative of stress level and workload.

Electroencephalogram (EEG)

The EEG is a highly complex signal and has an array of possible analysis techniques (both well established and those under research). A standard method for EEG signal analysis is examination of power level in the traditional frequency bands: alpha (8-12 Hz), beta (13 - 30 Hz), theta (4-7 Hz), and delta (<4 Hz). These specific frequency bands have historically been used because activity in these bands has been shown to occur during different mental states. Examination of power levels in each of these bands (and/or shifts of power between bands) is one method that can be examined for indicators of cognitive workload.

Much research and development has been performed towards the development of methodologies and algorithms to classify mental/cognitive states using the EEG signal. These methods may include utilization of the traditional frequency band powers, or more advanced information such as the full frequency spectrum or time series based parameters of the signal. Topographic features of the EEG (i.e. spatial distribution of EEG activity over different regions) are also important for analysis and classification of the EEG. Several methods for spatial analysis of EEG were presented in Section 3.2.10.

In addition advanced methods for EEG analysis that are still primarily undergoing continued research (rather than widespread clinical use) include time-frequency, bispectral, and coherence analyses.

Evoked Potentials

Evoked potentials are EEG responses elicited by a specific stimulus or event, and are buried in other ongoing EEG activity not associated with the stimulus/event. Since the evoked potential has a low magnitude relative to the other ongoing EEG activity it must be extracted from this background EEG "noise". This is typically performed by averaging multiple responses to the same stimulus/event in order to improve the signal to noise ratio of the evoked potential. Once an evoked potential with sufficient signal to noise ratio is obtained, it is then usually characterized by amplitude and latency of significant peaks in the response. These peaks have been shown to change due to different cognitive states and/or disorders. Other advanced methods that may be considered include spectral analysis, time-frequency analysis, and bispectral analysis of the evoked potential signal.

4. Recap of Phase I Effort and Results

This section provides a brief review of the Phase I effort, the foundation it provided for continued work, and how this was transitioned into the Phase II effort.

The basic goal of the Phase I effort was to address the need for a systematic approach and comprehensive methodology for more effective design of human-operator interfaces. More specifically, we set out to identify a path of research and development that would lead to the implementation of a real-time human performance measurement system. This human performance measurement system would provide valuable insight into the human operator's performance level, and include assessments such as attention, fatigue, stress, cognitive state, and workload.

We envisioned that this technology would ultimately be applied to the task of systematically designing and evaluating interfaces for advanced military computer-based operations. As military computer systems and their corresponding interfaces grow more complex, the operator's (soldier's) task is also becoming more difficult. Interface designs that take into account the operator's cognitive processing will provide a higher level of *cognitive congruence* between the system the operator is using and the operator's existing internal mental models of environment and situation.

This Phase I proposal identified following set of Technical Objectives:

Develop "Human Performance Measurement" Technology Roadmap

This research survey, or 'roadmap', had the following criteria:

- Survey academic, commercial, and government research.
- Identify all relevant human performance related sensory, psychomotor, physiological and cognitive processes relevant to evaluating human performance.
- Identify research issues, challenges, etc., associated with measuring these human processes relative to human performance evaluation.
- Identify potential representative (military and private sector) technology applications (current /future) for overlay on the roadmap.
- Identify data collection hardware and software issues and challenges associated with identified applications.

Demonstrate "Human Performance Measurement System" Technology

The Phase I effort included a brassboard system which demonstrated Cybernet's existing capabilities in each of the critical technologies. These capabilities became the Phase II building blocks upon which a full scale performance measurement system was ultimately developed.

Develop Preliminary Phase II Plan

This objective entailed the development of a prototype "human performance measurement system" design for development and evaluation in the Phase II. Along with this design was a preliminary plan for carrying out the Phase II effort.

The Phase I effort was highly successful in achieving these objectives, and in fact broadened the scope of the proposed concept to encompass a wider range of human operator performance applications. The Phase I effort accomplished the following tasks:

- Surveyed broad set of human performance related research
- Developed a human performance measurement taxonomy
- Defined data collection hardware/software requirements and issues
- Identified wide range of candidate human operator applications
- Demonstrated the concept with a Phase I prototype system
- Designed a preliminary Phase II system
- Developed a Phase II implementation and validation plan

Figure 34 illustrates the overall concept of the total human performance assessment concept that resulted from the Phase I effort.

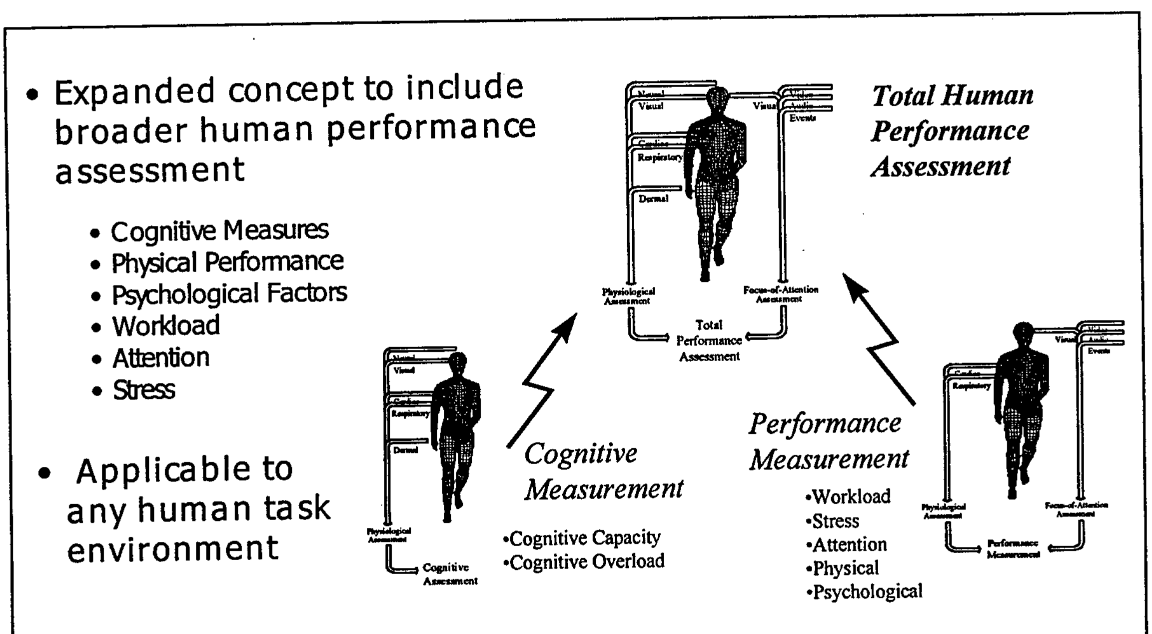


Figure 34: Illustration of the Concept for Total Performance Assessment that Resulted from the Phase I Effort

5. Overview of Phase II Objectives and Accomplishments

The Phase II effort set out to accomplish the following ultimate goal:

> *Develop and implement a highly flexible, modular system for human performance measurement, capable of evaluating human performance throughout a broad range of application environments*

The approach taken was to integrate an array of state-of-the-art measurement systems and data collection/analysis software into a comprehensive system for performance assessment. This successful development built off of several prior and ongoing Cybernet R&D and product development efforts for the following subsystems:

Physiological measurement systems
Eye tracking systems
Motion capture system
Distributed data collection and analysis software
Other data capture devices

Through the development and integration of this system we incorporated methods for both measurement and analysis of the identified array of performance-related parameters (physiological, psychological, and performance measures). The Phase II effort also addressed validation and application testing by conducting an initial set of experiments aimed at identification of performance-related indicators.

The Phase II proposal identified the following set of broad objectives:

1. **Requirements definition**
    - Review the Phase I study and design specification
    - Re-evaluate the latest state-of-the-art technology
    - Prepared an updated design specification

2. **Development of the complete Human Performance-Based Measurement System (HPBMS)**
    - Develop a modular system for application to a wide range of human operator task environments
    - Define the basic structure and essential hardware and software components
    - Develop specific measurement and analysis solutions for assessment of a wide range of performance parameters (both physical and cognitive)

3. **Implementation and evaluation**
    - Construct, integrate, and test a comprehensive modular HPBMS system
    - Implement and test HPBMS scenario specifically tailored for HCI applications

- Implement and test HPBMS scenario specifically tailored for mobile task applications
- Perform array of system validation tests
- Conduct preliminary set of research-oriented performance assessment experiments

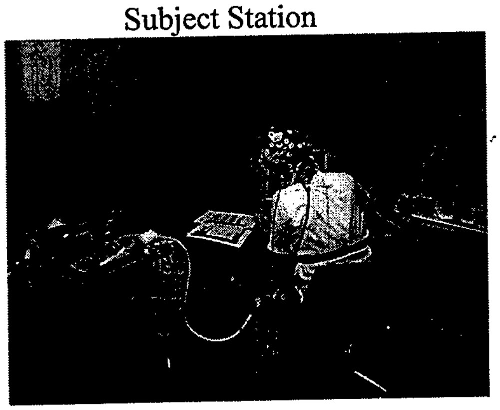
Each of these objectives was successfully accomplished through this Phase II effort. The following details the specific accomplishments achieved.

ESTABLISHED CYBERNET'S HUMAN PERFORMANCE LABORATORY

At the outset of this Phase II effort we established a controlled "Human Performance" laboratory at Cybernet's facilities. This laboratory was used for the progressive implementation, integration, evaluation, and experimental testing of the developed HPBMS.

Figure 35: Early HPBMS Implementation for Driving Simulator Interface Evaluation

Subject Station



Investigator Station

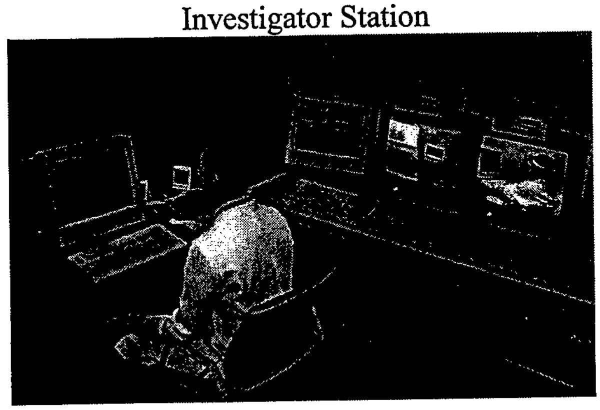


Figure 36: Comprehensive HPBMS Implementation for HCI Task Experiments

INTEGRATED CYBERNET'S 16 CHANNEL PHYSIOLOGICAL MEASUREMENT SYSTEM

As a key component of the developed HPBMS, Cybernet's 16 channel portable physiological measurement system (PPMS) was the first components to be integrated. The 16 channel device is the physiological (and other sensor) data acquisition system for use in desktop environments (i.e. computer interface tasks). This system was designed to operate within the DCAE software system architecture for distributed data collection and analysis operations.
Through this Phase II effort, extensive software enhancements to the PPMS and the associated DCAE software components were performed in order to meet the specific needs of the HPBMS. Specific details of the PPMS are provided in Section 6.6.

COMPLETED CYBERNET'S 8 CHANNEL PHYSIOLOGICAL MEASUREMENT AND INTEGRATED INTO THE HPBMS

The goal of the HPBMS to provide performance assessment in mobile task environments (such as dismounted soldier operations) presented the need for a more wearable version of the physiological measurement system. Through this Phase II effort, we helped complete the implementation of an 8 channel physiological measurement system, which is a smaller, lighter, and more power efficient version of the 16 channel PPMS.

The 8 channel PPMS was designed for use in mobile task environments where a wearable, untethered acquisition system is required. As with the 16 channel device, this system operates within the DCAE distributed collection and analysis architecture, in the same manner. Specific details of the PPMS operations are provided in Section 6.6.

INTEGRATED AND ENHANCED CYBERNET'S EYE TRACKING SYSTEM

The eye tracking system uses a video based approach, based on a device manufactured by ISCAN, Inc. (custom modified by Cybernet)[9] and specialized eye tracking algorithms developed by Cybernet. Through this Phase II effort we made significant improvements to the image processing algorithms and greatly enhanced the user interface and operational features. Using this software, eye tracking results can be measured, and synchronously captured along with other performance measurements, through one or both of two different methods.

The first method utilizes the VCR interface to record video images of the eye tracking results. These video images provide a real-time display of the tracked pupil, and a view of the user's field of view with an overlaid cross hair indicating where the user is looking. In the second method, numerical results of the eye tracking are captured within the synchronized networked data collection structure along with all other measured parameters. This was accomplished through the development of a custom software driver

[9] Cybernet has also developed our own eye tracking device which will be available for integration into the HPBMS in the very near future.

and interface that acquires eye tracking results through the DCAE software. Data provided by the eye tracking system can include: pupil location, gaze location, gaze location within a tagged area (see description of focus of attention algorithms that follows), pupil size, and blink. Details of the eye tracking system are provided in Section 6.7.

Developed and Implemented Automated Focus of Attention Algorithms

The automated focus of attention algorithms were developed through this Phase II effort, as a key enhancement to the eye tracking system, in order to meet the requirements of the HPBMS. Prior to development of the focus of attention algorithms evaluation of a user's point of regard had to be performed by a observer watching the recorded video and making note of where the user is looking. Now, the focus of attention algorithms provide for quantitative determination of gaze location within a computer monitor (or other "tagged" region within the user's field of view).

Quantitative determination of the user's point of regard is of significant advantage because it allows for automated analysis and numerical manipulation of a user's gaze location. For instance, one can easily perform calculations of how often, how many times, or how long a user looks at a certain object or area. This has tremendous advantage for the performance assessment application. Quantitative results of the focus of attention are output via the DCAE interface previously discussed. Details of the eye tracking system and the focus of attention algorithms are provided in Section 6.7.

Developed Interface and Software Components for Motion Capture System

Through separate research and development efforts Cybernet has developed an optical motion tracking system, called the FireFly, which is now available for commercial purchase. At the outset of this Phase II effort it was decided that the HPBMS should possess the capabilities to interface to this device to allow for the measurement of human body position and motion, as related to performance assessment. Therefore, through this Phase II effort we developed the necessary software components for acquisition, analysis, and display of position data within the HPBMS. Using the FireFly system, the HPBMS can acquire time-stamped, multi-tag (up to 32) position capture within the synchronized DCAE architecture. Details of the motion tracking system and the developed interface are presented in Section 6.8.

Developed and Enhanced Data Collection and Analysis Environment Software

Through this Phase II effort we conducted an extensive software development effort for enhancement of the pre-existing DCAE software foundation and for creation of numerous new features and components within the DCAE.

The DCAE software is a highly complex system for real-time, networked data collection and analysis that must balance competing demands for computational resources across a highly distributed network. Updates to the fundamental software architecture and existing foundation focused primarily on speed, performance, and reliability enhancements. The results of these enhancements yielded greatly improved performance, such as increased bandwidth capabilities, reduced delay times, etc. Furthermore, we made extensive improvements to the user interfaces that have resulted in a highly complex system that is surprisingly user friendly, easy to understand, and straightforward to operate.

In addition, many new features were added to meet the specific requirements of the HPBMS application. Specifically, we developed an array of new system interface drivers for acquisition of performance related data. These include the eye tracking system interface, the body tracking system interface, the updated VCR control interface, and the updated physiological measurement system interface. An array of signal analysis functions were also developed to meet the processing needs of the human performance related data. These include functions such as heart rate determination (from a measured EKG), respiration rate determination, artifact detection, filtering and smoothing operations, etc.

Other new components developed for the DCAE software system include specialized data and signal viewing tools. Specific viewers required by the HPBMS that were developed include: an EEG topographical brain map viewer, a evoked potential viewer, a body tracker data viewer, and a tag editor/viewer. Enhancements were also made to previously existing viewer, such as the multi-channel strip chart viewer, in order to meet the requirements of the HPBMS.

Specific details of the DCAE software system are addressed in Section 6.5.

DEVELOPED AND VALIDATED EVOKED POTENTIAL MEASUREMENT SCHEME

Given particular interest in the cognitive assessment capabilities of the HPBMS, the ability to acquire, process, and evaluate Evoked Potentials (EPs) was addressed through this Phase II effort. Specifically, we developed and implemented a protocol for EP measurement utilizing the physiological measurement system and custom developed DCAE components for processing and display of the averaged EP waveform.

Acquisition of the stimulus trigger signal is performed using one of the channels of the PPMS (while EEG is recorded on other channels), and a DCAE signal viewer was developed for the processing and display. The viewer provides for display of successive averaged EP waveforms, each labeled with the amplitude and latency of significant peaks, as is customary for EP signal evaluation. Functionality of the EP measurement protocol was validated using a visual evoked potential presented on a computer monitor.

CONDUCTED DRIVING SIMULATOR EXPERIMENTS

As a preliminary evaluation and assessment of the HPBMS concept, we conducted driving simulator (computer interface) experiments, during the early stages of the Phase II system integration process. This effort was performed in conjunction with an Air Force SBIR project that was focused on the development of innovative cognitive capacity measurement system. Measurements performed were: multi-channel EEG (brain activity), ECG (cardiac activity), respiration, EMG (muscle activity), and EOG (eye motion). This preliminary evaluation demonstrated the feasibility and potential benefit of EEG and other measures for cognitive and other performance assessment. Results are presented in Section 7.1.

CONDUCTED HMMWV DRIVING EXPERIMENTS

As another preliminary evaluation and assessment of the HPBMS concept, we conducted experiments of a human driving task using a HMMWV on a standard test track. This experiment was conducted jointly with another ARL SBIR project which was focused on the development of a model for human driving. This experiment evaluated the measurement of EOG, ECG, EMG, and within this type of performance assessment environment. In addition to providing indications of potential benefit, the results of this experiment provided initial feedback on the operational, procedural, and functional issues involved in the execution of performance assessment experiments in the field,. This helped guide continued development and enhancement of the HPBMS. Results of these experiments are presented in Section 7.2.

CONDUCTED COMPUTER INTERFACE TASK EXPERIMENTS

This set of experiments was conducted toward the latter part of the Phase II effort, once the comprehensive HPBMS had been fully integrated and validated. These experiments therefore exercised the complete array of standard HPBMS tools. A protocol was designed to analyze human performance in standard computer interface tasks, to achieve both a demonstration of the HPBMS capabilities and to conduct a preliminary investigation into potential indicators of human performance.

The result of this experimental protocol was highly successful. It demonstrated the power of the developed HPBMS as a research tool, and identified specific areas for continued research. Details of these experiments and the results are presented in Section 7.

VALIDATED MOBILE ENVIRONMENT OPERATION

To validate operation of the HPBMS for evaluation of mobile tasks, we examined functionality of the physiological measurement system as a wearable data collection system. Testing performed on the 8 channel physiological measurement system device (which is intended for the wearable application) included a basic shake test and an examination of the communications range using the currently configured wireless networking card. We also determined the capabilities and limitations of currently available laptop systems for real-time viewing of measured data over the limited bandwidth wireless network.

CONDUCTED SYSTEM TRAINING SESSION FOR ARL REPRESENTATIVES

A comprehensive training procedure was conducted towards the end of the Phase II effort to demonstrate and teach operation of the HPBMS to ARL representatives. The initial training session was held at Cybernet's facilities, and covered complete use of all HPBMS subsystems and operations. Feedback was received from the ARL representatives and used to make a few enhancements to the software prior to delivery.

DOCUMENTATION

As part of this Phase II effort extensive documentation was prepared, including user's manuals for the HPBMS as a whole, for each subsystem, and for all components of the data collection and analysis software. Troubleshooting guides and other application notes were also developed.

6. Detailed Description of the HPBMS System

6.1 HPBMS Overview

The Human Performance Based Measurement System (HPBMS) is a comprehensive set of hardware and software tools for evaluation of human-system task performance. The HPBMS facilitates measurement and analysis of performance-related variables through a distributed network of collection devices. The data collection network operates over standard TCP/IP protocols, which allows for easy setup of both local and remote collection nodes using existing local area networks, wide area networks, and the Internet.

Performance related data may be measured/collected from the following devices:

- Cybernet's physiological measurement systems (wearable/portable data acquisition systems)
- Eye Tracking Systems with Cybernet's Image processing software
- Cybernet's Motion Capture (Body Tracking) System
- VCRs with RS232 interface (for video and audio capture)
- Any device with serial data output
- Any collection system with data output through TCP/IP network socket
- Any computer application with data output through TCP/IP network socket (provides means for recording performance variables during HCI task)

Basic operations of the HPBMS include:

- Interconnection of distributed collection nodes over network
- Synchronized collection of data over all nodes
- Real-time viewing of any data from any node
- Synchronized playback of post-collection data from all nodes
- Analysis of collected data using built in functions
- Use of plug-in functions for customized on-line analysis
- Event marking (tagging) with range-based analysis operations

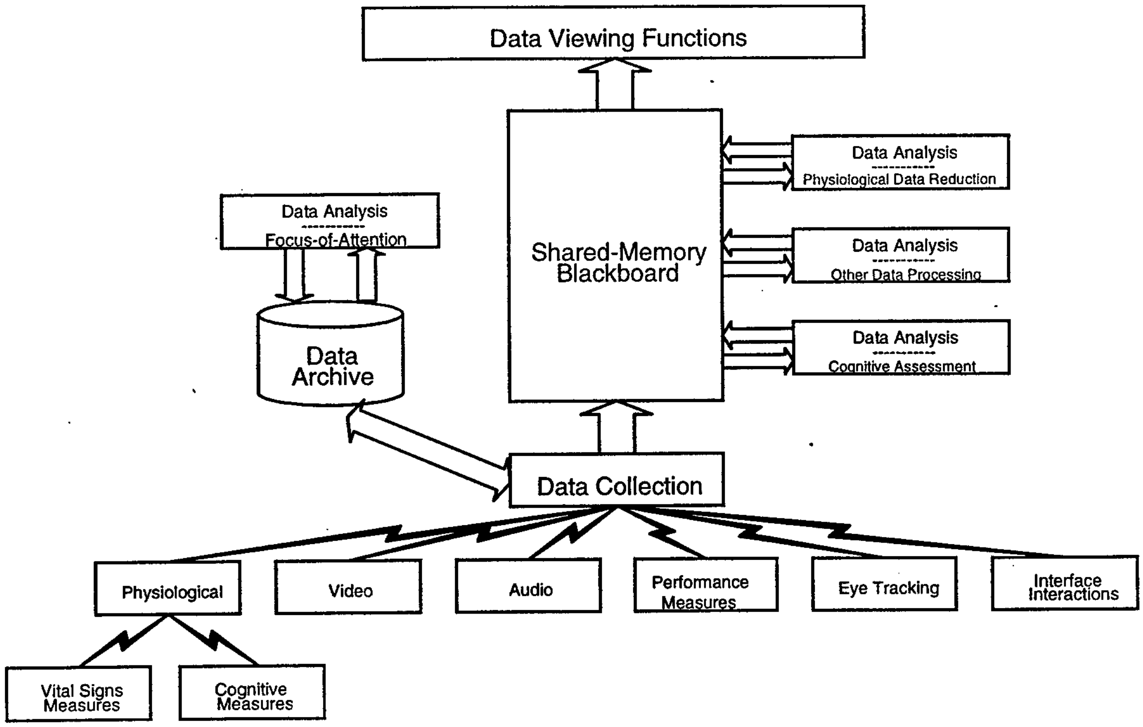


Figure 37: Block Diagram of Human Performance Measurement System illustrating the multiple data measurement systems integrated into a comprehensive, distributed, data collection and analysis architecture

6.2 HPBMS Applications and Usage

The HPBMS is a comprehensive and highly flexible tool intended to be used in a wide range of performance assessment and human factors related research. A researcher may easily configure an implementation of the HPBMS that uses any number of collection nodes. A setup may use one or more of the Cybernet developed data collection systems, and/or any number of customized data collection devices that have serial or network socket data output. Because the system works over standard TCP/IP network protocols the data collection network is quickly and easily established over existing networks and the Internet, allowing remote collection anywhere.

Example applications of the HPBMS include:

- Study of Human Computer Interface (HCI) tasks
- Evaluation and design of improved computer interfaces
- Psycho-physiological research
- Cognitive research and assessment
- Posture, gait and mobility analysis
- Productivity analysis and modeling
- Study of human interaction in virtual environments

Figure 38, below, illustrates an example scenario for study of a human computer interface (HCI) task. This HPBMS setup may be grouped into two functional components: 1) the User Interface Station, and 2) the Investigator's Station. The User Interface Station is where the subject performs the HCI task and performance-related data is measured using various data collection devices. The data collection devices are: 8 channel and 16 channel physiological monitors, eye tracker, body tracker, and video camera.

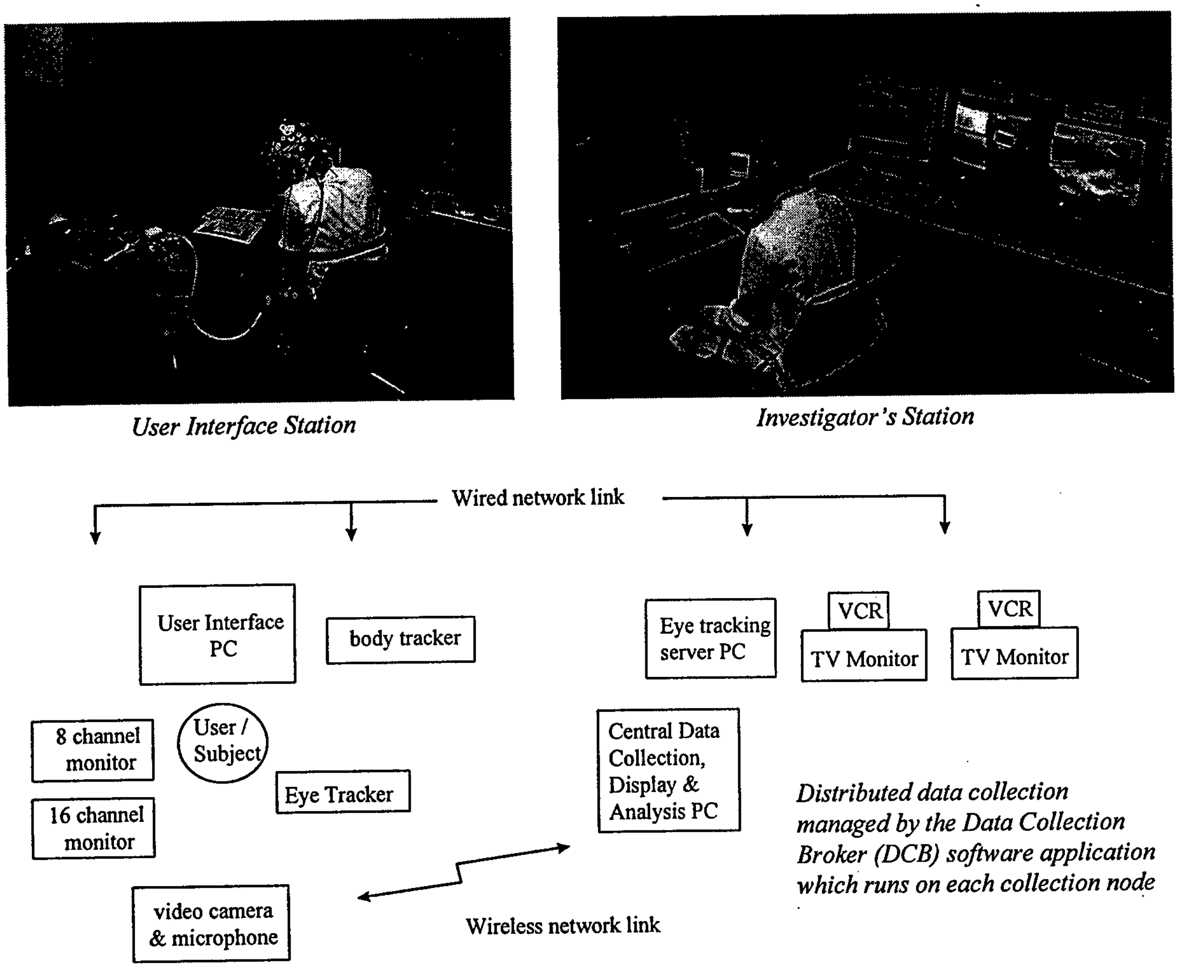


Figure 38: Example Scenario for Study of Performance in HCI Task

The Investigator's station is where the researcher controls and monitors the data collection and experiment process. The central data collection, display, and analysis PC provides the interface for initiating data collection, as well as viewing and analysis of the data. The eye tracking server PC performs the image processing algorithms for computing eye position; the results are then recorded on VCR (gaze location indicated on video of user's view taken from eye tracker) and/or recorded through the DCB software. A second VCR and TV monitor is also used to record video and audio from an optional video camera capturing a view of the user interface station.

User Interface Station:
- User Interface PC
- Task interfaces
- Keyboard, mouse, and joystick inputs
- Network communications to a DCB node for recording interface events
- Eye tracker client application for calibration grid display
- Physiological measurement systems
- Physiological sensor input and signal conditioning
- DCB software for networked data collection and communication
- Local data storage medium
- Wired or wireless networking
- User Interface Station (continued):
- Eye tracker
- Video output of eye to Eye Tracking Server PC
- Video output of users view to Eye Tracking Server PC
- Video camera
- Video and audio output of user interface station to VCR
- Body tracker
- Serial communication link to central collection node

Investigator's Station:
- Central data collection, display, & analysis PC
- DCB for networked data collection and communication
- Data collection drivers (serial or socket communications) to Eye Tracker Server, Body Tracker, and PC controlled VCRs
- Wireless LAN link
- Eye tracker client application for control operations
- Analysis software for real time viewing and synchronized playback
- Investigator's Station (continued):
- Eye Tracking Server PC
- Eye tracker server application (socket comm. link to the other PCs)
- 2 channel video input from head-worn eye tracker device
- Eye tracking display and video output to VCR
- VCRs
- Serial link to central data collection PC for control
- Video and audio input from camera (VCR 1)
- Video output from Eye Tracking Server display (VCR 2)
- TV monitor display

6.3 HPBMS Equipment List

Depending on the specific application, the HPBMS will be configured and utilized differently. The following provides a list of the basic components of the HPBMS, that may be included, and built upon, for a particular application:

16 Channel PPMS
Typical configuration:
- Network card (PCMCIA)
- Hard drive (PCMCIA)
- Electrode/sensor cable
- Auxiliary cable
- Power converter
- Power cable
- AC power supply

8 Channel PPMS
Typical configuration:
- Wireless network card (PCMCIA)
- Flash data storage (PCMCIA)
- Electrode/sensor cable
- Auxiliary cable
- Rechargeable battery pack(s)
- Battery cable

PPMS Battery Charger

Eye Tracking System, consisting of:
- Head-worn eye tracking device (manufactured by ISCAN, Inc. with custom modifications)
- Eye tracker server PC with:
  - Matrox Meteor frame grabbers (2)
  - Video scan converter (VGA to NTSC)
- Eye tracking software

Video camera with microphone (optional)

VCR and TV monitor

Central Collection and Display/Analysis PC, with:
- Wireless networking card (ISA) and antenna (for use with wireless PPMS)

Physiological sensors, which may include:
- EEG cap and disposable electrodes
- Electrodes for ECG, EMG, EOG, etc.
- Respiration band (piezo-crystal or strain guage)
- GSR sensor (optional)
- Temperature sensor (optional)
- Other purchased or custom sensors

Electrode lead wires and splitters, as needed for sensor inputs

Event marking switch (5 volt)

DCAE software (HPMS Installation CD)

Body Tracker System (optional)

Other items that may be necessary include rubbing alcohol for application of electrodes, a static mat (to be placed under the subject's seat) to minimize noise induced in lead wires, and a surge protector for all AC powered equipment.

6.4 List of HPBMS-Related Documentation

- **HPBMS System Overview**

This document describes the high level functionality of the Human Performance-Based Measurement System and general usage. The HPBMS subsystems are introduced in this manual, however, operational details of the individual subsystems are addressed in separate documents, as described next.

- **Data Collection and Analysis Environment (DCAE) Software Documentation**

The DCAE software is instrumental to the operation of the Human Performance Based Measurement system. It coordinates all collection, storage, transmission, display, and analysis of measured data. Documentation for the DCAE software consists of 3 separate documents:

<u>DCAE System Overview</u>

This document contains a general overview of the entire DCAE system. It describes the architecture and capabilities of the two primary components of the system – the Data Collection Broker (DCB) and the Analysis and Playback System (APS). The DCB controls the acquisition, communication, and management of data over the distributed collection network, while the APS provides tools for viewing and analysis of the data.

<u>DCB User's Guide</u>

This document describes the user interface for the Data Collection Broker (DCB) portion of the DCAE software. It details both the command line interface and the Graphical User Interface (GUI), either of which may be used to control networked data collection operations. Topics covered include system configuration, user-level commands, scripting, and how to run a simple data collection.

<u>APS User's Guide</u>

This document describes the user interface to the Analysis and Playback System (APS). It guides the user through the menu operations and describes each of the data viewing and analysis functions. It also illustrates the real-time viewing and synchronized playback capabilities.

- **Physiological Measurement Systems User's Guide**

This document describes configuration and use of the physiological measurement systems. It provides technical specifications for both the 8 channel (wearable) system and the 16 channel (portable) system. These devices may be used independently or in conjunction with other HPBMS data collection devices.

- **Eye Tracking System User's Guide**

This document describes use of the eye tracking system. It addresses both independent operation and operation within the HPBMS data collection environment. The eye tracking system is based on a video processing technique that produces gaze location within the user's field of view (captured with a head mounted camera) or within a viewed computer display.

- **Firefly User's Guide (Body Tracker - Optional Subsystem)**

This is the user's guide for the Firefly Body Tracking system. It addresses both independent operation and operation within the HPBMS data collection environment. The Firefly uses three cameras to track the location of infra-red tags (LEDs) in three-dimensional space. These tags can be placed on a person's body to track limb positions, on objects to track their motion, or anything which you want to collect exact position data about.

- **Tips & Troubleshooting Guides**

This document pair covers all portions of the Human Performance Measurement System. They contain useful shortcuts, important reminders, and tips and tricks to achieve better performance. The Troubleshooting Guide contains a list of possible errors and problems which might occur while using the system, and how to correct them.

6.5 The DCAE Software

6.5.1 Introduction

The distributed Data Collection and Analysis Environment (DCAE) is composed of four parts that work together to make up a comprehensive collection, test, analysis, and validation suite. These four parts are:

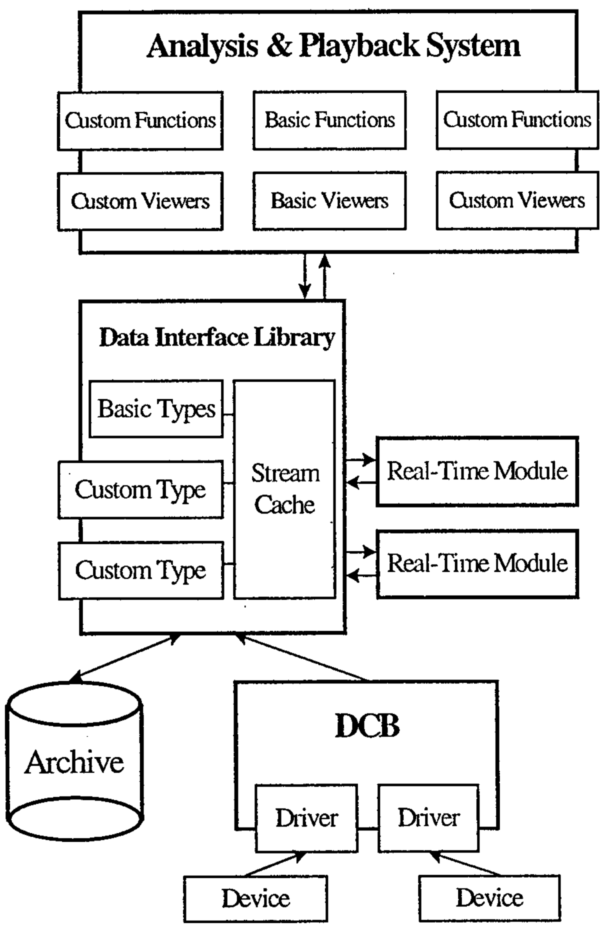
DCB The Data Collection Broker is a multi-platform console and Java GUI based application which is the backbone of all data collection operations. This system is capable of controlling and collecting data from a variety of low-level hardware devices over a heterogeneous distributed network. This is the starting point for all data collections.

DCB Drivers DCB Drivers are loadable modules which control the collection of data from hardware and virtual devices. These drivers are responsible for parsing and decommutating the data received by the device into an object oriented data framework.

APS The Analysis and Playback System is the primary method for monitoring, replaying, analyzing, manipulating, and exporting data collected using the DCAE.

Analysis Toolboxes A toolbox extends the standard functions and visualization tools to support advanced data analysis. These toolboxes can either be pre-packaged or custom-programmed based on customer needs.

The system block diagram below shows the integration of the parts mentioned above into the DCAE System.



Toolboxes are plug-ins which provide *custom functions and viewers* to extend the APS.

The *Data Interface Library* provides a standard, open API to handle streams of fixed- and variable-size data. It is implemented using shared memory to give many applications seamless and timely access to its data.

Real-Time Modules process data in the DIL to create new data. These modules can run on any node which is running the DCB, allowing for distributed computing.

Custom Data Types support specific drivers (i.e. an MPEG data type for full- motion video).

Drivers plug in to the DCB to provide support for hardware devices. Examples include VCR, Eye Tracker and serial port drivers.

All of the plug-in modules (drawn slightly displaced from the container module) are implemented as Dynamic Link Libraries (in Windows) or shared libraries (in UNIX). This allows the modules to be loaded at run-time for seamless integration with host applications.

All of the applications interact through the Data Interface Library. Any combination of applications can be used. The applications can start up and shut down independently of one another.

6.5.2 List of DCAE Software Documentation

DCAE System Overview
This document contains a general overview of the entire Data Collection and Analysis Environment (DCAE) system. It describes the architecture and capabilities of the two primary components of the system – the Data Collection Broker (DCB) and the Analysis and Playback System (APS).

DCB User's Guide
This document describes the user interface for the Data Collection Broker (DCB). It covers system configuration, system inputs, user-level commands and scripting, as well as the graphical user interface (GUI). A "getting started" section is included which describes the necessary steps for a simple data collection using the GUI. It also details a DCB session which guides the user through a sample data collection using the command line interface.

APS User's Guide
This document describes the user interface to the Analysis and Playback System (APS). It guides the user through menus and describes each available data viewer and analysis function.

Tips & Troubleshooting Guides
While these documents cover all portions of the Human Performance Measurement System, they also include extensive sections on the DCB GUI, DCB Console, and APS. Refer to them for help with any problems that may occur while using the DCAE, and for helpful tips and suggestions.

6.5.3 Description of the Data Collection Broker (DCB)

The DCB is the primary software component and interface that coordinates all data collection operations within the DCAE architecture. It captures synchronized data from networked collection devices that run generic or custom acquisition drivers that operate within the DCB. It has the following characteristics:

- Works on a variety of operating systems including DOS, UNIX (FreeBSD), and Windows NT.
- Allows simultaneous data collection from multiple devices. Each device represents a single stream of data (from a physiological monitor, eye tracking system, digital VCR, etc.).
- Can be used to communicate with other remote nodes to control, collect, and/or stimulate devices connected to them. Data collected from the remote nodes can be monitored in real time (actual rate depends on connection bandwidth).
- Supports multiple data types including float, double, long integer, integer, boolean, graphic, and string types.
- Can archive collected data to the local computer. The Analysis and Playback System can then be used to replay the collected data.
- Can use scripts to configure, control, and execute pre-arranged data collections.
- Can incorporate real-time modules which support concurrent real-time processing during data collection. Some examples of real-time modules are: Expert Systems, Neural Networks, Limit Checking Alerts, and other custom functions.

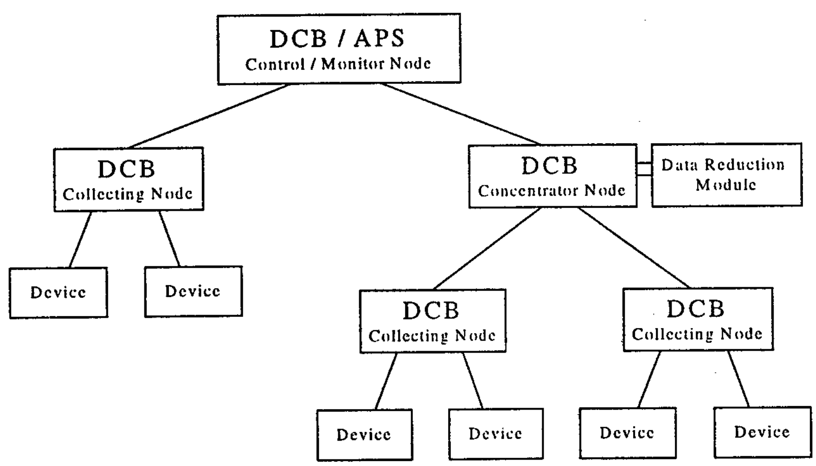


Figure 39: Example of a DCB Network Configuration

The DCB is operable in two different forms: a DOS-like console application (the DCB Console), or a Graphical User Interface application (the DCB GUI). The figures below illustrate these applications. For more detail on these software applications, refer to the DCB User's Guide.

List of Developed DCB Drivers

Currently the DCB supports the following collection devices:

- *Serial Driver*
  This is a generic interface for collecting any data off of a serial interface. The packet format is defined in the configuration and then the driver can collect that data.

- *Packet Driver*
  This is a generic interface for collecting any data through network socket link. The packet format is defined in the configuration and then the driver can collect that data.

- *PPMS Driver*
  This is the driver that performs data collection operations on the portable physiological measurement system (PPMS). The PPMS unit and its driver extend the Data Collection Broker (DCB) to perform multi-channel acquisition and analysis of physiological signals. The PPMS unit is a portable DCB node specialized for use as a data-acquisition engine. The PPMS Driver interfaces the PPMS hardware to the DCB system, which provides data-management functionality, network connectivity, and time synchronization of multiple DCB nodes. Together, the hardware and software combine to form a complete solution for the collection of physiological data under local or remote control.

- *Pulse Oximetry Driver*
  The Pulse Oximetry Driver interfaces the DCB to a pulse oximetry module manufactured by the Nonin Corporation, providing plethysmograph, blood oxygenation, and pulse rate data. Typically this module is operated through the serial port interface of the PPMS device, but may also operate independently.

- *Blood Pressure Cuff Driver*
  The Blood Pressure Cuff Driver provides an interface to an automated blood pressure cuff via either RS-232 or IRDA communication modes. Typically this module is operated through the PPMS device, but may also operate independently.

- *VCR Driver*
  This driver provides an interface for the control of a digital VCR with serial port interface, to provide time-synchronized collection and playback video data.

- *EyeTracker Driver*
  This driver receives data from Cybernet's eye tracking system, using network socket communications.

- *BodyTracker Driver*
  This driver receives data from Cybernet's body tracking (motion capture) system, using serial port communications.

- *TestWave Driver*

This driver generates pairs of sine and cosine waves for testing and validation purposes. Amplitude, frequency, and number of pairs generated are among the parameters which can be manipulated.

6.5.4 Description of the Analysis and Playback System

The APS is the primary software component and interface that coordinates all data analysis, manipulation, and viewing within the DCAE architecture. It is a Windows based interface that has the following features:

- Can create views of sets of data fields. Strip charts, bar charts, text views, and other standard views are supported. Toolboxes can be used to provide additional or customized views.
- Can coordinate and synchronize playback of data displayed in the opened views.
- Can apply functions to the data fields to create new data fields. Some supported functions are filters, FFT's, and smoothing and resampling operations. Toolboxes can be used to provide additional or customized functions.
- Allows you to manipulate the data fields. You can cut, copy, and paste fields or sections of fields to move them from one collection set to another.
- Allows you to annotate and select data of interest for further analysis. This is done by creating tag fields. The tag fields are used to mark and record user observations made while analyzing the data, and can be used to define ranges for playback and function execution.
- Allows workspaces to be created, saved, and restored. This allows for the automatic restoration of a set of views and their attributes (position, size, scaling properties) when a collection set is loaded.
- Can monitor data collected from the DCB in real time, automatically adapting to network bandwidth constraints.
- Can export data for further analysis and/or display using third party software.

Figure 40 shows a sample Analysis workspace configuration, demonstrating EEG signal and topographic display; numeric and text viewers for ECG, respiration, and EMG signals; a VCR control viewer window; and synchronized playback controls. For more details on operation of the Analysis and Playback System software, refer to the APS User's Guide.

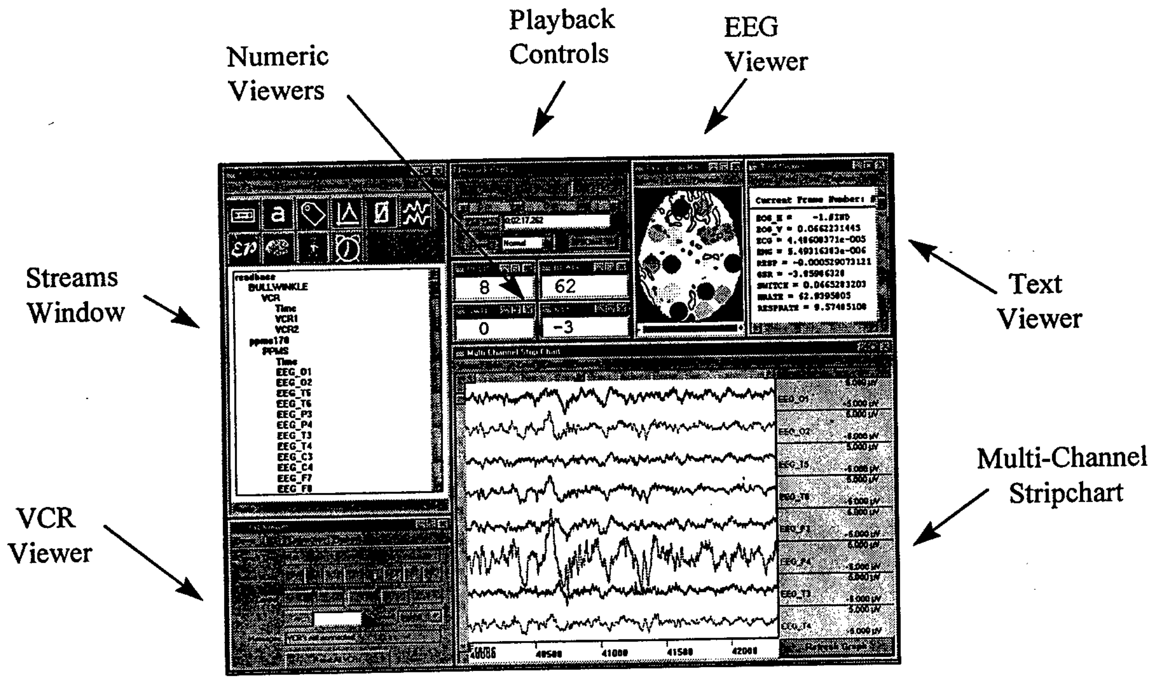


Figure 40: Analysis and Playback System Sample Workspace Screen Shot

Available Analysis Viewers

Following is a list of currently available viewers within the APS interface:

- VCR Viewer
- Text Viewer
- Tag Editor/Viewer
- Spectrum Viewer
- Numeric Viewer
- Multi-channel Stripchart Viewer
- Evoked Potential Viewer
- EEG Brain Map Viewer
- Motion Capture (Body Tracker) Viewer
- Alarm Viewer

Analysis Functions

Following is a list of the currently available analysis functions, for processing collected data, within the APS interface.

- Scientific Calculator Operations
- FIR (Finite Impulse Response) Filter
- Moving Window Average
- Median Filter

- Noise Generation
- Rate Detection
- RMS Power
- State Classification (threshold detection)
- Artifact detection
- Statistical Operations (via Tag Viewer)

Data Export
The APS interface also allows the user to export data to a text file (tab, comma, or space delimited) or to a Matlab format file for further data analysis and/or manipulation.

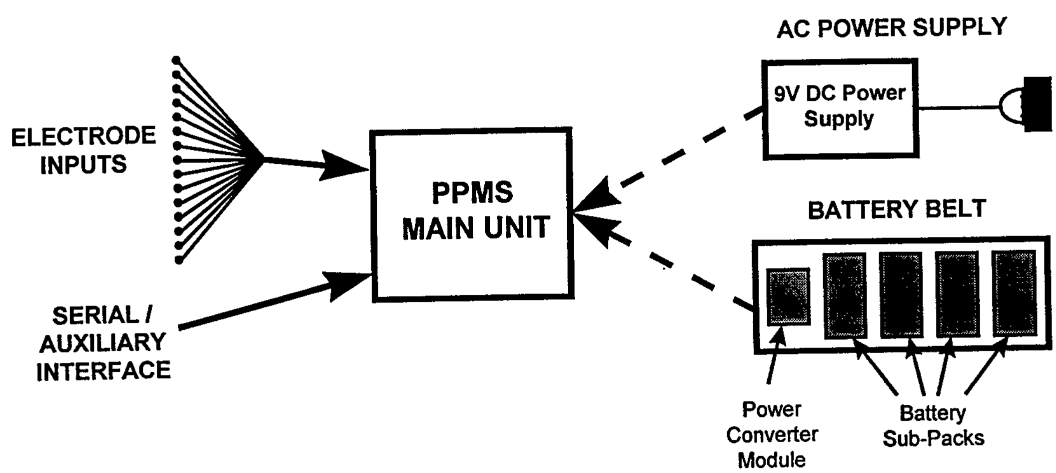
6.6 Physiological Measurement Systems

6.6.1 Overview

The Portable Physiological Measurement System (PPMS) is a miniature computing platform that performs multi-channel data collection and provides network interoperability. The system operates within Cybernet's Data Collection and Analysis Environment (DCAE) architecture for distributed data collection over networks (see separate DCAE manuals).

Programmable signal conditioning features of the PPMS allow for measurement of any signal ranging from 1 uV to ±5 V, and provides selectable filtering and other conditioning operations. The system has a PCMCIA interface providing convenient hardware configuration using PC-cards for data storage (hard drives, FLASH cards), networking (Ethernet, wireless LAN), and other functions.

Currently two versions of the physiological measurement system are available: a 16-channel device, and an 8-channel device.



Software for the physiological measurement system is based on the DCAE system. The physiological measurement system runs a DOS version of the Data Collection Broker. All remote operability and interaction is achieved through the DCB interface, and remote viewing and analysis of data can be performed through the Analysis and Playback (APS) software.

The system may be operated through three different methods: 1) the front panel interface (16 channel system only), 2) the DCB console running on a networked machine, or 3) the DCB graphical user interface running on a networked machine. The following sections provide a description of the PPMS devices and some examples of operational use. For more details on configuration and operation of these devices, refer to the PPMS Users Guide document.

6.6.2 Hardware Descriptions

6.6.2.1 The 16-Channel Device Specification

Figure 41: The 16 Channel Portable Physiological Measurement System

Cybernet's network-operable physiological measurement system is a portable data collection device that supports a wide range of physiological and other signal measurements. It is a miniature PC-based system that offers extensive programmability and flexibility. Uniquely designed signal conditioning circuitry allows for connection of any channel to almost any sensor type, including biopotential electrodes for ECG, EMG, EEG, etc. The system has 2 serial communications interfaces as well as 4 PC-card slots for data storage (hard drive or flash memory), networking (wired or wireless), and other functions (such as global positioning). Integrated blood pressure (NIBP) and pulse oximetry modules are also available. For applications requiring more than 16 channels, multiple devices may be used simultaneously.

The 16-Channel PPMS is designed to be as light as possible while still allowing for 16 channels on which to collect data. It is ideally suited for use as a portable table-top machine, although it is small and light enough to be worn on a belt or carried in a backpack.

16 Channel PPMS Technical Specifications:

Physical Dimensions (approx.):	4" x 5.5" x 8", contoured
Weight (approx.):	3.5 lbs. (approx.)
Network Protocol:	TCP/IP (Ethernet or wireless)
Signal Conditioning	
Amplification:	Differential
Isolation (channel to channel):	500 volts
Isolation (channel to system):	1,500 volts
Input noise (gain > 10,000):	< 1 μV RMS
Input voltage range:	+/-5 V
CMRR:	>107 dB @ 60Hz
Gain:	1 to 300,000
Coupling:	AC or DC
High pass Filter:	4-pole, 4 frequency options
Baseline restoration:	Programmable on/off
60 Hz notch filter:	Programmable in/out
Low pass filter:	4-pole, 8 frequency options
DC offset:	-5 volts to +5 volts
A/D Conversion:	12 bit resolution, 10 volt range
Power Supply:	AC, or Battery Pack (6-15 volts)
PC Card:	3 available slots
Data Storage:	Up to 2.08 Gbytes
LCD Display:	128 x 64 graphical, w/ backlight
User Input:	8 button
Auxiliary Interfaces:	Two RS-232 serial ports

16 Channel PPMS Hardware Configuration:

The 16 channel PPMS device is pre-configured for the typical operational scenario, however the flexible platform allows for configuration of the hardware to meet specific application requirements.

Please note: if you wish to reconfigure the PPMS hardware it is strongly recommended that you contact Cybernet technical staff and arrange for proper handling. Improper handling of the internal hardware components can damage the device.

The hardware is already configured to meet the needs of most applications, however you may wish to configure it with different PC Cards to meet the particular needs of your application. For this purpose, the back end of the PPMS is removable. First, disconnect any ethernet attachments that exit the PPMS through the rectangular slot on the back, and all other cables (battery cables, patient cables, etc…). To remove the back cap, press in on the short sides, then slowly pull the cap away from the main body of the unit *while continuing to keep pressure on the sides of the cap.* There are 2 clips on each side of the cap which must be pressed on in order to remove the cap.

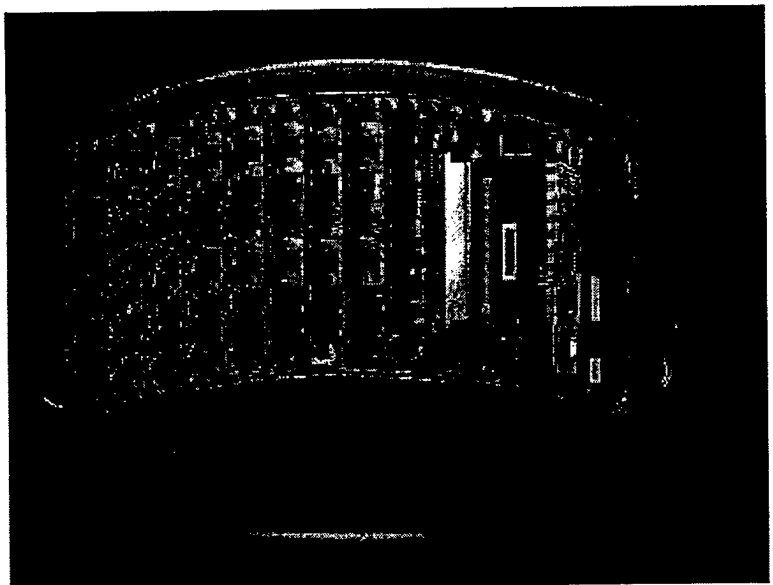


Figure 42: View of the 16 Channel PPMS Hardware Components Inside Back Panel

Looking directly at the back of the open 16-Channel PPMS, the interior of the unit is arranged as follows (from left to right):

<u>8 Programmable Amplifier Boards</u> - each board supports 2 channels of data independently. The boards are numbered 1-8, starting with 8 at the left. Board 8 supports channels 15 and 16, Board 7 supports channels 13 and 14, etc.

<u>4 PCMCIA Slots (2 carrier boards with dual slots)</u> - In the default configuration a hard drive (520 MByte) and Ethernet networking card are currently located in the PCMCIA (PC Card) slots. Two slots are potentially available for additional PC Cards if desired for your application – these may be used for additional data storage or other functions. Some PC Cards (such as the hard drive) require the space of two slots and may limit the number of Cards that may be used. Additional space is available between the rightmost slot and the CPU carrier board – double width Cards should therefore be placed in the rightmost slot when trying to maximize the number of PC Cards that may be used.

<u>CPU Carrier Board</u> - This board contains the CPU and associated hardware. The system may be configured with a 386 or 486 based processor unit depending on the desired tradeoff between power consumption and performance. The default configuration contains the 486 processor. If it is deemed necessary to change the CPU configuration please contact Cybernet technical staff for more information.

6.6.2.2 8-Channel Device Specification

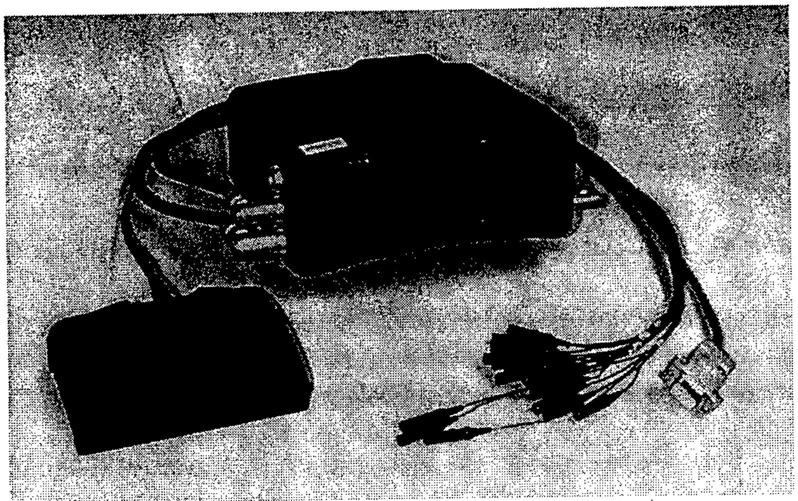


Figure 43: The 8 Channel Portable Physiological Measurement System

Cybernet's wearable physiological measurement system is a smaller, lighter, lower-power version of the 16 channel physiological monitor described above. It has the same programmable functionality of the 16 channel system, except for fewer channels, fewer PC-card slots, and a less extensive user interface.

8 Channel PPMS Technical Specifications:

Physical Dimensions (approx.):	2.6" x 5.7" x 6.5", contoured
Weight (approx.):	1.9 lbs. (without battery)
Network Protocol:	TCP/IP (Ethernet or wireless)
Signal Conditioning	
Amplification:	Differential
Isolation (channel to channel):	500 volts
Isolation (channel to system):	1,500 volts
Input noise (gain > 10,000):	< 1 µV RMS
Input voltage range:	+/-5 V
CMRR:	>107 dB @ 60Hz
Gain:	1 to 300,000
Coupling:	AC or DC
High pass Filter:	4-pole, four frequency options
Baseline restoration:	Programmable on/off
60 Hz notch filter:	Programmable in/out
Low pass filter:	4-pole, eight frequency options
DC offset:	-5 volts to +5 volts
A/D Conversion:	16 bit resolution, 20 volt range
Power Supply:	AC, or Battery Pack (6-15V)

PC Card:	2 available slots
Data Storage:	Up to 2.08 Gbytes
User Control:	Power-up and shutdown

8 Channel PPMS Hardware Configuration:

The 8 channel PPMS device is pre-configured for the typical operational scenario, however the flexible platform allows for configuration of the hardware to meet specific application requirements.

Please note: if you wish to reconfigure the PPMS hardware it is strongly recommended that you contact Cybernet technical staff and arrange for proper handling. Improper handling of the internal hardware components can damage the device.

The hardware is already configured to meet the needs of most applications, however you may wish to configure it with different PC Cards to meet the particular needs of your application. For this purpose, the back end of the PPMS is removable. First, disconnect any ethernet attachments that exit the PPMS through the rectangular slot on the back, and all other cables (battery cables, patient cables, etc...). To remove the back cap, you will need a hex wrench to unscrew the three silver screws holding the back cap on. It is suggested that when removing the back, you tilt the PPMS up so that it is resting with the front face down.

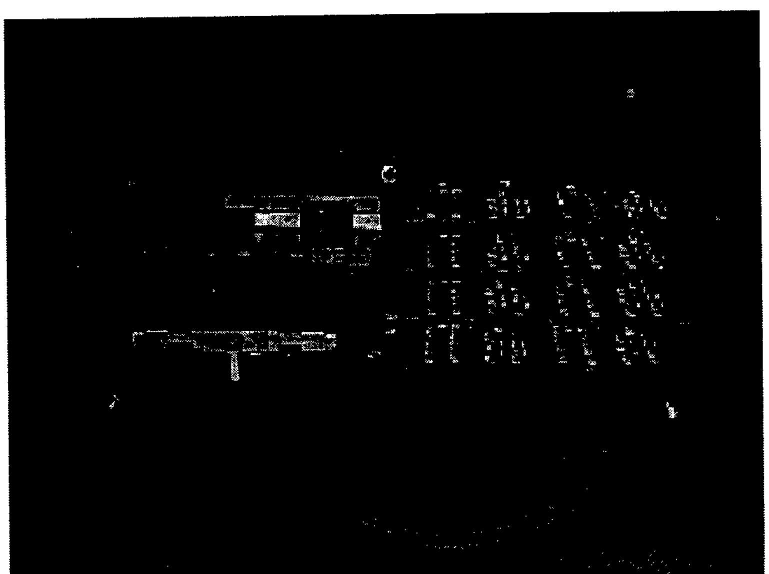


Figure 44: View of the 8 Channel PPMS Hardware Components Inside Back Panel

Looking directly at the back of the open 8-channel unit, the boards are arranged as follows:

From top left to bottom left:

CPU Carrier Board - the default configuration uses a 486 based processor

2 PCMCIA slots (1 board with dual slot) - in the default configuration the two slots are occupied by an 85MByte Flash (data storage) card and a Proxim RangeLAN2 wireless networking card

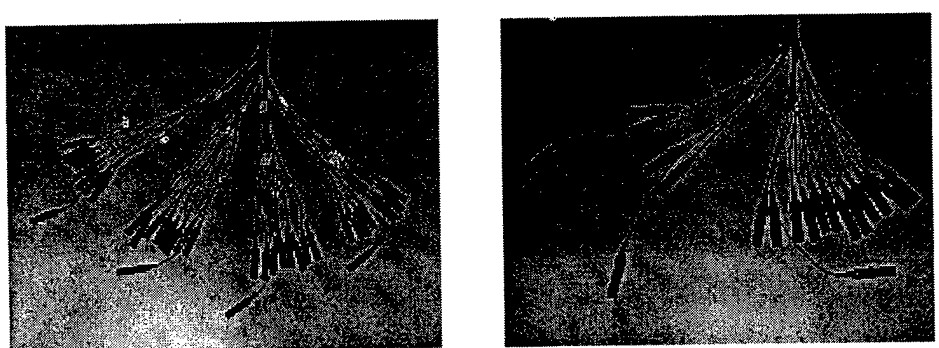
From top right to bottom right:

4 Programmable Amplifier Boards - each board supports 2 channels of data independently.

Do not remove any of the boards without first consulting Cybernet technical staff. The PC Cards may be removed and replaced, however power should first be turned off and all cables disconnected.

6.6.2.3 The Patient Cable

The Patient Cable is the means by which physiological signals are captured and recorded by the PPMS. There are several different versions of the cable, but they all follow the same basic design. At one end is a plug for connecting the cable to the PPMS. The other end contains a number of electrode pairs (8 or 16 pairs, depending on which PPMS you are using) and connections for electrical grounding. Each of the pairs is numbered - this number corresponds to the PPMS channel to which it is linked. Each pair consists of a black and a red connector pin: red is the positive input, black is the negative input.



(a) (b)

Figure 45: View of the Standard Patient Cables for (a) the 16 Channel Device, and (b) the 8 Channel Device

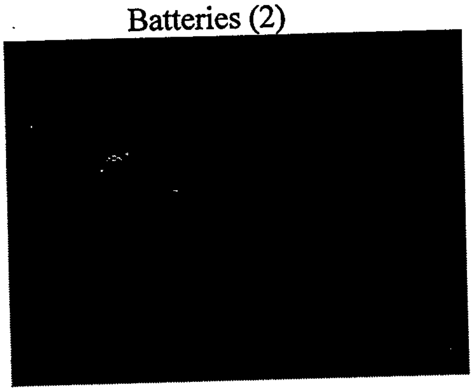
The 16-Channel patient cable has a rectangular clip at the PPMS end. The electrode leads are paired off as normal. There is one shared ground for every 4 channels and which is bundled with its respective group: channels 1 - 4, 5 - 8, 9 - 12, 13 - 16.

The 8-Channel patient cable has a circular L-connector at the PPMS end. The electrode leads are then paired off as normal. There is one common ground (green wire) for channels 1 - 6. Channels 7 and 8 each have independent grounds that are bundled with the respective inputs.

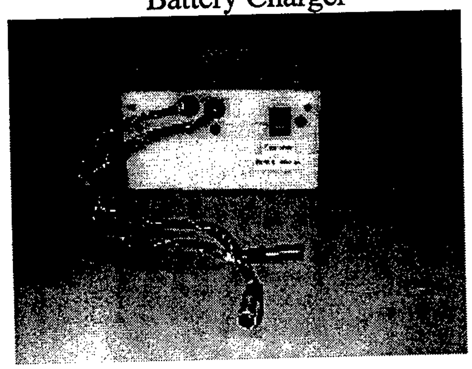
The connectors at the end of the patient cable are male, and will accept the female connector ends of standard medical electrodes.

6.6.2.4 Additional Components

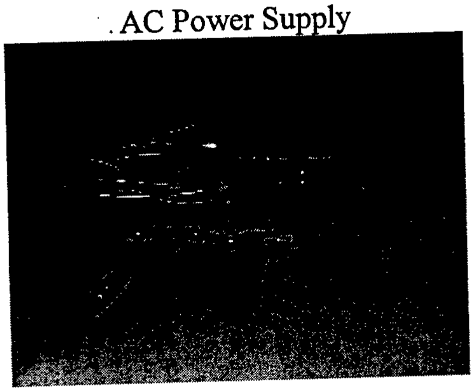
Batteries (2)



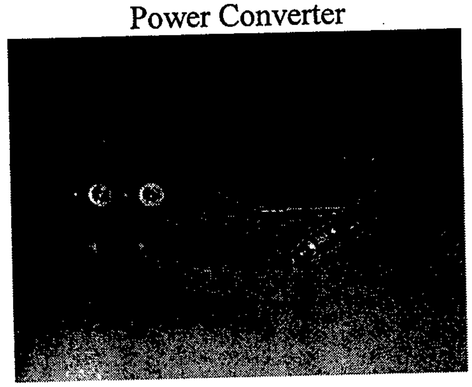
Battery Charger



AC Power Supply

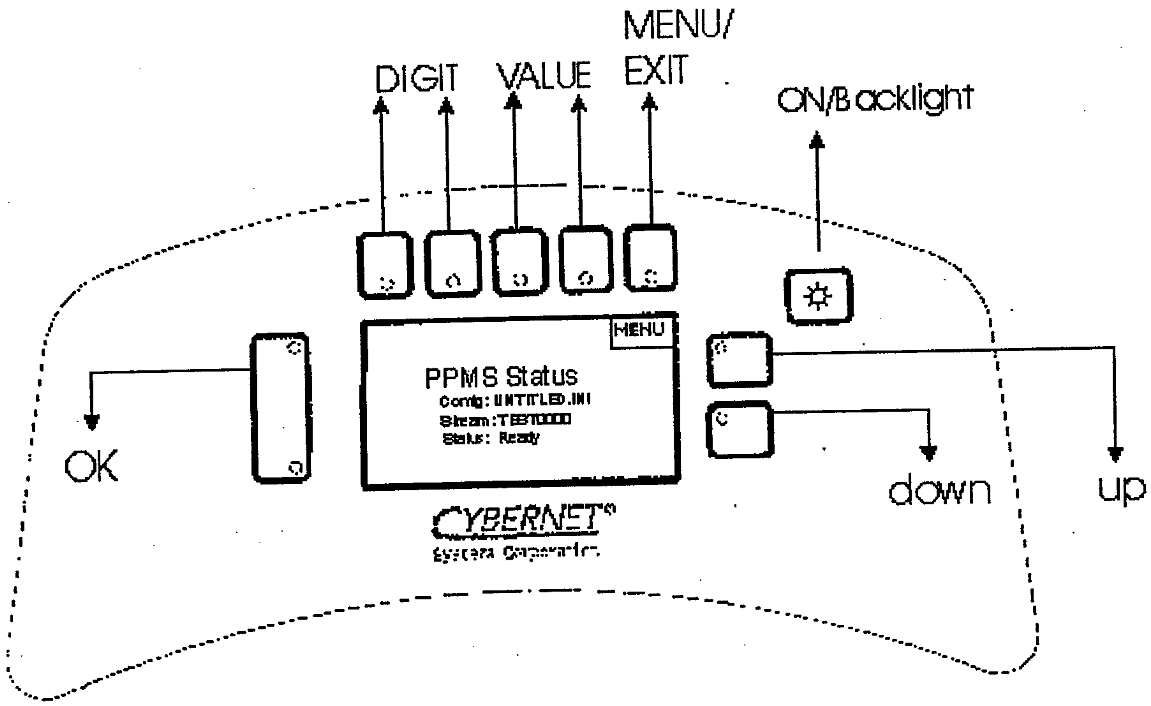


Power Converter

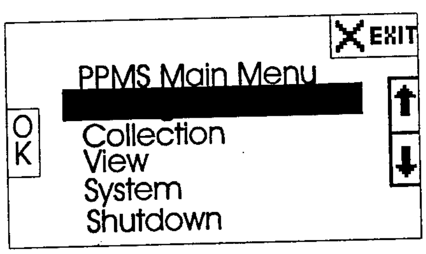


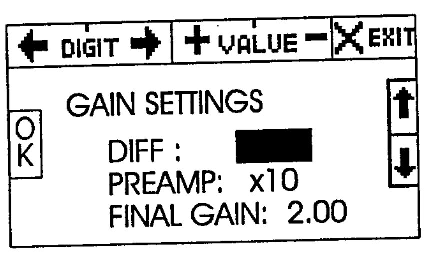
6.6.3 The PPMS Front Panel Interface

The front panel local menu interface is available only for the 16 channel version of the system. This interface provides complete control over operation of the system (for the 8 channel device, control must be performed through remote operation using the DCB command console or the DCB graphical user interface).



The menu system is composed of three main elements. The user can select the various options using the five buttons above, the two buttons to the right, and the single button to the left of the display. The five buttons above the display provide menu selections as well as text and numeric manipulation functions. The two buttons to the right of the display provide the ability to scroll up or down through a list of choices. The single button to the left of the display is often utilized as an "OK" button to commit to changes. An example menu illustrating the various button functions is shown below.

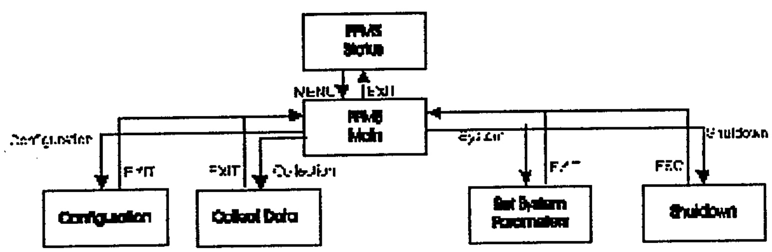




The example menu shown above allows the user to set the gain of one or all of the physiological channels in the PPMS. The row of icons at the top of the display identifies the function of each of the five buttons located above the display. The buttons labeled ←

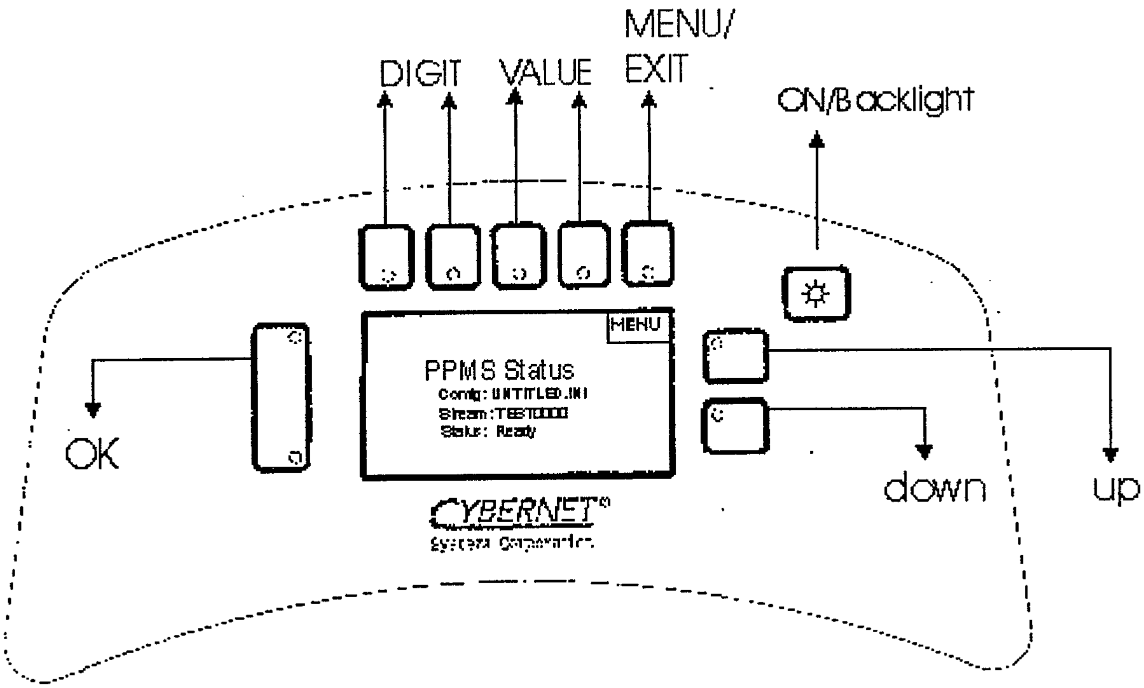
and → allow the user to move the cursor left and right, respectively, for example, to select a digit to modify. The buttons labeled + and – allow the user to increment and decrement, respectively, either numeric or alphabetic fields. The EXIT button allows the user to return to the previous menu without making any changes. The two buttons to the right of the display labeled ↑ and ↓ allow the user to scroll up and down, respectively, through the displayed list of options. The button to the left of the display labeled OK allows the user to commit to the changes, thus altering the configuration, and return to the previous menu. The numeric entry editor, for modifying parameters which can be set to a range of arbitrary values, works as follows: when the left or right arrow is pressed, it will move to an existing digit if there is one, otherwise it wraps around to the other end. If the decimal point is selected, the + (increment) or – (decrement) buttons will slide the decimal point left or right. If the leftmost digit is highlighted and incremented past 9, the result is a "carry" (i.e. a new leftmost digit appears set to 1). Decrement of most significant digit (MSD) of numeric parameters is reduced to the next smaller place value when the MSD is 1.

All the necessary functionality of the PPMS can be accessed through this menu system. The user can choose to configure the PPMS driver, start and stop a collection, view single-channel stripcharts or multi-channel bar charts, set various system parameters, or shut down the PPMS unit. The figure below illustrates the top-level view of the PPMS menu system.



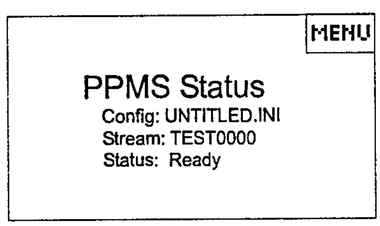
6.6.4 Quick Start Operation Using the Front Panel

The recommended method for PPMS operation is by using the DCBGUI application (see Section 6.6.4), however the front panel can be extremely useful for some situations. Following is an excerpt from the PPMS User's Guide that provides a sample operation scenario for PPMS data collection using the front panel interface of the 16 channel device.

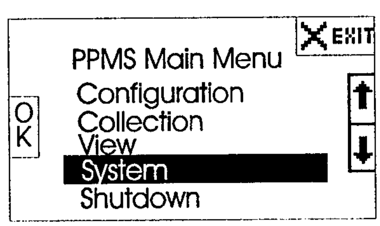


(1) Turn on the PPMS by pressing the "ON/Backlight" button.

(2) In approximately 25 seconds the computer will completely boot up. Once the boot up is complete the Cybernet Systems Logo will appear followed by the **PPMS Status** menu.



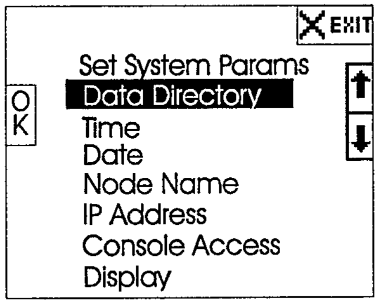
(3) Press the "MENU/EXIT" button above the display labeled *MENU* to get into the **PPMS Main Menu.**



(4) Your current selection will be *Configuration*. Select *System* by using the *up/down* buttons and press the red *OK* button.

(5) You will now be at the **Set System Params** menu. Highlight the selection you wish to modify and press OK. You will probably need to change or create the *Data Directory,*

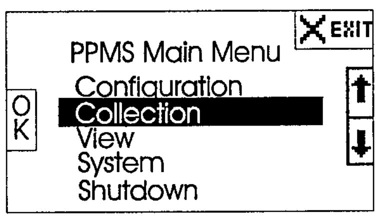
Time, Date, Node Name, and IP Address if this is the first time you are using the PPMS. For a more detailed explanation of these menu options, consult the Front Panel Operations Section of this manual.



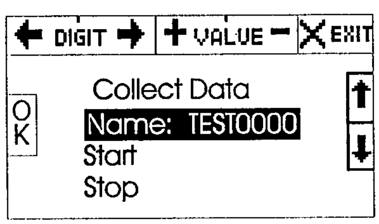
When you have finished correctly setting the system parameters, press the exit button from the Set System Params menu to return to the PPMS Main Menu.

(6) The PPMS will already have a default .ini file loaded (as indicated on the PPMS Status Screen). For more information on changing this .ini file, selecting a different .ini file, or creating a new .ini file, refer to Section 7.5.

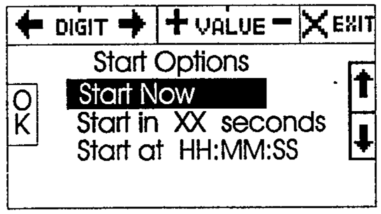
(7) From the **PPMS Main Menu** highlight *Collection* from the list and press OK.



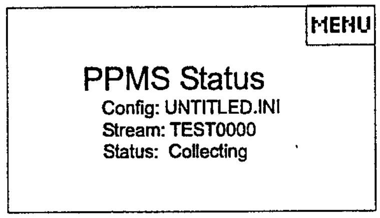
(8) You will now be at the **Collect Data** menu. Enter name of file to store data. Make sure file name does not already exist; if it does select another name.



(9) Then highlight *Start* from **Collect Data** menu and press OK. The **Start Options** menu has *'Start Now'*, *'Start in 10 seconds'* and *'Start at ---'* options. The *Start at* time should default to the time previously set. To start immediately without a delay, highlight *start now* to start data collection. Press OK.

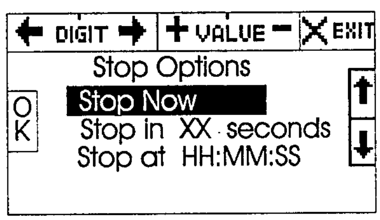


(10) If collection can startup you will be returned to the **PPMS Status** menu. *Status: Ready* will change to *Status: Collecting* once the PPMS has started collecting.

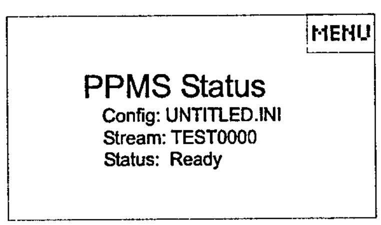


(11) Press the *Menu* button to get into **PPMS Main Menu**. Highlight *collection* to get into **Collect Data** menu. Select *stop* and press OK.

(12) You will now be at the **Stop Options** menu. Set a delay for stopping collection using the '*stop in XX seconds*' option. Select '*stop at —*' to set a specific time for halting collection. Or, select *stop now* to stop the collection immediately. Then press OK.



(13) You will now be returned to the **PPMS Status** menu. The *status* will change to *Status: Ready.*



6.6.5 Sample Operation of the PPMS using the DCBGUI

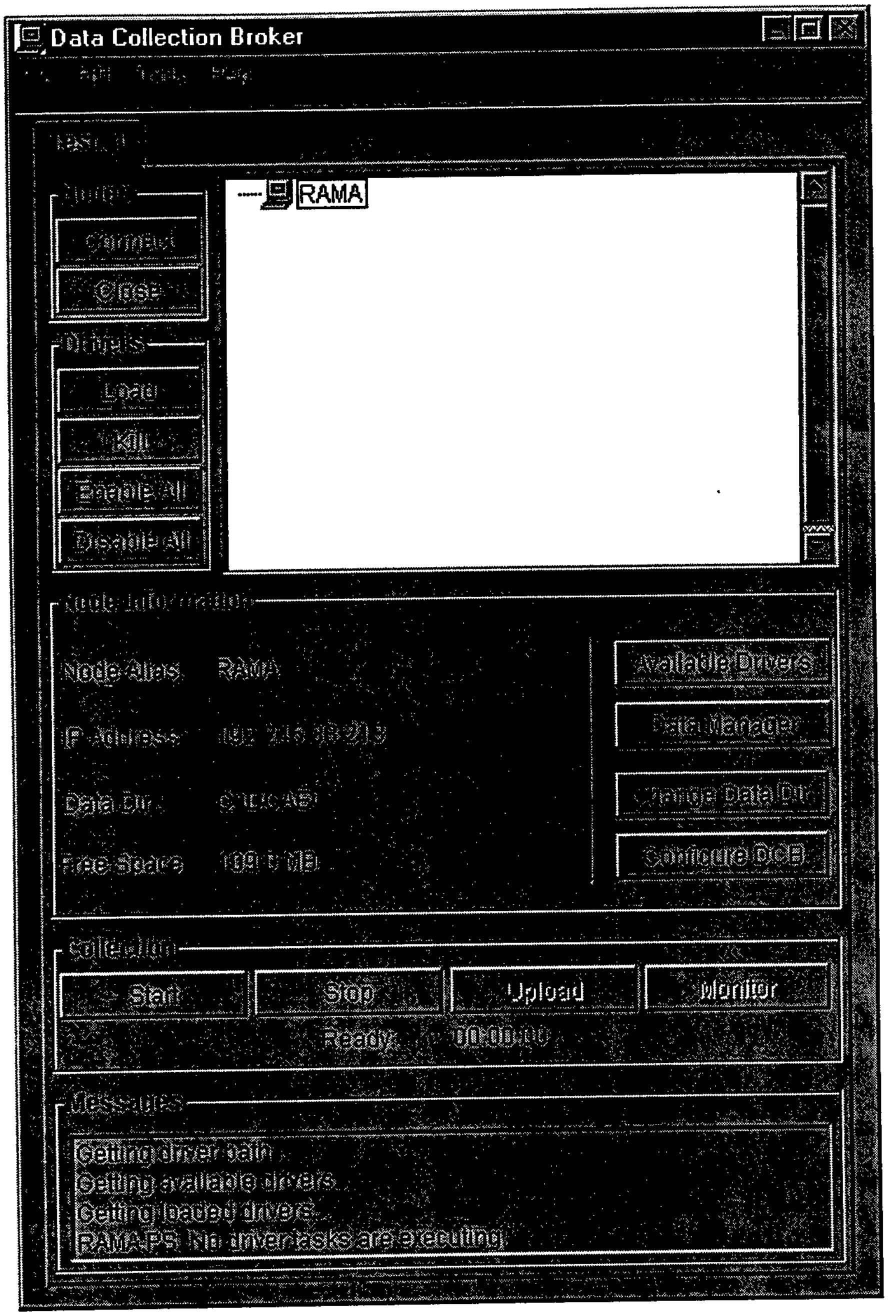
Following is an excerpt from the PPMS User's Guide that provides a sample operation scenario for PPMS data collection using the DCBGUI application. Operation requires prior installation of the HPBMS software system (see the HPBMS Overview document).

(Please note that any IP address that appears within this manual *will not work* on your system. For appropriate IP addresses, consult individual PPMS or HPMS documentation.)

(1) From the Start Menu, open the DCB GUI icon. Follow the path from the Start Menu → Programs → Dcae → DCBGUI.

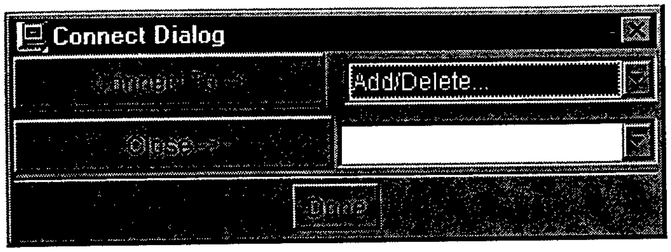
DCBGUI

The DCBGUI Main Window will then appear.



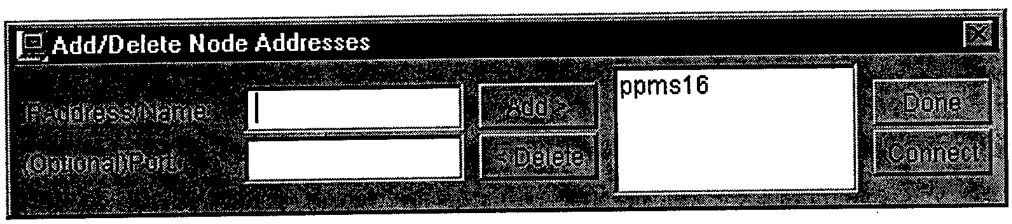
This window will display all the controls for running the PPMS: the Node and Driver controls, the graphical node and driver window, the Information area, and the Collection controls, and feedback message area. After startup, the only node that will appear in the node view window will be a representation of the computer on which the software is running.

(2) The first thing you must do is connect to a PPMS. In the System Controls area, press the Connect/Close button.



From the pull-down menu next to the 'Connect To ->' button, you will need to select the IP address of the PPMS which you want to connect to.

If this is the first time you are using the software or a particular PPMS, you will need to select the 'Add/Delete…' option from the pull down menu. This will bring you to the 'Add/Delete Node Address' dialog.

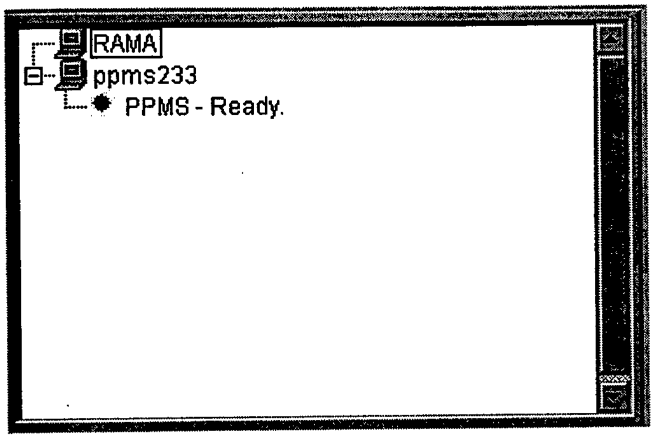


You will need to know the IP address of the PPMS which you want to connect to (see the Front Panel Operations section of this manual). Enter that value into the IP Address/Name field, then click 'Add >'. The IP address will appear in the window on the right. If you incorrectly entered the address, select it from the right window, then click '< Delete'.

When you have entered the correct address, you can either click 'Done' to return to the Connect Dialog and connect from there, or select the IP address from the right window and click 'Connect'.

Note that the PPMS must be fully powered up before you will be able to connect to it.

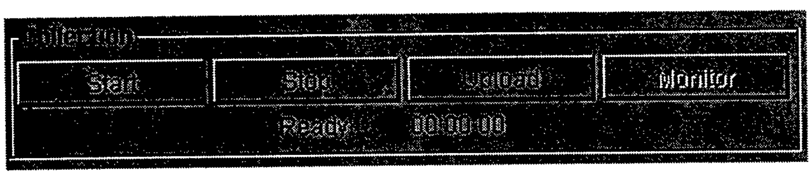
(3) After a connection has been established, you will be returned to the DCB Main Window. Now 2 nodes will appear in the node view window - the node representing the computer that is running the DCB, and the PPMS.



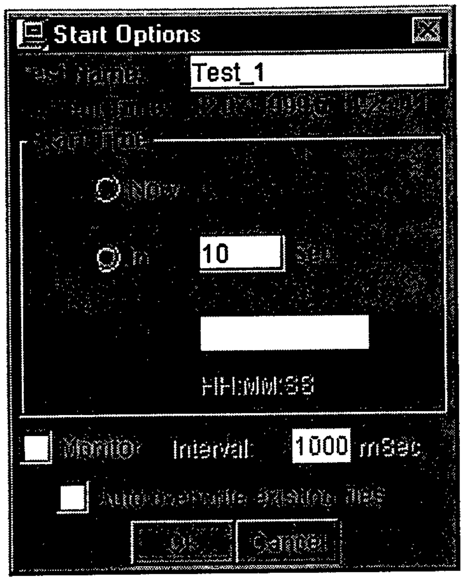
The - box next to the PPMS icon indicates that there are drivers running on the PPMS, listed below it. By clicking on the - box, it will 'close' the open listing of the drivers, displaying only the name of the PPMS and + box. The + box can be clicked at any time to re-display the drivers.

(4) Now that you have connected to the PPMS you are ready to begin collecting data.

From the Main DCB window, select 'Start' in the Collection area of the window.



This action will bring up the start menu. From this menu you can edit the name of the test to be collected, and select the start and stop times for the collection. Start **Now** will start a collection as soon as you press 'OK'. Start **In** ___ **Sec.** will start a collection in the indicated number of seconds. This time defaults to 10 seconds, but you can change this number as you see fit. The Start **At** _____ selection requires you to indicate a time in 24 hour time when the collection will begin. This is based off of the internal clock of the DCB, *not* the internal clock of the PPMS. (This option is currently disabled, but will be added in later software releases.)

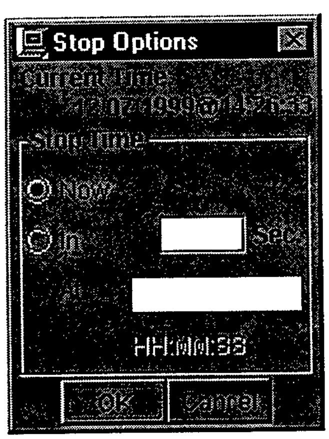


If you are planning on viewing the data in real time using the APS, then you must check the 'Monitor' option. For more information on the Monitor command and Monitor Interval, consult the later chapters. You can also choose to monitor a collection after you have started collecting data by clicking the 'Monitor' button in the collection area of the Main DCB window.

Checking 'Auto overwrite existing files' will allow multiple collections with the same name to be copied over each other.

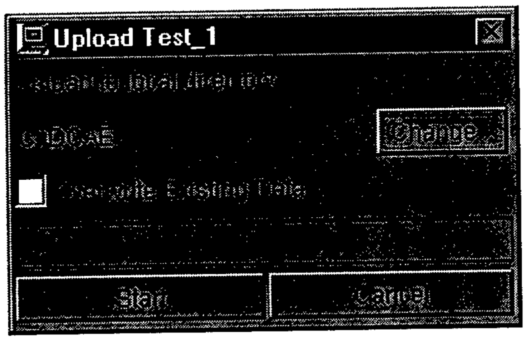
Hitting the OK button will return you to the DCB main window, and messages will appear in the message window indicating that the collection is waiting to start, and then starting. In the node view window of the Main DCB window, you will see that once collection has started the PPMS driver is listed as 'Collecting' rather than 'Ready'.

(5) When you are ready to stop the collection, click the 'Stop' button from the Collection area of the Main DCB window.



The stop options are very similar to the start options. Stop **Now** stops the collection when you click OK. Stop **In** ___ **Sec.** stops the collection in a number of specified seconds. **Stop At** _____ stops the collection at a specific time. (This option is currently disabled, but will be added in future software releases.)

(6) After a collection has ended, you can also upload the data from the Main DCB window, using the upload button in the collection area.



(9) To exit the DCB graphical user interface, click either the X box in the upper right corner, or select the 'Exit' option from the File Menu.

6.6.6 The PPMS Configuration File

The PPMS configuration file sets the operational and data collection parameters of the PPMS that are user programmable. This includes selection of the programmable signal conditioning features of the data collection channels, as well as establishment of system level parameters such as time, date, etc.

Note: when using the DCBGUI or front panel interface for operation of the PPMS the user does not need to know the format of the configuration file – the interface provides a user friendly means for creation and editing of these files. However, if the DCB console is used (see PPMS User's guide for details) the user will need to directly create and edit the configuration files. Therefore, a description of the configuration file format is provided here.

The configuration file is stored on the PPMS, by default in the c:/dcemmds1 directory. PPMS configuration files can be put elsewhere, however the GUI looks only here for available configuration files.

PPMS configuration parameters are divided into categories based on the devices to which they apply. Thus, parameter names (or "keys") have a multi-level hierarchical structure, i.e. `section:sub-section:key = value`. Some PPMS configuration keys do not contain sub-section entries. In this structure, `section` and `sub-section` (if present) specify the PPMS sub-device to which the parameter applies, `key` determines what aspect of that device's configuration will be affected, and `value` determines the precise nature of the change.

In the following discussion, the word "key" (when it does not appear in `mono-spaced type`) refers not to the `key` portion of the parameter name as defined above, but rather to the entire parameter name (i.e. the fully-specified combination of `section:key` or `section:sub-section:key`).

Conventions: Sections and parameters are entered as shown, with the following exceptions:

{ n..m } should be replaced by a number between *n* and *m*, inclusive. The braces *{ }* should be omitted. If this notation appears within a key, the number should be entered with no white space between it and the characters that surround it. Values, however, can be separated from the assignment operator (the = sign) by one or more spaces. In value notations, the default value is specified in boldface. Example: `ch{1..16}:amp:gain = { 1..1000 }` means that `ch1:amp:gain = 500` is a valid key and value combination, but that `ch1:amp:gain = 1001` or `ch17:amp:gain = 1` are not valid combinations. A gain setting of 1 is indicated as the default setting.

*{ **choice1** | choice2 | choice3 }* expresses a list of valid values from which a single value must be chosen. The braces (*{ }*) and separators (|) should not be included in the value. The default value of the parameter is shown in bold. Example: `sys:display:backlight = { on | off }` means that the only acceptable assignments for this key are `sys:display:backlight = on` and `sys:display:backlight = off`, and that the default setting for the backlight is "off".

See the PPMS User's guide for more information on configuration.

6.7 Eye Tracking System

6.7.1 Overview

The eye tracking system (ETS) provides for measurement of a user's point of regard (gaze location) and other eye-related parameters, such as pupil size and blink. The eye tracking hardware consists of a head mounted eye tracking device that captures a video image of the eye as well as a video image of the user's field of view. The specialized software system utilizes a client/server approach, where the user interface application runs on a client PC, and the eye tracking algorithms run on a server PC. This two system approach maximizes performance of the eye tracker. The eye tracking system may be used independently or as part of the HPBMS, where eye tracking results are recorded through the DCAE software.

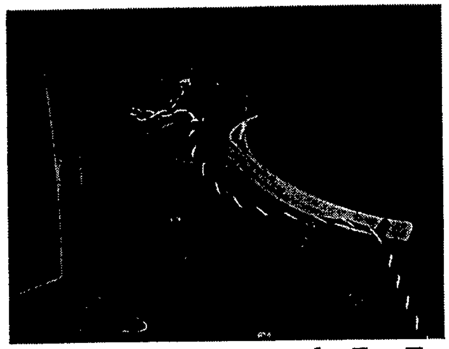


Figure 46: Picture of User Wearing the Eye Tracking Device

Figure 47: Picture of the ETS Monitoring Station (from left to right: ETS server monitor, VCR and TV capturing eye tracking results, VCR and TV capturing video of user interface station)

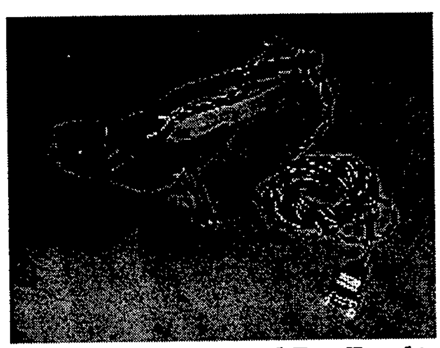


Figure 48: The Head Mounted Eye Tracking Device

Figure 49: The Camera Control and Interface Unit

The ETS client application provides the user interface and relays operational commands to the server application. It operates on a Windows platform and has minimal computational requirements, since the image processing algorithms are performed on the ETS server PC.

The server application receives video from the eye tracking device, controls the real-time video acquisition loop, processes the images, displays live video, and handles the requests of the client by inserting tasks into the video acquisition loop. Tasks include tracking, data output, information updates, etc. The eye tracking system may be used independently or as part of the HPBMS, where eye tracking results are recorded through the DCAE software. The server PC uses two Matrox Meteor image acquisition cards for capture of both the eye image and the field of view image. These acquisition cards support frame rates up to 30Hz depending on frame size. With the additional overhead of the image processing algorithms, the ETS outputs tracking results at a rate of about 24-28 Hz, depending on the image characteristics (and the specifications of the server PC).

6.7.2 Image Processing Algorithms

The eye tracking system uses a series of algorithms to accomplish the goal of gaze determination. The algorithms support four major functions – localization, calibration, pupil detection, and automated focus of attention determination – in order to accomplish the goal of real-time eye gaze determination and cursor control. The following subsections will describe these algorithms in detail.

Localization

The localization process is an optional feature (selectable through the client interface) that can be used to increase the frame rate of eye position determination. This process uses image differencing to detect motion in eye images and localize the pupil search area. This results in increased frame rates by negation of false positives caused by background clutter. When the device is first placed on the head, images are captured as the user fixates on the four corners (extremes) of the viewing screen. Images are differenced and then the localization area (where eye motion is expected to occur) is determined by the region within images where change has occurred (See Figure 50).

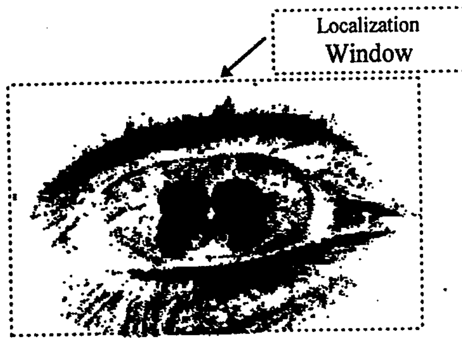


Figure 50. Localization Window Derived from Binarized Difference Image

Erosion-dilation algorithms may be used to further refine the pupil search area, depending on user configuration choices. Erosion iteratively eats away at the boundaries of objects in an image. Dilation then iteratively adds to the boundaries of objects. Thus, erosion can be used to remove smaller objects, and dilation can be used to restore the remaining objects in the image. Since the movement of the pupil results in a large object around the pupil area in difference images, erosion-dilation will remove small elongated objects, such as those caused by eye lash movement, and retain the area of pupil movement (See Figure 50 and Figure 51)

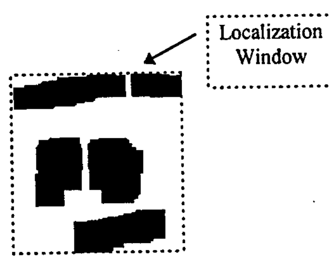


Figure 51. Resultant Erosion-Dilation Image Offers Refined Localization Window

Calibration

The eye tracking calibration process derives coefficients for a fifth order polynomial mapping function used to calculate gaze coordinates from pupil coordinates. The user interactive portion of the process requires the user to focus on known calibration points on the screen. This results in a set of calibration point coordinates and the respective calculated set of pupil center coordinates derived during focus periods. Least squares processing then determines the coefficients of a fifth order polynomial that optimally maps pupil coordinates to gaze coordinates (See Figure 52). The calibration process has been optimized to automatically advance calibration points once the user has fixated on each point. The default calibration process is a 9 point procedure that takes approximately 30 seconds to complete.

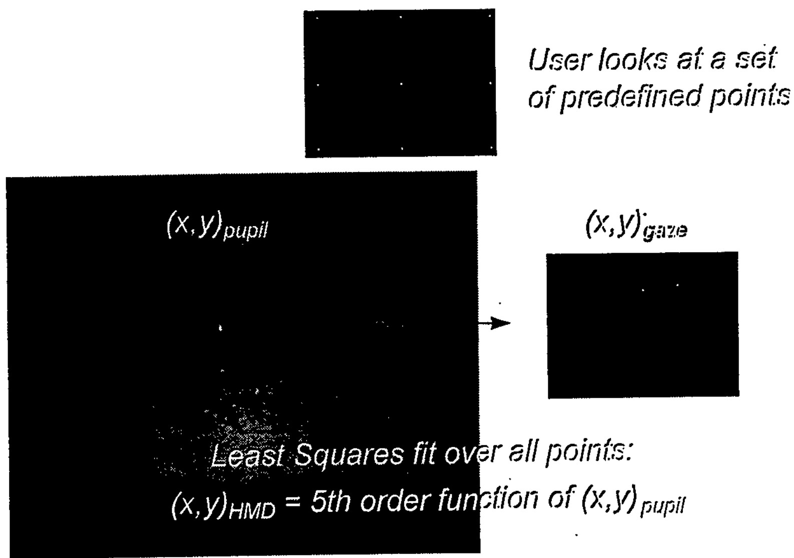


Figure 52: Interactive Calibration Process

<u>Pupil Detection and Center Determination</u>

The pupil detection algorithms begin with identification of a seed point within the pupil area. This can be performed by one of two methods, which may be selected through the ETS client application: 1) using a threshold comparison, or 2) using the reflection (glint) generated on the eye from the illumination LED. The default method is a threshold comparison, because it is the most effective for the range of possible users. The glint based approach can be more efficient, but should be used with caution because for some user's the glint does not always remain within the pupil.

Once found, the seed pixel is then utilized for an intensity/density based region growing algorithm. The region growing algorithm fills the pupil area until certain conditions are met that are based on the density of like neighborhood pixels and the intensity of the pixel as compared to the seed pixel. The two extreme horizontal points of the pupil are then used to determine the center of the pupil. Use of the horizontal pupil extremes allows for accurate determination of the pupil center even when there is significant pupil occlusion caused by the eyelid.

As a final step, the pupil center is then mapped to a gaze coordinate (within the field of view image) using the mapping function derived from the calibration process. Other parameters that are generated from the pupil detection algorithm are the pupil size and blink detection.

Automated Focus of Attention

Prior to development of the focus of attention algorithms evaluation of a user's point of regard had to be performed by a observer watching the recorded video and making note of where the user is looking. This is because as the user moves around the objects in the captured field of view also move around. However, the developed focus of attention algorithms provide for quantitative determination of gaze location relative to a "tagged" region within the user's field of view (such as a computer monitor).

Quantitative determination of the user's point of regard is of significant advantage because it allows for automated analysis and numerical manipulation of a user's gaze location. For instance, one can easily perform calculations of how often, how many times, or how long a user looks at a certain object or area.

The basic algorithmic process is based on determination of the center of the monitor (or tagged region). This is performed by tagging the monitor with identifiable markers, as shown in Figure 55. The monitor tags used are four 2-inch diameter red circles used to mark out a rectangular area in which the software will compute X and Y coordinates. They were designed to be placed on the frame of a monitor, to calculate the gaze position on the screen, or, they can be placed on a wall, floor, ceiling, vehicle windshield or any flat surface to provide a coordinate system.

Monitor Tags must be placed in a diamond formation, with the intersection of the horizontal pair and the vertical pair being at the center of the area in which you wish to determine a coordinate system.

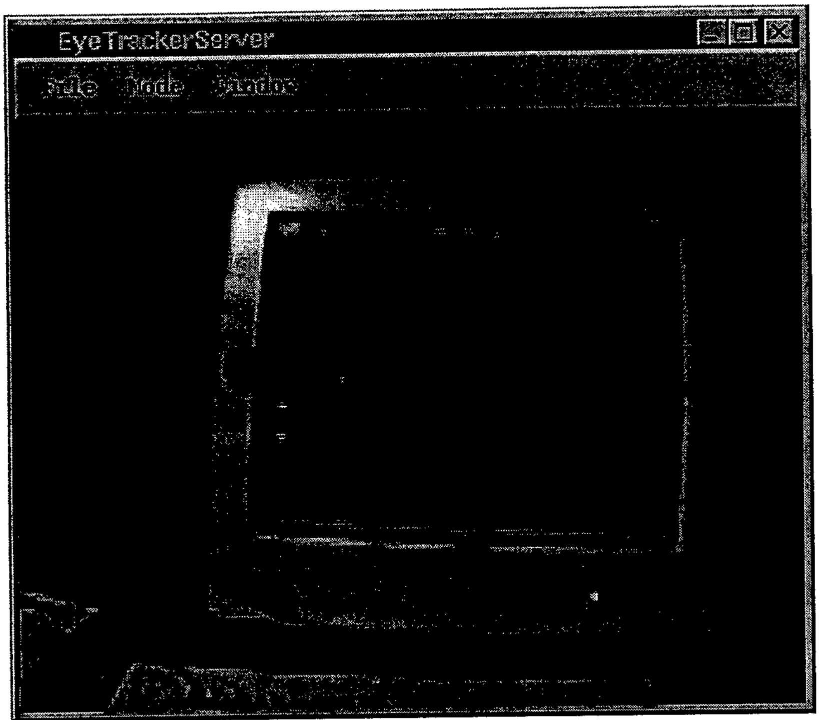
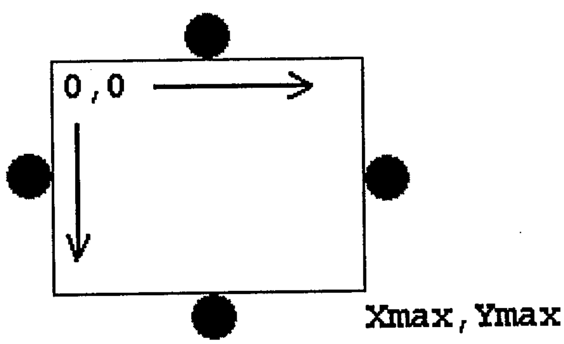


Figure 53: Picture of Monitor Tags for Focus of Attention

The Monitor Tags form a coordinate system based on the following diagram. Results outside of the monitor boundary (i.e. X,Y < 0,0 or X,Y > Xmax, Ymax) are valid.



Accurate determination of the center point can be determined while only 3 of the tags are within the captured field of view image, allowing for signification motion of the user. Based on this determination, the gaze location computed by the eye tracking algorithms is then converted to a specific coordinate location within the monitor screen. This computation takes into account the particular screen size and accounts for the rotation angle.

6.7.3 Sample (Quick Start) Operation of the Eye Tracking System

This section contains an example of only the basic procedures necessary to start and stop a single session of eye tracking. For more detailed information refer to the Eye Tracking System User's Guide. This procedure requires that the Human Performance Based Measurement System Software be previously installed.

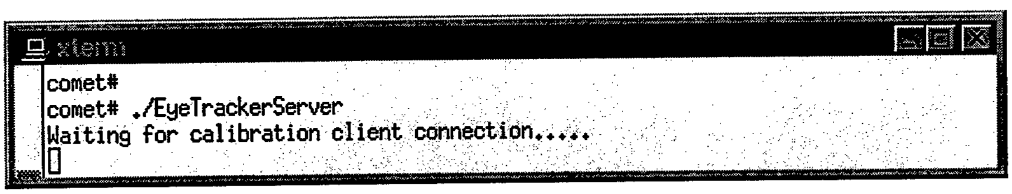
6.7.3.1 Starting the ET Server

Once the ET Server has started, you will be presented with a login prompt. See the ETS User's Guide for login information.

After you have successfully logged in, at the command prompt type: "`startx`" This will start the X-Windows interface from which the ET Server is run.

All operations from here on are performed in the 'xterm' window on the desktop.

Change directories by typing the following: "cd /EYETRACKER/bin". Then, type in "./EyeTrackerServer" to begin the server application. You will see the following:



6.7.3.2 Starting the Calibration Client

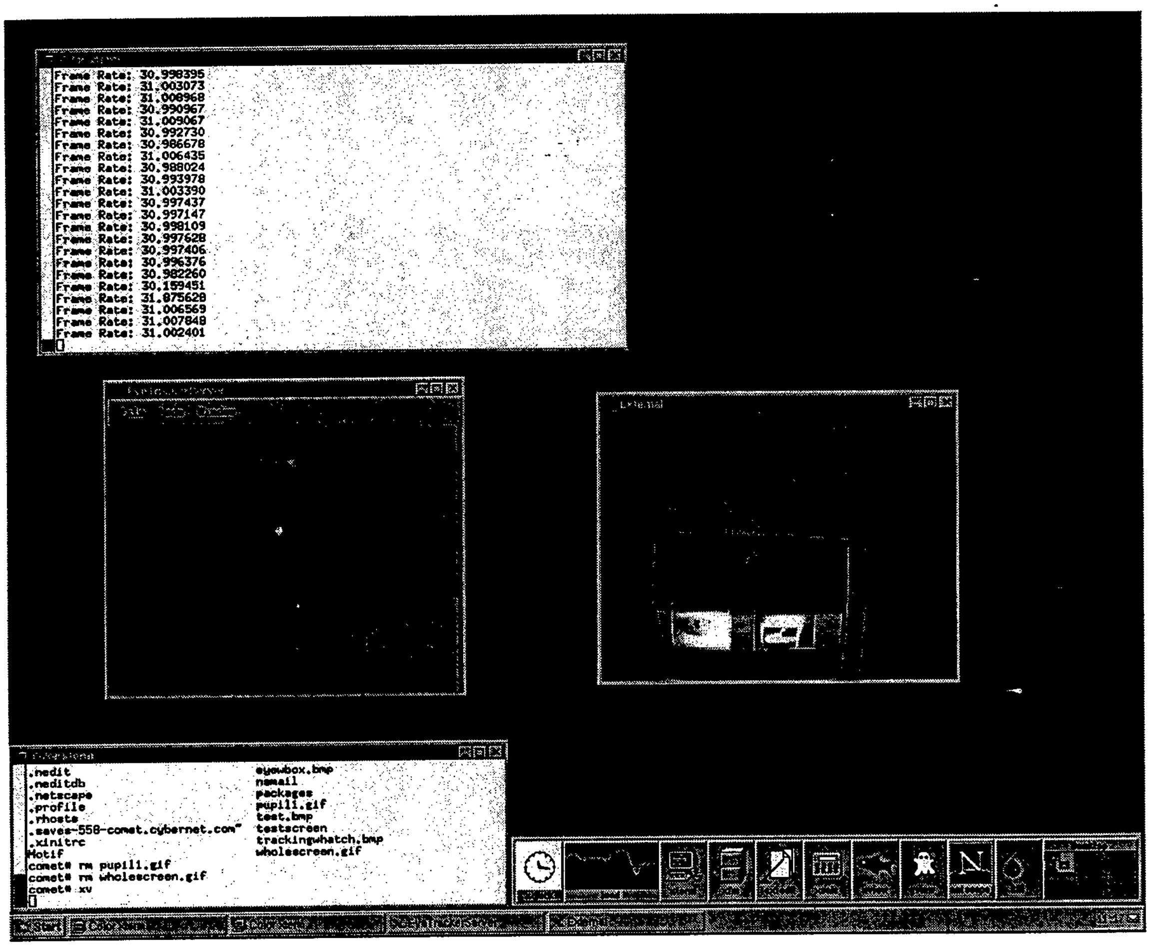
This step is only necessary if you are going to be running eye tracking experiments on a different computer than the one running the ET Client. The Calibration Client Icon can be reached through the Start Menu → Programs → DCAE → EyeTracker Calibration Client path on the subject interface machine. The program will run minimized, so as not to take up and space on the screen.

6.7.3.3 Starting the ET Client

On the ET Client computer, select the EyeTracker icon from the Start Menu → Programs → DCAE → EyeTracker.

The main window of the interface will appear, and the message console window will appear minimized. At startup the ET Client should automatically connect to the ET Server. Connection may not occur if the Server IP address is not set properly or other networking problems exist. In this case, fix the problem, and then select the "Connections" menu in the Client interface, and choose "connect to the ET Server."

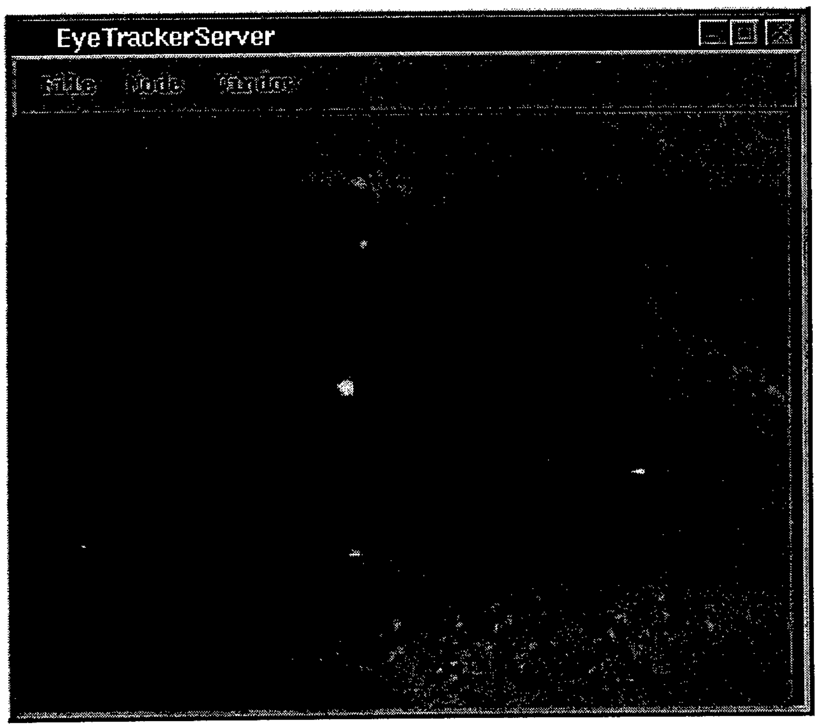
On the ET Server machine, the following will appear in the text window, and 2 video feed windows, "External" and "EyeTrackerServer," will appear. The two video windows may appear overlapping each other, and you will want to move them so that you have an unobstructed view of each.



6.7.3.4 Wearing the Eye Tracker Correctly

The Eye Tracker should be placed on the head so that the arms sit above the ears, much like a pair of glasses, and the brim should stick out in front like the rim of a baseball cap. The subject's left eye should be situated directly in front of the glass mirror. The mirror should not be resting against the subject's cheek. The Eye Tracker is designed to fit tightly, to avoid motion artifacts, but not painfully. If the Eye Tracker bands are too tight, they can be adjusted slightly with a flathead screwdriver.

The Eye Tracker must be placed so that the subject's pupil is completely visible in the EyeTrackerServer window. This can be acheived by manipulating the placement of the Eye Tracker on the subject's head.



If you are using Monitor Tags, then use the External window to make certain that at least 3 of these tags are visible in the External video feed. You may need to move the position of the subject, or adjust the angle of the external camera.

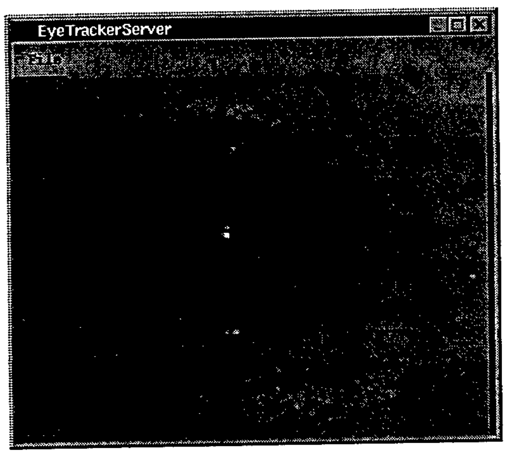
6.7.3.5 The Calibration Procedure

Once the ET Server is running, and the Eye Tracker is arranged on the subject's head and they are positioned in front of a wall-mounted calibration grid or a monitor running a Calibration Client, click the Calibration button. The subject will then focus on each point on the grid either as they appear (monitor calibration) or as indicated by an audio tone (wall grid calibration).

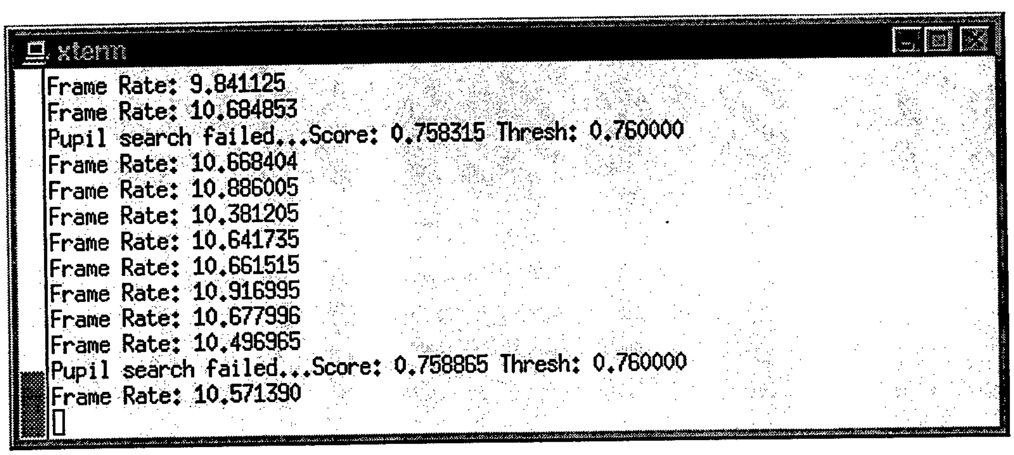
The points should be followed in a top-to-bottom, left-to-right manner.

You can check calibration by watching the External view on the ET Server. When the software has calibrated a point, you will see a red circle and crosshairs appear in the External view at the location the software thinks the subject is looking.

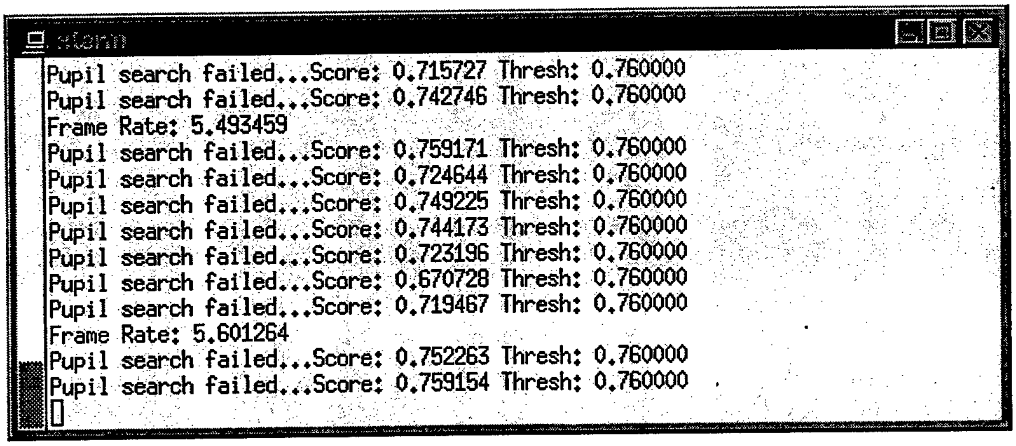
If calibration is running slowly, and/or you think there is an error with the system, you can cancel calibration by clicking the mouse into the calibration window (on the system that is running the ET Client) and pressing CTRL-X on the keyboard. The most common problem is that the software is not finding the pupil. While the ET Server is active, and a subject is wearing the eye tracker, you should see a red box surrounding the pupil as an indicator that the software is finding the pupil. This box (and sometimes a small crosshairs inside the box) will blink on and off. *The red box should be on more than it is off.* If you do not see the red box, it means that the software is not finding the pupil, and therefore cannot track the eye.



Another means of determining if you are finding the pupil is by watching the output in the xterm window on the ET Sever machine. When the algorithm is finding the pupil, a listing of the frame rates will scroll down the window.



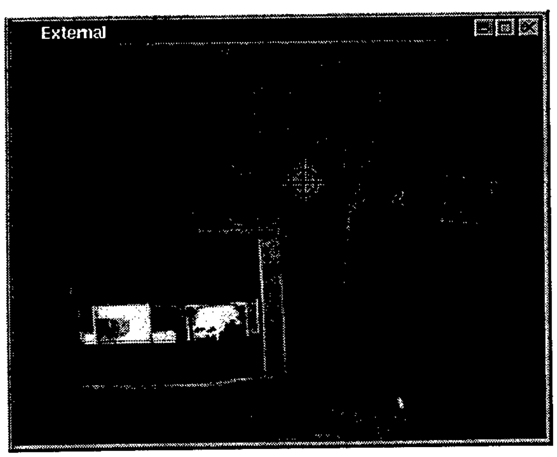
When the algorithm is not finding the pupil, the window will display that the pupil search failed.



Generally, no matter what settings you are using, the algorithms will occasionally fail to find the pupil. A good tracking session will find the pupil more often than it does not. If you are having trouble calibrating a subject, you may need to adjust the settings.

6.7.3.6 Tracking the Eye

After calibration, all red indicators in the External and EyeTrackerServer windows will disappear. By clicking the Track button, the software will begin to track gaze position, and that will be indicated in the External view by a red crosshairs. The pupil should also again be surrounded by a red box in the EyeTrackerServer window.



6.7.3.7 Running A Collection through the DCB

Collecting Eye Tracking data through the DCB is done as a standard DCB collection (for more information on the DCB and its operation, please refer to the DCB Manual).

First, open the DCB by double clicking on it's icon. (Now you will have both the ETS and the DCB running.)

Before the DCB will accept eye tracker data, you must load the EyeTracker driver. Choose the 'Load Drivers' button, then from within the 'Load Drivers Dialog', load the eye tracker driver for the node on which you are running the ET Client.

Start a DCB collection. You may start a collection at any time during the first 6 steps (from Starting the ET Sever 3.1 through Tracking the Eye 3.6). However, data is not collected into a DCB stream until the Eye Tracker has actually begun tracking the eye (3.6). Once the Track button in the ET Client has been clicked, the Eye Tracker will send data to the DCB, even after a DCB collection has ended. You must stop tracking using the ET Client in order to stop data flowing into the DCB.

6.7.3.8 Stopping an Eye Tracking Session

To stop tracking the eye, simply click on the Stop Eyetracking button. (Note that this will only stop the operation of the Eye Tracker; it will not stop a DCB collection, even a collection that is running the EyeTrackerDriver.)

6.7.3.9 Exiting the Eye Tracking System

Before exiting the ET Client, disconnect from the ET Server through the Connections Menu. This will also shut down the ET Server.

You should also disconnect from the Calibration Client at this time, if you were running one.

To exit the Eye Tracker, simply click the corner X button of the main ET Client window, or select the Exit option from the Action Menu.

6.7.4 Eye Tracking System Configuration and Control Options

Calibration Options

The following options can be modified through the client interface:

1. Save calibration results on/off.
2. Screen Size - this is for determining the size of the screen where the computerized calibration grid will be displayed.
3. Remote Calibration - checking this box will display the calibration grid on a remote machine. That remote machine must be running the Calibration Client, and the ET Client must be connected to it (see the Connections Menu).
4. Calibration Type Selection:
    - Wall Grid Calibration - this is for using a wall grid calibration
    - Monitor Based Calibration - this is used to select the computer to display a calibration grid on a screen. It is used in conjunction with Remote Calibration and Screen Size options.

Vision Algorithms Options

The following options can be modified through the client interface:

1. Display Processed Video on/off.
   Choosing display processed video will inform the server to display live video of the users eye on the server's monitor. The video will be marked with a square to show pupil diameter, a large cross to show pupil center, and a small cross to show seed location.
   For optimum performance processed video should not be displayed as this slows the system down considerably.
   However, having the processed video displayed can often be of great assistance in centering a subject's eye in the camera view (for better performance), and can be used to 'debug' why certain subjects have poor performance.
2. Display Secondary Video on/off.
   Choosing display secondary video will inform the server to display the video from the second camera (the external world view). The video will be marked with a single red cross to indicate gaze location. It may also be marked with a small red box indicating the center of the Monitor Tags if they are being used.
   Since the information gathered from the eye tracker is mostly visual, display secondary video should be on. However, it can be turned off to increase the update rates if the results are to be viewed in another form (such as the raw data stored in the output file, or collected through the DCB software).
3. Find Monitor Tags
   This will indicate that the software should look for 4 red dots arranged in the standard positions. This is used to give a set of coordinates when the subject is looking within the area of the tags.

4. Mark Monitor Center
   This is useful only if you are displaying the secondary video, and using Monitor Tags and the Find Monitor Tags box is checked. It will place a small square at the intersection of the lines created by the Monitor Tags, and appear in the Secondary Video window.
5. Glint Based Region Growing / Dark Pupil Based Region Growing radio buttons
   The region growing routine can determine the pixels which makeup the pupil when supplied with one pixel within the pupil. There are two methods to finding a point inside the pupil:
   - Glint Based Region Growing uses the IR reflection (glint) as a guide to pupil location. It is assumed that the pupil will be within a certain area above the glint. Therefore, a vertical offset is added to the glint location and the result is used as the seed location.
   - Dark Pupil Based Region Growing uses the dark characteristics of the pupil to find a point within the pupil. Basically, the dark areas of the image are analyzed to determine where the pupil is most likely to be. Then this location is used as the seed to the region growing algorithm to produce a more accurate determination of the pupil center. This is the default setting because it generally produces the best results with the eyetracker supplied.

Servers Options

The following parameters can be modified through the client interface:
1. Eye Tracker Server IP Address
2. Eye Tracker Client Input and Output Sockets
   Input Socket defaults to 3508.
   Output Socket defaults to 3507.
   Both of these values must be the same as the Eye Tracker Server, and are by default. If they need to be changed, refer to the Eye Tracker Server Section in this manual. Whenever socket numbers are changed, the client must be restarted before they will take effect.
3. Calibration Client IP Address
4. Calibration Client Input and Output Sockets
   Input Socket defaults to 3516.
   Output Socket defaults to 3515.
   Both of these values must be the same as the Calibration Client, and are by default. If they need to be changed, refer to the Calibration Client section in this manual. Whenever socket numbers are changed, the client must be restarted before they will take effect.

Files Options

The following parameters can be modified through the client interface:
1. Calibration File

Used to create calibration grid for computer screen calibrations. This file is nothing more than a list of X and Y coordinates, 1 coordinate set per line, that indicate where on the screen points should be placed. Points are used for calibration one at a time, from the top of the file to the bottom:

100	100
200	200
300	300
...	...

Threshold Controls

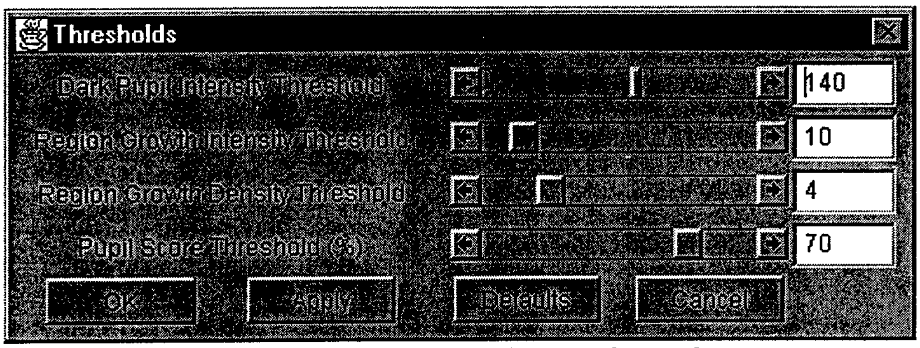


Figure 54: The Threshold Control Interface

The Threshold window is used to adjust the mathematics of the algorithms used to detect and track the pupil. Difficulties that occur because the software is not 'finding' the pupil can be corrected here.

The following parameters can be modified under the Thresholds Option:

1. Dark Pupil Intensity Threshold
   This value indicates the brightness or darkness that the software expects the pupil to be. The lower the value, the software looks for a darker pupil; the higher the value, the software looks for a brighter pupil. This is examined on a pixel by pixel basis across the entire image captured by the Matrox cards.
2. Region Growth Intensity Threshold
   The range that a nearby pixel must be within in order to be considered a part of the dark pupil. This value is used to look for the edges of the dark pupil. This variable should generally be set low to avoid the software blending the pupil and the surrounding white eye togther.
3. Region Growth Density Threshold
   The number of neighboring pixels that must meet the above two criteria in order for the initial pixel to be considered part of the pupil.
4. Pupil Score Threshold (%)
   The Pupil Score is a measure of how well the shape of the detected pupil matches the shape of the ideal pupil. Requirements for a perfect match would be 100%, but this is unrealistic. Generally, a 70% match (the default setting) produces good performance.

Output Format:

The Output Format Window is used to determine which bits of data are included in any data files created or exported to the DCB software. When running the eyetracker through the DCAE, all fields must be selected to be a part of the Output Data.

The following parameters can be modified:

1. Text File on/off
   Toggles the creation of a text file (containing the data indicated below) named eyetrack.dat. The created file will appear in the directory that the ET Client is in.
2. Data Socket
   This is the value of the data socket connection to the DCAE. It must match the socket number listed in the eyetracker.ini file. For more information, consult the DCAE Software manuals (specifically the DCB User's Guide).
3. Pupil Center on/off
   Toggles the inclusion of the X and Y pupil center data
4. Gaze Position on/off
   Toggles the inclusion of the X and Y gaze position data
5. Time Stamp on/off
   Toggles the inclusion of the ET Server time stamp data. (The DCB time stamp will have some transfer delays, so the ET Server time stamp can be used to provide the most accurate timing information, when desired).
6. Monitor Gaze Position on/off
   Toggles the inclusion of the gaze position data which has been set to a coordinate system based off of the Monitor Tags. If Monitor Tags are not going to be used during a collection, this data field will return incorrect data.
7. Pupil Size on/off
   Toggles the inclusion of Pupil Size data.
8. Pupil Score on/off
   Toggles the inclusion of the Pupil Score data. The Pupil Score is a rating of how well the software thinks it captured and tracked the pupil during a particular frame.
9. Blink Status on/off
   Toggles the inclusion of the Blink Status data. Blink Status is a field indicating if the eye was blinking during a particular frame.

6.8 Body Tracking System Interface

6.8.1 Overview

The Firefly optical motion capture system is designed to track the motion of any object (a human body, vehicles, models, etc…). It is ideally suited for the development of computer games, the production of computer animation, as a input device for virtual reality applications, and in providing data for human biomechanic or ergonomic studies. The most common systems used today utilize either magnetic field or optical tracking techniques to capture human motions. In comparison with the Firefly, the magnetic systems are costly, not as accurate and suffer from inherent limitations when used near metal objects and structures. The optical systems most commonly used today are accurate, very expensive, and require extensive calibration before the motion capture sessions, and off-line processing after the sessions.

The basic Firefly motion capture system consists of one camera array, one tag controller, 32 tags, and accompanying cables. The Firefly measurement system consists of three charge-coupled device (CCD) cameras mounted on a 1 meter rigid bar. By imaging infrared light emitting diode (IR LED) tags, this camera array can accurately determine their 3D position in real time. Since the camera array is precalibrated, there is no calibration required which means that you can immediately begin using the system to accurately track tags.

The tag controller is a small, battery operated waist mounted unit that is used to strobe the active tags. The tag controller does not need to be tethered to the array, since the system is auto synchronizing when the tags are in view of the array. Should the tags be not in near continuous view of the array, then a synchronizing cable is recommended (included.) The system can be configured to track up to 256 tags with multiple slaved tag controllers.

The tags are small, wide angle emission IR LEDs that are virtually massless. They are designed to be attached by adhesives to a persons skin, or can be attached via thread to gloves, elastic bands, special garments, etc. To be tracked they must be in the simultaneous field of view of all three cameras in the camera array. When not in view, the data can be filtered to produce continuous uninterrupted data at a greater latency. Alternately, multiple camera arrays can be slaved together to eliminate virtually all line of sight problems.

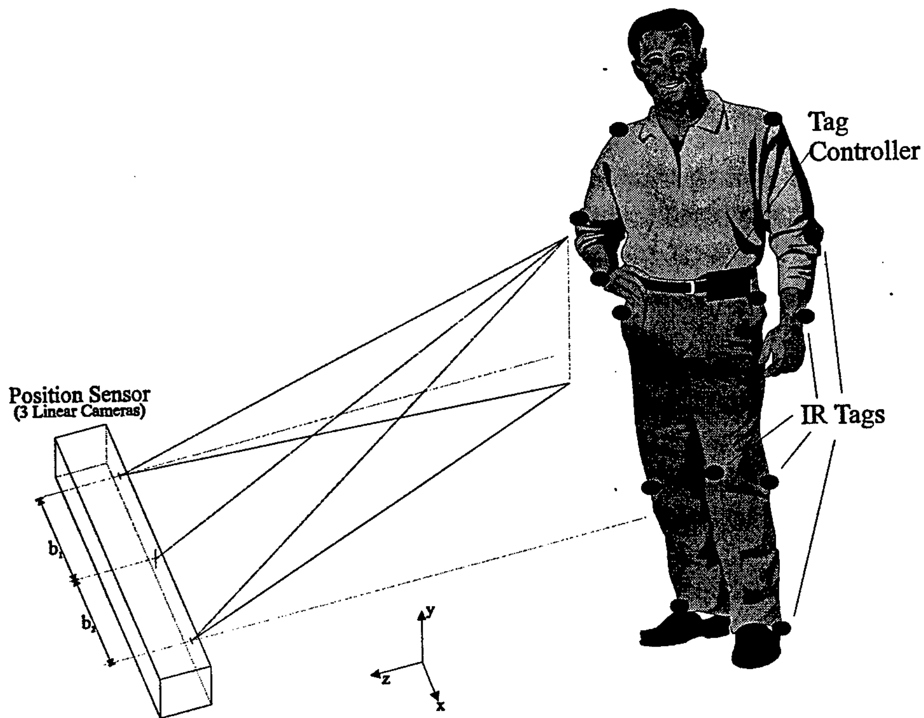


Figure 55: Illustration of the Firefly System Operation

This system was developed through other research and development efforts, but was identified for integration into the HPBMS early in this Phase II effort. As a result, the interface capabilities and data viewing tools were integrated into the HPBMS. While the Firefly system itself is not a part of the delivered system for this Phase II, it can be readily integrated into the system if acquired separately.

6.8.2 Sample Operation of Body Tracker

Following is an excerpt from the Body Tracker User's Guide that provide a "Quick Start" guide to operation of the Firefly within the HPBMS. Refer to the User's Guide for more details.

1. Start the DCB GUI. It can either be reached from it's icon in the DCAE folder, or from the Start Menu, Programs, Dcae, DCB GUI.
2. Load the Bodytracker driver. Under the Drivers option from the main GUI window, select the 'Load' button. From the Node pull-down menu, select the machine that the Firefly is connected to. From the Driver pull-down menu, select Body Tracker. You may give the driver an alias. If a configuration file exists for the Body Tracker, it can be edited by clicking change at this point. If a configuration file does not yet exist, the driver must be loaded with the default settings. Add the driver by clicking Add, then click Done. The driver is now loaded.
3. Start a collection. The Firefly must be turned on, connected to the computer running the DCB GUI, and the Tag Controller must be turned on.

4. Open the APS (if necessary). If the APS is already open, refresh the stream view so that the new data being collected will be available to view.
5. Select all of the necessary data.
6. Open the Bodytracker Viewer.
7. If you are viewing data in real-time, from the Viewer Menu, select the 'Real-Time' option. If you are playing back previously recorded data, open the Playback Controls from the Playback Menu. Note that the Bodytracker Viewer works best when displaying data by Frame #. This setting can be changed through the Playback controls.
8. Create and/or Select a configuration file. A configuration file will draw lines to connect the points of data being displayed to better represent the object being tracked. For more detailed information on how to create a configuration file, see below. From the Viewer Menu, select 'Properties', then the 'Configure' option. Select the appropriate configuration file, and it will automatically be applied to the data being displayed.
9. Exit the viewer when finished.

7. Experimental Procedures and Results

7.1 Driving Simulation Experiment

As a preliminary evaluation and assessment of the HPBMS concept, we conducted driving simulator (computer interface) experiments, during the early stages of the Phase II system integration process. This effort was performed in conjunction with an Air Force SBIR project that was focused on the development of innovative cognitive capacity measurement system. This preliminary evaluation demonstrated the feasibility and potential benefit of EEG and other measures for cognitive and other performance assessment.

7.1.1 Experiment Description

The driving task experiment was conducted assess the feasibility and potential benefit of physiological measurement for cognitive and other performance assessment. The specific protocol was designed to begin studying the neuro-cognitive and psychophysiological responses to differing levels of workload in a visuo-motor task. Driving was performed using computer-based driving simulation tools.

The driving simulator has several variables that can be altered such as track geometry, lane indicators, visibility, frame rate, etc. For this initial experiment only one parameter – track geometry – was varied, as a means to creating different cognitive load requirements. Full force feedback on the steering wheel and auditory feedback were provided, with the graphics displayed on the computer monitor at the maximum frame rate (25 frames per second) and a zero frame lag setting.

Electrodes and sensors were placed on the subject to measure the signals listed in Figure 56. A limited set of measurements was used for this initial experiment.

Figure 56: Physiological Signals Measured for Preliminary Driving Simulator Experiment

Measurement	Methods / Sensor	Location
Heart Rate	Plethysmograph	Ear Clip
Respiration Rate	PiezoCrystal Respiration Band	Placed around chest/stomach
EEG	Surface Electrodes using eNet cap and Biodot electrodes (Physiometrics)	P3-A1
		P4-A2
		C3-A1
		C4-A2
		T5-A1
		T6-A2

The experiment consisted of an 8 minute session, as shown in Figure 57. Subjects were seated at the driving simulation station, consisting of the computer screen, steering wheel, pedals, and keyboard. First the subject was asked to rest for 1 minute with eyes open, and then rest for an additional minute with eyes closed, in order to obtain baseline measurements. Then two driving tasks were performed. Each task, including program startup time, lasted approximately three minutes. The order in which the subject performed the tasks (driving on easy track and driving on difficult track) was randomly selected.

Figure 57: Phase I Experiment Stages

State / Task	Duration
Resting - eyes open	1 minute
Resting - eyes closed	1 minute
Driving - track 1	3 minutes
Driving - track 2	3 minutes

In both task conditions, the subject was asked to drive as fast as they could without leaving the road. It was stressed that both driving speed and remaining on the track were equally important. The subject controlled the car by using a keyboard to start the car and to change gears of the car. Steering wheel and pedals (gas and brake) were used to control direction and speed. A picture of the driving simulation display interface is shown in Figure 58.

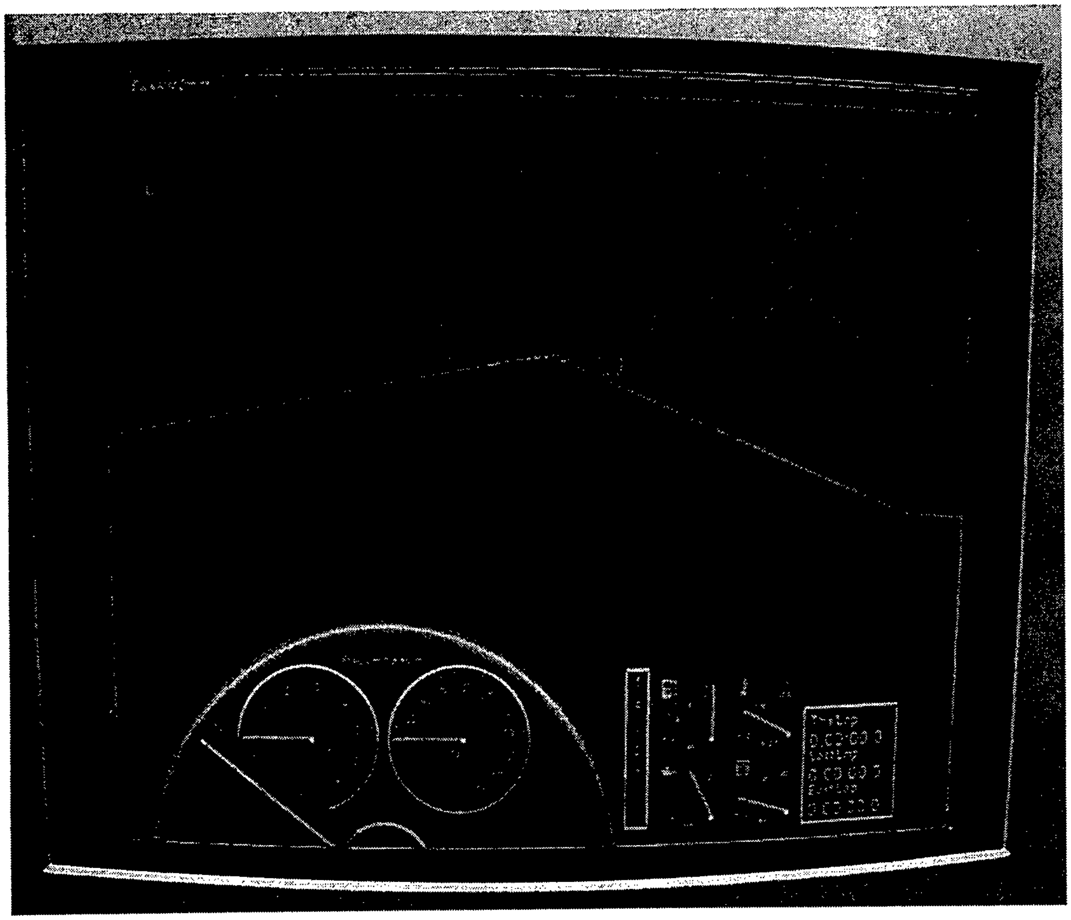


Figure 58: Picture of Driving Simulator Display

Complete data collection during the experiment included the physiological signals that were listed in Figure 56, video and audio captured using the VCR, and the following driving parameters captured from the simulator:

Position on the track
Speed
Steering wheel position
Gear
RPM
Brake pedal activation
Gas pedal activation
Sound (on/off)
Frame rate
Frame lag
Off road (left/right)
Force-feedback activations
Collisions

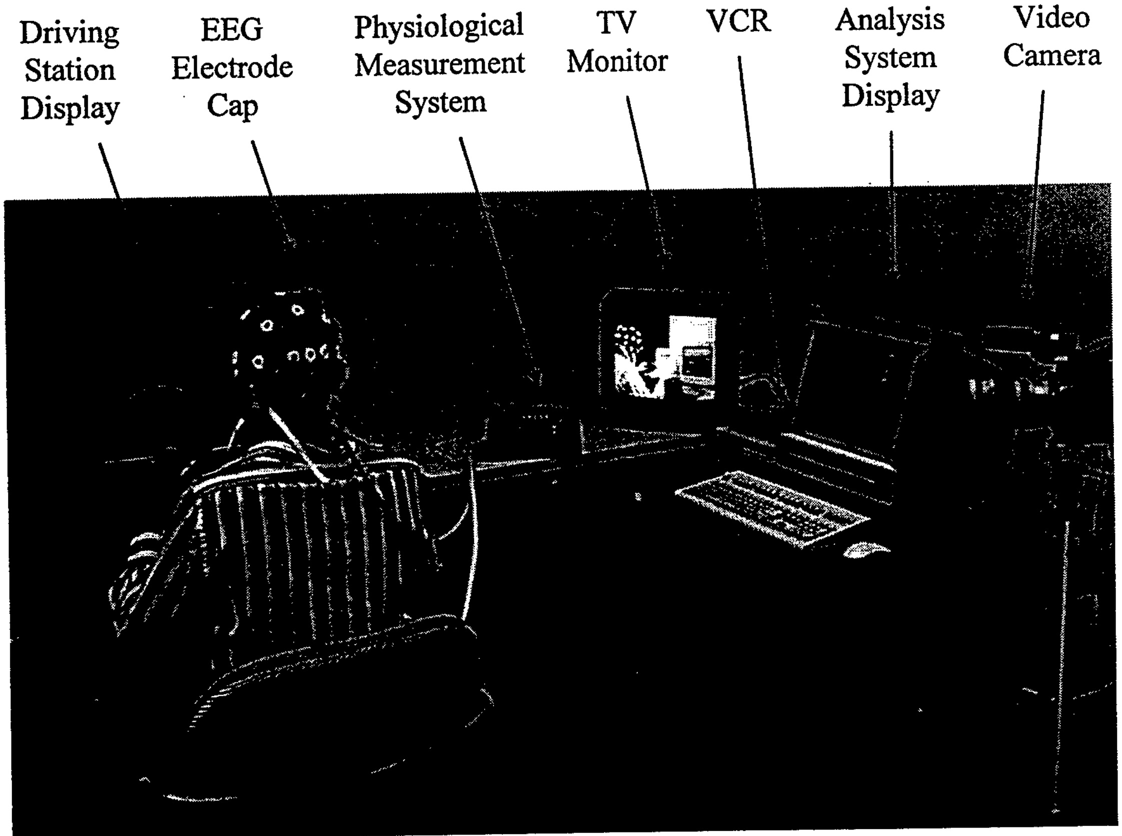


Figure 59: Picture of Laboratory Setup for Driving Simulation Experiments

7.1.2 Results and Discussion

Several validation exercises and two complete were performed as part of this effort for preliminary assessment of the HPBMS concept. Robust statistical analysis of the data is not possible without a much larger set of experiments (to be conducted through future research effort). As such, the following figures and data present the results of one of the experiments as a demonstration the potential effectiveness of the developed system, and to suggest the benefit of continued development, testing, and research.

Figure 60, Figure 61, and Figure 62 show measured EEG during eyes open versus eyes closed at three different electrode locations (T6, P4, and C4). These plots demonstrate strong alpha waves during eyes closed (particularly at location T6) and alpha suppression during eyes open.

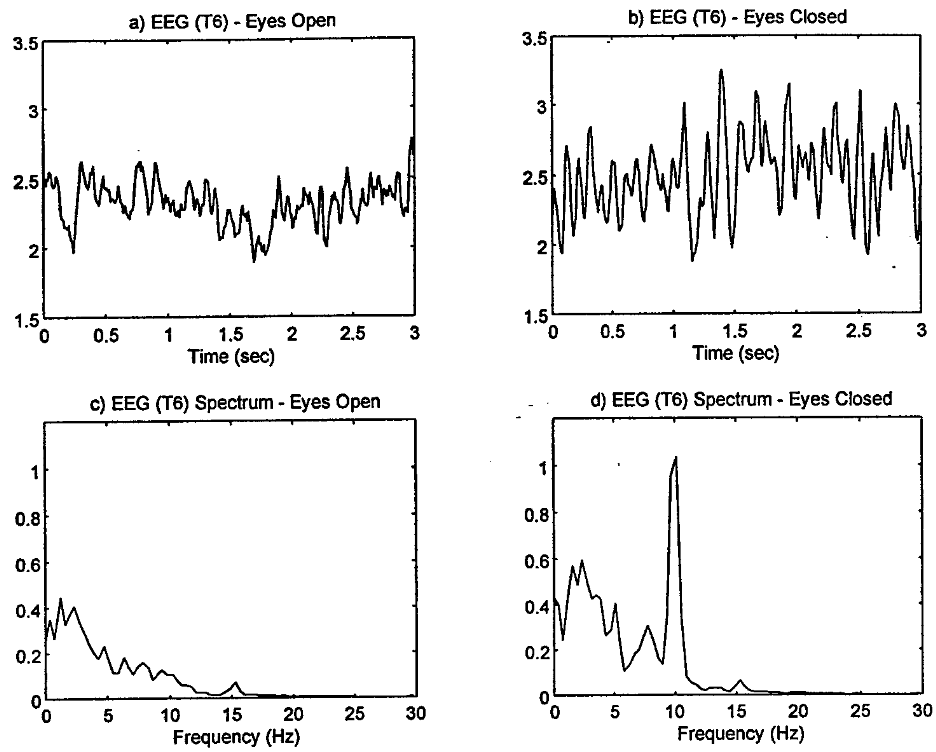


Figure 60: EEG Characteristics, at T6-A2, for Eyes Open Versus Eyes Closed. a) 3 second segment of EEG during eyes open period, b) 3 second segment of EEG during Eyes Closed period, c) EEG spectrum over entire 60 seconds of Eyes Open period, d) EEG spectrum over entire 60 seconds of Eyes Closed Period. Spectrum plots indicate strong alpha wave content during eyes closed and alpha suppression during eyes open.

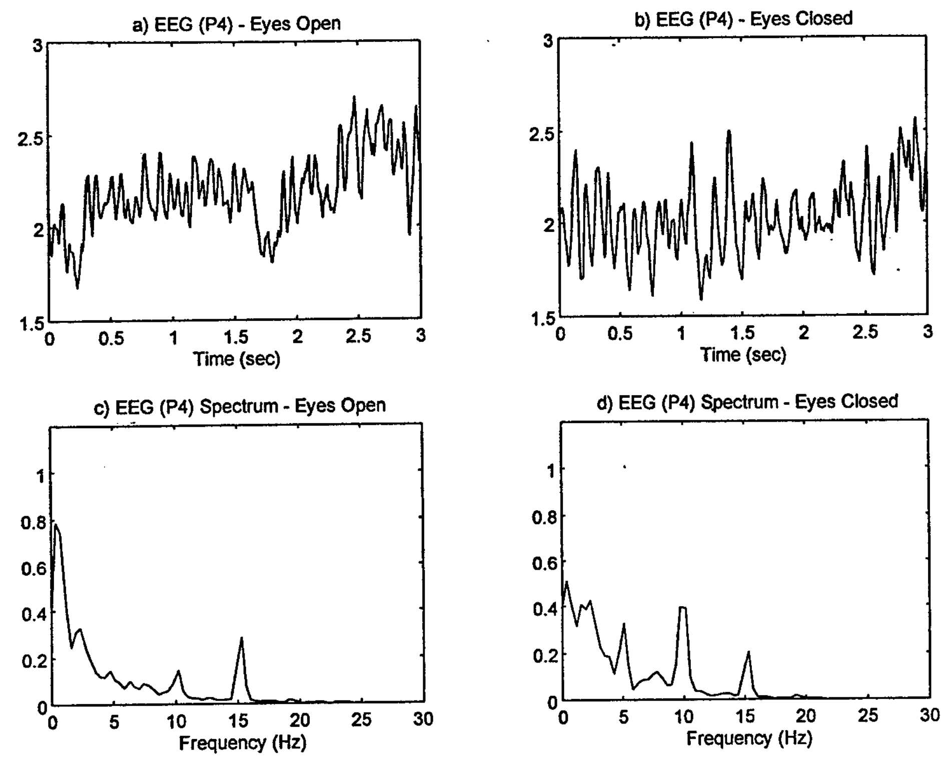


Figure 61: EEG Characteristics, at P4-A2, for Eyes Open Versus Eyes Closed. a) 3 second segment of EEG during eyes open period, b) 3 second segment of EEG during Eyes Closed period, c) EEG spectrum over entire 60 seconds of Eyes Open period, d) EEG spectrum over entire 60 seconds of Eyes Closed Period. Spectrum plots indicate moderate alpha wave content during eyes closed and alpha suppression during eyes open.

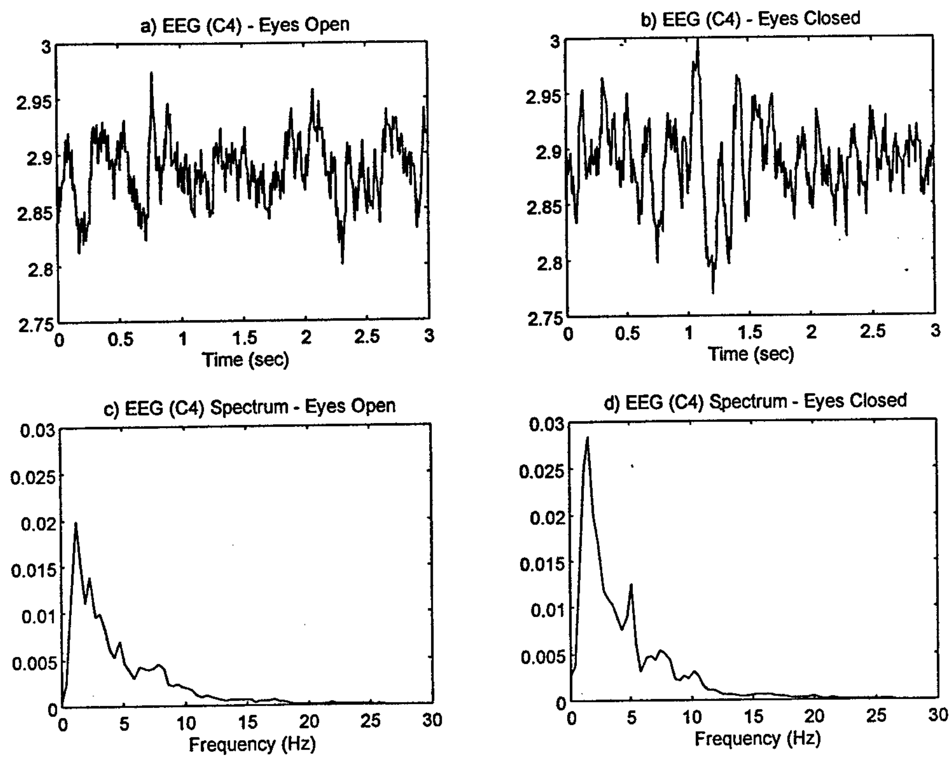


Figure 62: EEG Characteristics, at C4-A2, for Eyes Open Versus Eyes Closed. a) 3 second segment of EEG during eyes open period, b) 3 second segment of EEG during Eyes Closed period, c) EEG spectrum over entire 60 seconds of Eyes Open period, d) EEG spectrum over entire 60 seconds of Eyes Closed Period. Spectrum plots indicate minimal differences at this site between eyes open and eyes closed.

Figure 63, Figure 64, and Figure 65 show measured EEG during easy driving and difficult driving tasks, at the same three electrode locations (T6, P4, and C4). These plots demonstrate a dominance of low frequency activity (<4 Hz) during both easy and difficult driving, with greater power during difficult driving for all electrode locations.

This suggests that EEG variations occur between resting and driving states, as well as between easy and difficult driving. The increased EEG power seen during difficult driving, however, may be due to the increased physical activity required by the difficult road which had more curves. Future experiments should be designed to examine the difference between physical loading and cognitive loading factors. In addition, tasks which involve varied cognitive load but consistent physical load can be examined to remove the effect of varied physical loading. These methods will help better identify specific indicators of cognitive capacity and overload.

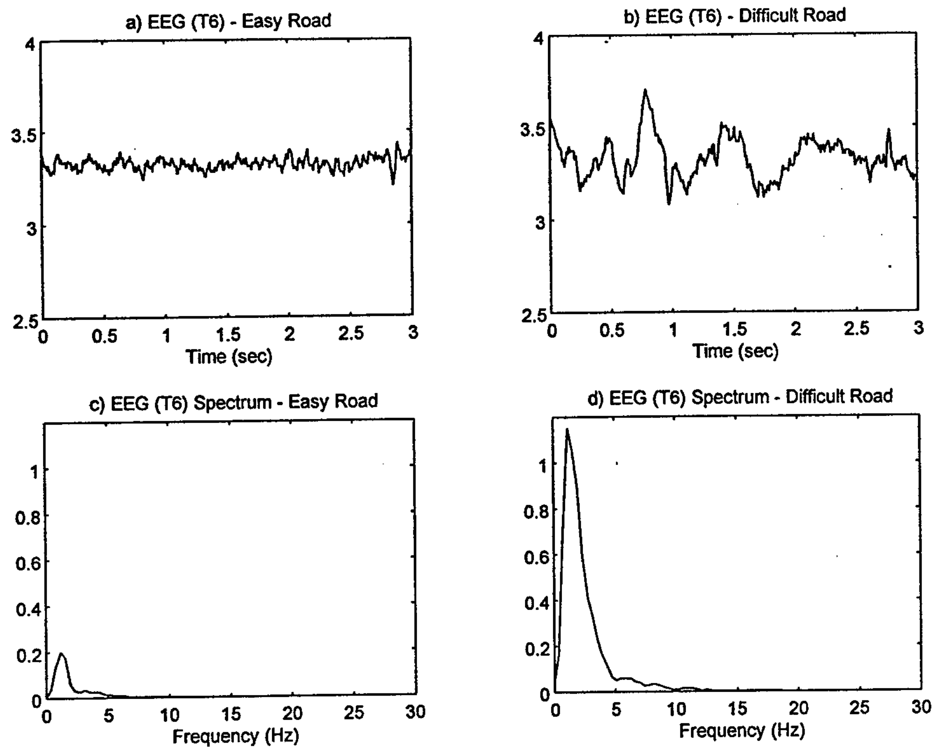


Figure 63: EEG Characteristics, at T6-A2, for Easy Driving and Difficult Driving Tasks. a) 3 second segment of EEG during Easy Driving period, b) 3 second segment of EEG during Difficult Driving period, c) EEG spectrum over 2 ½ minutes of Easy Driving, d) EEG spectrum over 2 ½ minutes of Difficult Driving. Both easy and difficult driving tasks are dominated by Delta wave frequencies, with greater power during difficult driving.

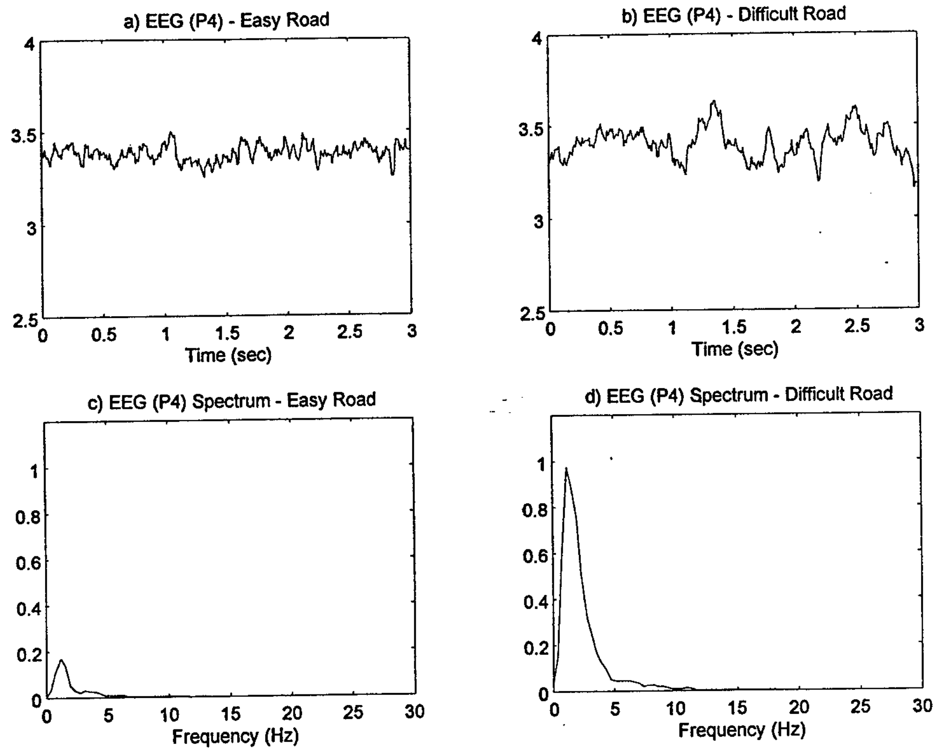


Figure 64: EEG Characteristics, at P4-A2, for Easy Driving and Difficult Driving Tasks. a) 3 second segment of EEG during Easy Driving period, b) 3 second segment of EEG during Difficult Driving period, c) EEG spectrum over 2 ½ minutes of Easy Driving, d) EEG spectrum over 2 ½ minutes of Difficult Driving. Both easy and difficult driving tasks are dominated by Delta wave frequencies, with greater power seen in the difficult driving.

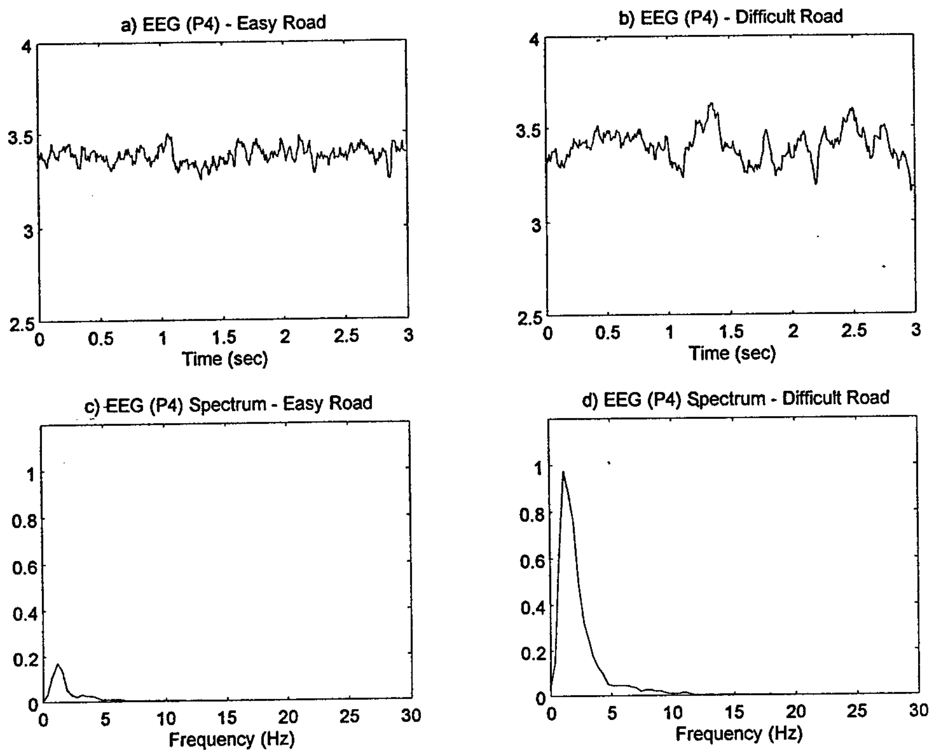


Figure 65: EEG Characteristics, at C4-A2, for Easy Driving and Difficult Driving Tasks. a) 3 second segment of EEG during Easy Driving period, b) 3 second segment of EEG during Difficult Driving period, c) EEG spectrum over 2 ½ minutes of Easy Driving, d) EEG spectrum over 2 ½ minutes of Difficult Driving. Both easy and difficult driving tasks are dominated by Delta wave frequencies, with greater power seen in the difficult driving.

Finally, Figure 66 lists average heart rate and average respiration rate during different stages of the experiment. These results indicate no significant variation in either heart rate or breathing rate between the different stages of the experiment. It is possible that longer task durations may be required to observe changes in these parameters. Also, there can be variations in the pulse and respiration waveforms that are not reflected in the rate.

Figure 66: Average Heart Rate and Average Respiration Rate During Experiment Stages

	Resting Eyes Open	Resting Eyes Closed	Driving Easy Road	Driving Difficult Road
Heart Rate (beats/min)	77	79	79	78
Respiration Rate (breaths/min)	19	20	19	20

For example, Figure 67 shows a representative segment of the respiration waveform during each of the different experiment stages. These plots show that during the resting stages (eyes open or eye closed) the respiration waveform is very regular, while during the driving task (easy or difficult) the waveform is irregular. The data also suggests that breathing may be more erratic during the more difficult task, however more extensive testing would be required to determine significance. In addition, motion may be partially contributing to the irregularity of the respiration signal.

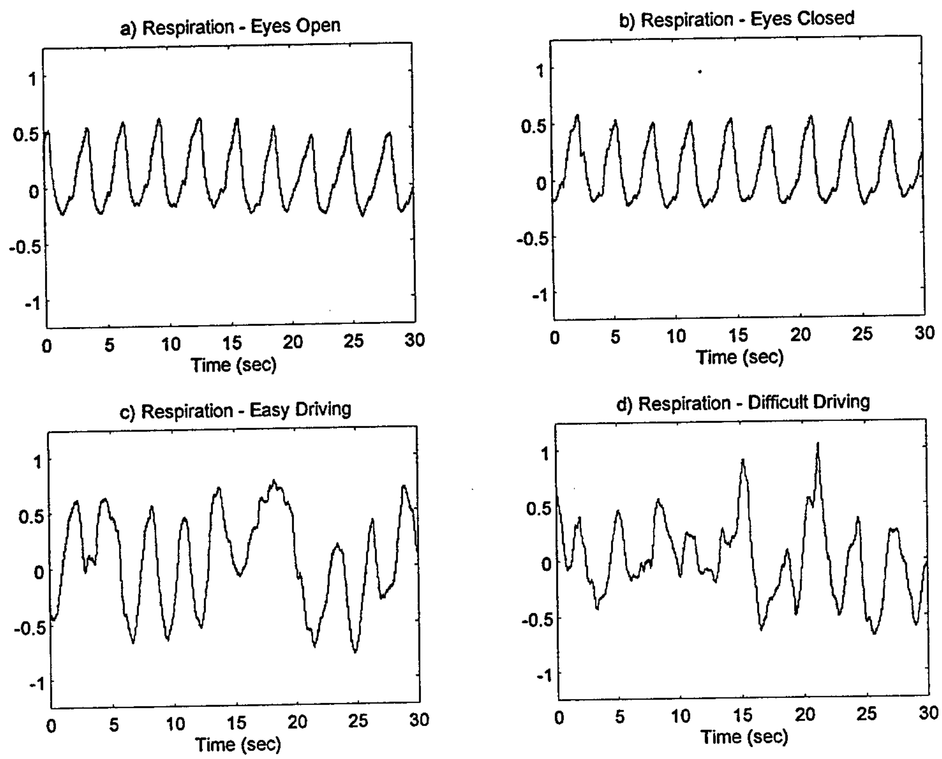


Figure 67: Respiration Signal During Experiment Stages.
Regular pattern is observed during resting phases (eyes open and eyes closed), while an irregular pattern is observed during driving tasks (easy and difficult).

7.2 HMMWV Driving Experiment

As another preliminary evaluation and assessment of the HPBMS concept, we conducted experiments of a human driving task using a HMMWV on a standard test track. This experiment was conducted jointly with another ARL SBIR project which was focused on the development of a model for human driving. In addition to providing indications of potential benefit, the results of this experiment provided initial feedback on the operational, procedural, and functional issues involved in the execution of performance assessment experiments in the field,. This helped guide continued development and enhancement of the HPBMS.

7.2.1 Experiment Description

The HMMWV, with early components of the HPBMS for data collection, was driven around the test track by two different subjects, for several trials each. The subject wore Cybernet's eye tracking goggles to provide a video recording of the driver's view, however eye tracking was not performed during this particular experiment. Electrodes were placed on the subject to provide measurement of four physiological parameters:

1) Electrocardiogram (ECG),
2) Electromyogram (EMG) of the upper trapezius muscle,
3) Electro-oculogram (EOG) for horizontal (left-right) eye motion, and
4) EOG for vertical (up-down) eye motion.

Cybernet's portable physiological measurement system was used to measure and capture the electrode signals.

In addition to the video of the driver's view (recorded on VCR) and the physiological signals, data from the vehicle controls (steering, gas pedal, brake pedal, gear, and speed) were also recorded.

Test Track Course

The test track course was prepared by ARL/HRED personnel to be similar to that used in previous studies. For the purposes of analysis, the track is divided into 5 consecutive segments. With a rest stage at the start and finish, the driving task consists of the following stages, in the order presented below:

- Initial rest
- Straight
- Curves
- Tight turns
- Cross country
- Slalom
- End rest

Subjects and Trials

Due to the limited time available to conduct the sample experiment, two subjects performed the driving task for several trials each. The following table summarizes the outcome of the trials, and indicates the data sets that were used for physiological signal analysis.

	Outcome	Data Set Label
Subject 1		
Trial 1	Successful data collection	Subject #1a
Trial 2	Successful data collection	Subject #1b
Trial 3	Successful data collection	Subject #1c
Trial 4 - Trial 7	Electrode signals corrupted	Not Analyzed
Subject 2		
Trial 1	Physiological data collection error	Not Analyzed
Trial 2	Successful data collection	Subject #2a
Trial 3	Successful data collection	Subject #2b
Trial 4	Successful data collection	Subject #2c

Figure 68: Trial Outcomes

Data Analysis

The data was analyzed by first dividing the recorded physiological data into the different stages of the driving task. This was performed by reviewing the video tape of the driver's view and recording the time of transition between individual stages – all data collected using Cybernet's Data Collection and Analysis Environment (DCAE) software is time synchronized.

For each stage of driving the following parameters were then computed based on the recorded physiological signals:

- Average Heart Rate
- Average EMG power
- Average EOG (left-right) power in band 2Hz-50Hz
- Average EOG (up-down) power in band 2Hz-50Hz

Heart rate (HR) was derived from the ECG signal. EMG power was computed from the time series of the signal, containing frequency components from 30Hz - 140Hz (as filtered by the physiological measurement system hardware). The EOG (left-right) and EOG (up-down) signals were processed by first deriving the frequency spectrum, and then computing the power contained only within the 2Hz to 50Hz frequency range.

7.2.2 Experiment Results

The tables and figures that follow summarize and graphically illustrate the results. The data suggest significant differences in all physiological parameters measured between different stages of the driving task. However, the experimental procedure was not robust enough to draw statistically significant conclusions – a larger number of subjects and a more controlled experimental procedure would be required.

Regardless, this work achieved significant results. The effectiveness of the HPBMS data collection systems and concept for workload and more general performance assessment was initially demonstrated.

For example, the results reported here suggest a consistent increase in heart rate as the driving task becomes more difficult, with a return to baseline levels after the driving task is completed. Similarly, EMG power (a measure of muscle tension) shows an increase through the more difficult stages of the driving task, and a return to baseline levels at the end. EOG characteristics also suggest a trend, with the horizontal eye motion generally increasing during stages with more turns, and vertical eye motion decreasing during more difficult stages. We hypothesize that this decrease in the vertical EOG is primarily due to a decrease in blink rate, since the EOG (up-down) signal also contains components due to blink.

Further study is needed to better identify the relationship between these (and potentially other) physiological signals and performance/workload parameters. The results of this work will be used to help define future research and experimental efforts.

Figure 69: Summary Data from Subject #1a

Stage	Duration	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:38	75.8	1.17E-09	1.75E-08	3.17E-08
Straight	0:26	77.1	1.65E-09	1.13E-08	1.27E-08
Curves	0:34	84.9	2.32E-09	2.41E-08	9.94E-09
Turns	0:42	87.4	2.16E-09	3.31E-08	1.48E-08
Cross C.	1:37	90	2.03E-09	1.59E-08	1.19E-08
Slalom	0:26	90	2.82E-09	2.67E-08	2.31E-08
End1	0:23	90	1.16E-09	2.78E-08	3.95E-08
End2	0:23	74.5	8.95E-10		

Figure 70: Summary Data from Subject #1b

Stage	Time	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:30	74	1.28E-09	1.36E-08	3.36E-08
Straight	0:22	76.4	1.31E-09	9.69E-09	8.25E-09
Curves	0:29	84.8	1.69E-09	1.54E-08	6.97E-09
Turns	0:39	87	2.11E-09	2.81E-08	1.70E-08
Cross C.	1:25	81	1.73E-09	1.49E-08	1.59E-08
Slalom	0:30	88	2.94E-09	1.95E-08	3.20E-08
End1	0:15	84	1.33E-09	1.75E-08	5.31E-08
End2	0:15	72	7.52E-10		

Figure 71: Summary Data from Subject #1c

Stage	Time	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:48	72.5	1.04E-09	1.58E-08	4.37E-08
Straight	0:19	82	1.43E-09	6.39E-09	1.00E-08
Curves	0:29	85.9	2.12E-09	2.09E-08	1.19E-08
Turns	0:45	84	2.16E-09	3.04E-08	1.79E-08
Cross C.	1:18		2.00E-09	1.64E-08	1.12E-08
Slalom	0:30	90	3.22E-09	2.43E-08	2.00E-08
End1	0:10	90	3.03E-09	2.97E-08	7.12E-08
End2	0:10	78	1.33E-09		

Figure 72: Summary Data from Subject #2a

Stage	Time	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:27	86.7	2.16E-09	1.35E-08	8.57E-08
Straight	0:36	80	2.32E-09	9.44E-09	4.24E-08
Curves	0:52	81	3.02E-09	1.80E-08	2.98E-08
Turns	1:19	85	3.79E-09	1.64E-08	2.36E-08
Cross C.	2:25	81	3.76E-09	1.15E-08	2.76E-08
Slalom	0:47	93.5	7.09E-09	1.11E-08	1.53E-08
End1	0:10	87.4	9.75E-09	2.54E-08	7.94E-08
End2	0:11	78.3	3.66E-09		

Figure 73: Summary Data from Subject #2b

Stage	Time	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:33	79	3.73E-09	2.34E-08	1.93E-07
Straight	0:29	80	2.66E-09	1.49E-08	8.68E-08
Curves	0:47	82	4.27E-09	1.14E-08	2.30E-08
Turns	1:15	81	4.41E-09	1.54E-08	2.36E-08
Cross C.	2:24	84	4.30E-09	9.83E-09	1.63E-08
Slalom	0:37	91	7.39E-09	9.68E-09	2.17E-08
End1	0:10	102	7.64E-09	1.78E-08	6.98E-08
End2	0:07	89	1.53E-09		

Figure 74: Summary Data from Subject #2c

Stage	Time	Heart Rate	Muscle	Left-Right	Up-Down
Initial	0:27	87.8	3.05E-09	2.27E-08	1.11E-07
Straight	0:23	84.8	4.09E-09	1.28E-08	1.30E-07
Curves	0:28	102.4	4.96E-09	1.16E-08	4.38E-08
Turns	0:42	101	6.11E-09	1.77E-08	2.98E-08
Cross C.	1:31	100	6.32E-09	9.58E-09	5.05E-08
Slalom	0:25	113	1.09E-08	1.35E-08	4.38E-08
End1	0:12	107	6.85E-09	2.30E-08	2.79E-08
End2					

7.3 Cognitive Workload/Computer Interface Experiments

7.3.1 Introduction

This set of experiments was conducted toward the latter part of the Phase II effort, once the comprehensive HPBMS had been fully integrated and validated. These experiments were designed to exercise every feature of the HPBMS software and integrated the hardware components. Additionally, we had the goal of testing the customization capabilities of the system – for example, the addition of new hardware (in this case, extra TVs, VCRs, a video camera and a third computer as a subject station).

As a result of sponsor interest, the validation experiments were designed to take a first step towards a protocol that would examine the effect of cognitive workload on human performance in human computer interface tasks. The specific goal of this set of experiments was to measure and analyze human performance-related data during standard computer interface tasks, in order to achieve both a demonstration of the HPBMS capabilities, and to conduct a preliminary investigation into potential indicators of human performance.

The result of this experimental protocol was highly successful. It demonstrated the power of the developed HPBMS as a research tool, and identified specific areas for continued research.

Please note that the descriptions, pictures, and instructions given here may vary from the final version of the HPBMS hardware and software. This portion of the report is intended to provide information on the experimental procedures conducted, not to provide instructional directions. Please consult the HPBMS documentation for instructions on use of the HPBMS.

7.3.2 Background

Detecting and recognizing indicators of physical workload, and based on those indicators *predicting* future physical performance, is perhaps an easy task. Most people will make predictions of this sort often during their lives - either predicting their own performance or predicting the performance of others. And, even without having been trained to know what signs to look for, a person can very accurately predict their own physical performance on a given task, and to a lesser degree, the performance of others. Those people with the appropriate training, doctors, athletic coaches, athletes, will have a greater degree of success predicting the physical performance of others.

Clues to physical performance (obtained without external hardware) include: breaths per minute, general fatigue, hunger and thirst. Because these clues are easily observable in ourselves, and we know through experience how we perform physically when breathing at a certain rate, or when hungry, we can gauge the performance of others by observing those same clues - the rise and fall of a chest, amount of sweat, speed and accuracy of motion, etc.

However, when attempting to gauge cognitive performance (decision time, accuracy of answers, good vs. bad decisions), the signs which would indicate performance are absent from casual observations. This is likely do to the fact that cognitive processes themselves cannot be casually observed.

Over the past several years, there have been many new techniques developed which can be used to search for the hidden indicators of cognitive performance. EEG, the reading of electrical signals produced by the brain, watching closely the movement of the pupil, and measuring pupil changes in size...These techniques can be used to monitor the brain and physiological functions (heart rate, etc....) in manners not possible by casual observation.

7.3.3 Hypothesis

Because the human brain is compartmentalized in terms of which areas are vital for which tasks, we will not expect to find a single physiological indicator for workload for all types of tasks. Visual tasks are dealt with in the visual cortex, language in X, memory in Y, etc.... However, this does not mean that a single experiment cannot be used to look for workload indicators across many cognitive venues at once.

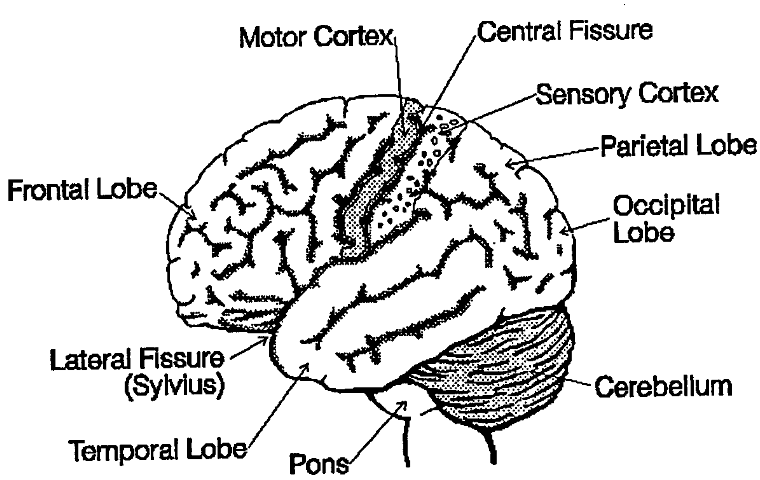


Figure 75: Diagram of brain sections

It is well known how the human body responds to physical workload - sweat, need to eat, drink, heart rate, breathing increase, etc. The physicality of the human body is often compared to a machine, and the brain to a computer. There exist established methods for evaluating and exploring the operations of both. If the human body displays measurable reactions to physical workload, then it must react to cognitive workload. Blood flow to different brain areas, changes in electrical activity (EEG), heart rate variability changes, etc.

Physical signs can be used to predict future physical performance: The human machine is not a source a limitless energy - in a given period of time, the human body has a finite source of nutrients required to keep it going. A hard physical task causes an expenditure of energy, depleting the energy supply. That expenditure is observable by an increased number of breaths per minute, increased heart rate, increased sweat production, etc. The increase of those variables are a measure of the energy expended on previous tasks. The more energy expended on previous tasks, as indicated by the amount of the increase in the previous factors, leaves less available energy for future tasks. Thus, based on heart rate, respiration rate, etc., we can predict future performance based (roughly) on the amount of energy expended during previous tasks.

The brain can be thought of in a similar manner: the brain has only so many resources to devote to processing information. When information is being processed, those resources are being used, and there must be some indicator of usage.

7.3.4 Experiment 1 - Recall, Sternberg, Tracking

7.3.4.1 Background

An effective methodology for workload research is the development and use of standardized tasks for calibrating and validating mental workload measures. The objective is to provide a controlled laboratory procedure which:

- Can present variable degrees of workload demand
- Is well understood in terms of subject behavior, repeatability, and statistical variables
- Offers easy training of subjects and acquisition of data
- Permits calibration of operator workload measures against norms
- Correlates subjective workload with workload task variables

These characteristics make such simulated tasks highly conducive to drawing conclusions about workload effects and developing psychophysiological indicators of workload. Laboratory methods provide the highest precision of measurement in the realm of operator behavior. The researcher has control over the performance demands imposed on the subject and the test procedures can be easily duplicated. Tasks can be varied easily and precisely to establish the sensitivity of task measures to variables of known experimental importance. And, safety can maximized.

Many psychophysiological workload tests have been developed, implemented, and reported in the literature. The tests selected for use in our experiments were chosen on the basis of the following criteria: 1) ease of use by the researcher and subject, 2) relevance of the exercised cognitive process to the simulated interface application, and 3) likelihood of the procedure to offer insight into the assessment of workload and other operator states. Those identified include: the Sternberg paradigm (Sternberg, 1966 & 1969), number recall, and object tracking tasks. Each of these task can be uniquely implemented to more closely simulate the types of processes required in the tactical command and control interface, as discussed in each task description.

In addition to examining these "basic" tasks independently, we also examined a multi-task scenario. It is important to recognize that human operators typically have to divide attention between more than one task. In this case, the operator must often postpone and/or compromise one task in order to maintain another. It is this division of attention between tasks in a complex multi-task interface environment that we would like to particularly focus on.

Number Recall Task

The number recall task tests the ability of a subject to recall material from his/her short-term sensory store (STSS) and short-term memory (STM). In its simplest form, the subject is shown a number consisting of (n) digits for a duration of (m) seconds. After this presentation, the subject is then requested to recall the number. Typically a computer screen and keyboard is used for presentation and number entry. The number of digits (n) and the duration of presentation (m) can be adjusted to create different levels of cognitive demand.

The appearance of a new number to be memorized is intermittent, and is generally repeated many times in order to achieve a representative average. The resulting performance measures for this task are the number of digits correct and the response time. The subject may also be asked to recall one or several of the numbers again (without another presentation) at some later time. This will test whether the subjects STSS went into his/her short-term memory (STM).

This procedure can be used to test a subject's cognitive capacity for STSS/STM and examine the effects of increased demand/workload.

Many variations on this basic theme can be (and have been) performed. For example, more complex information than simple digits may be used. The information may also be presented through sound, rather than sight, in order to assess the capability to recall auditory information versus visual information.

In regards to the military interface application, the number recall task can be used to simulate the cognitive process involved in receiving and communicating various types of military information including codes, tactical planning information, status reports, etc.

Both visual and auditory forms may be used for presentation and recall of the information.

Sternberg Paradigm

Cognitive ability tests have had a long history of use by large organizations for employee because of their validity and reliability. In addition to their low cost, cognitive test have the ability to predict worker performance (Hunter & Hunter, 1984). The Sternberg paradigm (Sternberg, 1966 & 1969) is often used for testing intermittent and response tasks.

In its basic implementation, the subject must memorize a list of (n) target digits in a range of 0 to 9. Then, a single digit in the 0 to 9 range is presented and the subject must respond immediately (by pressing a button or speaking) whether or not the number is among the target list. The appearance of a set of new target numbers (which can vary in length) will be intermittent, and is typically repeated many times in order to obtain a representative average.

The time the user takes to enter the number is recorded as a measure of his/her response time; the performance measure for this task is typically the response time only, with wrong responses ignored. Reaction time has been found to be dependent on the number of target digits and the number of concurrent tasks. The more targets the greater the mental demand, which increases reaction time. The subject response time is also dependent on skill level and the subject's sensitivity to training.

The Sternberg reaction time is a good calibrator for task workload since its demands can be easily controlled (usually through the target list length) and for its easy integration into continuous monitoring tasks. The Sternberg paradigm has real world applications, as it has proven useful in studying Parkinson's Disease (Schelosky, et al., 1991), as well as truck-driving and pilot workload (Rohrbaugh, 1997).

Variations on this basic approach in order to simulate the military interface can include using more complex alphanumeric or symbolic targets rather than simple digits. Auditory cues may also be added to the task. Relevant applications include recognition of significant targets on tactical planning maps (i.e. enemy vs. friendly targets), or detection of hostile elements in reconnaissance video.

Tracking Task

Another important "basic" task involves pursuit and/or compensatory tracking of an object.

In pursuit tracking the object moves randomly within a two-dimensional region (typically on a computer monitor). The subject must pursue the moving object, using the mouse or other input device, in an attempt to continuously follow the path of the object.

In compensatory tracking the object attempts to move around the screen while the subject must adjust its position (using the mouse or other input device) in order to keep it within a specific region. Maintaining the artificial horizon of an aircraft is an example of compensatory tracking.

Performance in the tracking task is measured by recording the error in each dimension. The target region, target size, lag of cursor and the allowable offset can be modified to create varying levels of the difficulty. Tracking tasks have been found to be useful in studying Parkinson's Disease (P. Soliveri, et al., 1997), and flight simulation (Roscoe, et al., 1981).

The tracking task offers many opportunities for variation of implementation in order to simulate various real-world environments. Military examples of applications that utilize tracking skills include: weapon targeting, vehicle driving, aircraft piloting, object pursuit, etc.

Combining Tasks

In many real-world environments the operator must perform and monitor multiple tasks simultaneously. Thus, it is often necessary to evaluate the impact of different task configurations, so that optimal performance can be achieved. The multi-task paradigm presents the subject with a combination of tasks to be operated on simultaneously, and then evaluates the way in which the subject divides attention across the different tasks and how this affects individual task and total task performance. The "workload test battery" developed by the Air Force to assess and predict pilot performance, uses a multi-task paradigm.

Using a similar multi-task paradigm will allow Cybernet to gain insight into:

(1) Attentional demands of each task
(2) Difficulty of each task with and without other demands
(3) Optimum display configurations
(4) Consequences of cognitive involvement in each task
(5) Effects of time stress
(6) Effects of anxiety about consequences

The attentional demand of each task can be monitored by eye-tracking which records where the subject is looking. The complexity and difficulty of the individual tasks can be analyzed by subjective evaluations and correlated to psychophysiological measurements.

Display characteristics can be changed and evaluated to see what features contribute to degraded and/or improved performance.

The questions this type of experiment aims to address are the following. Does the stress level of the operator increase with time? What happens to brain wave activity when the task becomes more difficult or easier? What are the frequencies of cognitive involvement in each of the different tasks? Does the subject become frequently overloaded? How many errors does he/she make during the tasks? If the subject is anxious about the tasks does this hinder his/her performance? Does it increase the number of errors that he/she commits? What do his/her subjective ratings tell about their anxiety and/or performance. Are there significant psychophysiological indicators of stress?

Experiments in multi-tasking may by their nature become overly elaborate and cumbersome. This is especially true when the experimenter yields to the temptation of collecting psychophysiological information about every task variable in each task. It would therefore be difficult to study all of the effects for every variable within the scope of this project, since there are simply too many variables involved. Therefore, certain task variables in the simulation experiments were chosen as the most appropriate means for collecting psychophysiological information about performance and cognitive workload. The effect of these key task variables are examined to determine their effect on human performance and cognitive processes.

7.3.4.2 Hardware Setup

This experiment required an enhanced version of the standard HPBMS. The additional hardware pieces were: video camera, extra TV and VCR pair (for recording and synchronizing the video camera output), and a computer and monitor on which to run the interface experiments. This computer served as the 'subject's station'. The 'subject's station' and 'experiment's station' has been explained previously.

The 16 channel physiological monitor was used to record 16 channels of EEG, and the 8 channel monitor was reserved for life signals and an event marker switch. For more information on the exact EEG and other signals monitored, please see the experimental procedure below.

7.3.4.3 Experimental Parameters

One of the purposes of this research is to illustrate how numerous specific task variables effect human performance and how psychophysiological measures may indicate cognitive workload or degree of difficulty. The majority of the differences between the task difficulties and workload may be attributed to cognitive effects (intellectual or information-processing) and/or limitations. Cognitive limitations can be can be linked to the limited ability to project the effects of a present decision into the future (predictability) and/or loss of decision time (reducing delay and presentation times).

If we can understand and model the human performance of well-trained subjects in these simple laboratory tasks, then perhaps this knowledge may be extended to more complex tasks. The ability to repeat laboratory experiments is a powerful tool, for it allows us to study inter-subject differences and the effects of different information, and it provides us with a measure of variability inherent in a human's cognitive and decision process.

The three "basic task" operations for selected for our experiment were discussed in the previous section. Here, we outline the parameters of each task procedure that may be varied in our experiment, and the questions they can address.

Number Recall

Presentation time

1. Is there a critical presentation time required for accurate memorization and recall?
2. How brief must the target digits be presented before a performance decrement is easily recognizable?

Delay time

1. Does decreasing the delay until the next presentation lead to a performance decrement and/or increase in cognitive load?
2. If so, how short should the delay be before a performance decrement is easily recognizable?

Number of digits

1. What is the limit and/or the critical number of digits before performance drops off dramatically?
2. If the digits are fixed (i.e. always the same) does the task become more predictable? If so, what is the effect when compared to a range of digits (unpredictable)?

Size/Font of digits

1. What happens when the size of the digits is decreased? Increased?
2. Is the effect of size dependent on the users ability to concentrate?
3. Is the effect of size dependent on the users vision?

Digit patterns

1. Do certain patterns of digits lead to easier recall? (i.e. 12345, 223334)

Sternberg Paradigm

Presentation time

1. Is there a critical presentation time for accurate target detection?
2. How briefly must the target digits be presented before a performance decrement is easily recognizable?

Delay time

1. Does decreasing the delay of the next presentation lead to a performance decrement and/or increase in cognitive load?
2. How short must the delay be before a performance decrement is easily recognizable?

Number of digits

1. What is the limit and/or the critical number of target digits (if any) before performance drops off dramatically.

2. If the number of digits is fixed, does the task become more predictable? If so, what is the effect when compared to a range of possible target digits?

Size/font of digits
1. What happens when the size of the digits is decreased? Increased?
2. Is the effect of size dependent on the user's ability to concentrate?
3. Is the effect of size dependent on the user's vision?

Pursuit Tracking

Speed of object
1. Is there a critical speed at which performance dramatically decreases?
2. If so, is it subject dependent or independent?

Size of object
1. What happens when the size of the tracked object is decreased? Increased?
2. Is the effect of size dependent on the users ability to concentrate?
3. Is the effect of size dependent on the users vision?

Motion of object
1. Does a more predictable non-random motion increase performance?
2. What type of motion leads to the greatest performance increase?

Size of tolerance region
1. To what degree does tolerance (i.e. how closely the object must be tracked) affect performance?
2. Will changing the tolerance region lead to a difference in cognitive load?

Cursor shape
1. Does cursor shape (i.e. a cross-hair versus an arrow) affect performance?

Cursor speed
1. Does the gain on the mouse affect performance?

Duration of task
1. If the testing is long is there a performance decrement as time goes on?
2. Does performance fluctuate with boredom, fatigue or distractions?
3. What are the effects of short vs. long tests?

Compensatory Tracking

Speed of object
1. Is there a critical speed at which performance drastically decreases- is it subject dependent or independent?

Size of object
1. What happens when the size of the tracked object is decreased? Increased?

2. Is the effect of size dependent on the users ability to concentrate?
3. Is the effect of size dependent on the users vision?

Size of tolerance region
1. To what degree does tolerance (i.e. allowable deviation of the object from desired location) effect performance?
2. Will changing the tolerance region lead to a differences in cognitive load?

Duration of task
1. If the testing is long is there a performance decrement as time goes on?
2. What are the effects of short vs. long tests?

Since a well designed experiment should only have a few variable parameters (in order to allow for effective data analysis), we selected a limited set of the above parameters to be varied in our experiments. Selected was based on those that were expected to have the most significant effect on performance. The following table identifies those parameters.

Task	***Task variables/conditions***
Number Recall	Presentation time Number of digits
Sternberg	Presentation time Number of digits
Pursuit Tracking	Speed of object Size of tolerance region
Compensatory Tracking	Speed of object Size of tolerance region

Figure 76: Selected Task Variables for the Number Recall, Sternberg and Tracking Tasks

The following sections specify the conditions that were to be applied for the set of experiments conducted.

Number Recall

Values for Non-Variables:
font name=sansserif
background color=white
font style=plain
loops=20
digit color=black
font size=26
sound=off

(1) Condition A: Variable = Number of digits: constant

Number Recall	*configuration 1*	*configuration 2*	*configuration 3*
minimum digits	3	6	9
maximum digits	3	6	9
time shown (sec)	3	3	3
time between (sec)	2	2	2

(2) Condition B: Variable = Number of digits: variable

Number Recall	*configuration 1*	*configuration 2*	*configuration 3*	**configuration 4*
minimum digits	2	5	8	2
maximum digits	4	7	10	10
time shown	3	3	3	3
time between	2	2	2	2

* optional

(3) Condition C: Variable = Presentation time

Number Recall	*configuration 1*	*configuration 2*	*configuration 3*
time shown	3	2	<1*
time between	2	2	2
minimum digits	6	6	6
maximum digits	8	8	8

* less than 1 second

Sternberg

Values for Non-Variables:

font name=sansserif
background color=white
font style=plain
loops=20
digit color=black
font size=26
sound=off

(1) <u>Condition A</u>: Variable = Number of digits: constant

Sternberg	*configuration 1*	*configuration 2*	*configuration 3*
minimum digits	3	5	7
maximum digits	3	5	7
time shown	3	3	3
time between	2	2	2

(2) <u>Condition B</u>: Variable = Number of digits: variable .

Sternberg	*configuration 1*	*configuration 2*	*configuration 3*	**configuration 4*
minimum digits	2	5	8	2
maximum digits	4	7	10	10
time shown	3	3	3	3
time between	2	2	2	2

* optional

(3) <u>Condition C</u>: Presentation time

Sternberg	*configuration 1*	*configuration 2*	*configuration 3*
time shown	3	2	<1*
time between	2	2	2
minimum digits	6	6	6
maximum digits	8	8	8

* less than 1 second

<u>Pursuit Tracking</u>

<u>Values for Non-Variables:</u>

fillColor=black
fillMode=empty
size=medium
lineColor=black
cursorSpeed=slow
type=pursuit
cursorShape=default
backgroundColor=white
testTime=2
sound=off

(1) Condition A: Variable = Tolerance region I

Pursuit Tracking	configuration 1	configuration 2	configuration 3
tolerance	40	30	20
movement	random	random	random
speed	moderate	moderate	moderate

(2) Condition B: Variable = Speed: tolerance 40

Pursuit Tracking	configuration 1	configuration 2	configuration 3
speed	moderate	fast	very fast
movement	random	random	random
tolerance	40	40	40

(3) Condition C: Variable = Speed: tolerance 30

Pursuit Tracking	configuration 1	configuration 2	configuration 3
speed	slow	moderately fast	very fast
movement	random	random	random
tolerance	30	30	30

(4) Condition D: Variable = Motion of object

Pursuit Tracking	configuration 1	configuration 2	configuration 3
movement	figure 8	bounce	random
speed	fast	fast	fast
tolerance	30	30	30

Compensatory Tracking

Values for Non-Variables:

fillColor=black
fillMode=empty
size=medium
shape=circle
lineColor=black
type=compensatory
backgroundColor=white
testTime=2
sound=off

(1) Condition A: Variable = Tolerance region I: moderate speed

Compensatory Tracking	*configuration 1*	*configuration 2*	*configuration 3*
tolerance	40	30	20
movement	random	random	random
speed	moderate	moderate	moderate

(2) Condition B: Variable = Tolerance region II: moderately fast speed

Compensatory Tracking	*configuration 1*	*configuration 2*	*configuration 3*
tolerance	50	40	30
movement	random	random	random
speed	moderately fast	moderately fast	moderately fast

(3) Condition C: Variable = Speed

Compensatory Tracking	*configuration 1*	*configuration 2*	*configuration 3*
speed	slow	moderate	fast
movement	random	random	random
tolerance	30	30	30

For each tracking task, the user was required to track the object for two minutes. In the number recall and Sternberg tasks, 20 iterations of each configuration was utilized to produce a total (individual configuration) task length of approximately two minutes.

7.3.4.4 Procedure

The following subject consent form, voluntarily signed by the participant before the experiment is conducected, outlines the experimental procedure conducted. An additional consent form for video recording of the experiment is also included.

7.3.4.5 Subject Consent Form

Project #303_02 (IRB 0004.1)

CONSENT TO INVESTIGATIONAL TREATMENT OR PROCEDURE

I, ________________, hereby authorize or direct the primary investigator, and associates or assistants of his choosing, to perform the following treatment or procedure upon myself:

This study is intended to assess human performance and examine your cognitive processing state when performing various tasks on a computer interface. While performing these tasks you will be monitored by electrodes to measure physiological data, such as Electrooculogram (EOG), Electromyogram (EMG) and Electrocardiogram (ECG). Video and audio will be recorded during testing. You will be wearing a Head Mounted Eye Tracking device or a Head Mounted Display with integrated Eye Tracker for particular parts of the test.

Confidentiality:

Confidentiality of the data as well as your identity will be maintained. All identifying information about yourself will not be shared with anyone outside of CSC, verbally or in writing, without the permission from you. Since the right is not absolute, there are some limits to confidentiality you should know about. These include:

1. When there is reasonable suspicion that you are likely to harm yourself or others. If this occurs protective measures will be taken. By law, these situations require us to reveal necessary information to persons or agencies.
2. If your records are subpoenaed by a legitimate court order.
3. Senior staff at CSC reserve the right to consult at CSC in staff meetings for consultation, supervision, or educational purposes.

The plans for future use of data as part of this study or use beyond this study will be approved by an IRB (Internal Review Board) committee prior to use. The use of existing data that were originally obtained for different purposes and that involve identifiable subject information, will require examination of the risk involved. There will be a determination of whether the new use is within the scope of the original consent or whether necessary or feasible to obtain additional consent. Anonymity of the subjects must be preserved.

The signed consent forms will be stored in the contract folder at CSC. These folders are contained in locked file cabinets and only authorized personnel are allowed to handle these documents. Your name will only be available to researchers for purposes of review of subject criteria for the experiment. Your name will not be published in any articles, journals or papers without your written consent.

Data Utilization

- Only those involved in the project #303 will have access to the gathered data
- Each session will be videotaped and audio taped. The tapes will be labeled only with a code number, which will be kept in the investigator's files. The tapes will be used to obtain brief excerpts for supporting data analysis and to illustrate Cybernet's findings in scientific publications or at professional meetings.

- Data gathered may be used for purposes of publication. Your name will be kept confidential.

Data Records:

Your data records, such as consent, are maintained in a locked cabinet at CSC. They are not part of any shared CSC file, and no one has access to them except CSC staff. The data will be coded to remove identifying information.

Data that could reveal your identity will be stored in files accessible only to the primary investigator and authorized staff.

Questionnaires, inventories and other data-gathering instruments and procedures will be carefully designed to limit the personal information to be requested only that which is essential.

Federal regulations require that all records relating to the IRB and to human subjects activities be retained for *at least three years* after completion of the research. Records, including signed consent form and collected data, must be accessible for inspection at any time and for copying by authorized representatives of Cybernet or the agencies sponsoring the research.

The experimental (research) portion of the treatment or procedure is:

The general procedure will be to instrument you with recording electrodes, and then have you perform some type of mental, memory and tracking task involving varying levels of cognitive effort. Physiological data will be recorded in synchrony along with task performance data. Upon playback, we will be able to analyze the task data and note significant cognitive events. We will then study the physiological data recorded during these events to determine which parameters exhibit changes that could be used as indicators of cognitive workload and/or cognitive capacity.

The following is the procedure the investigators will follow for the experimental set-up and collection.

1) Subject reports to the testing facility approximately 1/2 hour before the experiment starts.

2) The subject will fill out a demographic data sheet to collect pre-screening data. The demographic data will determine those subjects that best fit the selection criteria. The criteria that will be assessed will include: if the subject is willing to volunteer for the testing, whether they wear glasses and/or contacts, are void of neurological disorders, are between the age 20-45 years old, are not pregnant, and if they have no allergy to alcohol or tape. If the subject fails to meet certain criteria, the Investigator

will either recommend that they do not continue with the experiment or dismiss the subject.

Time : estimated 5 minutes

3) Subject will be informed about the procedure will read consent form, and if he/she wishes to participate will sign the consent form. Copies of the Volunteer Agreement Affidavit consent form will be provided to the subject for his/her records.

Time: estimated 30 minutes

4) The subject will be briefed on using the computer interfaces as well as the other computer peripherals.

Time: estimated 5 minutes

5) The subject will practice using the interfaces for up to 5 minutes for each of the 3 different task interfaces to become accustomed to the controls and display. The subject will practice until a certain performance criterion is met (performance criterion will be determined at a later time).

Time: estimated 15 minutes

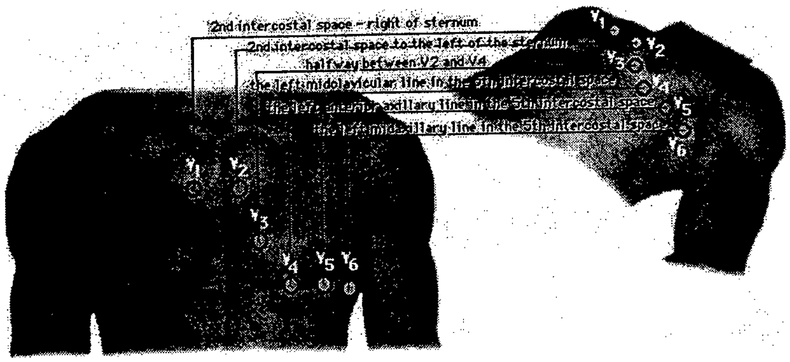
Electrodes will then be placed on the subject to provide measurement of the desired physiological signals.

6) ECG measurements will be taken via electrodes applied to the chest.

For application of electrodes the following will occur:

- The subject will remove any upper clothing (i.e. coat, shirt) to allow placement of the electrodes, after which the subject may put the clothing back on for the test. A private room or area will be available for placing the electrodes.
- The skin will be cleaned at electrode locations with an alcohol swab and allowed to dry.
- Two electrodes will be placed in precordial position. Precordial leads are: V1, V2, V3, V4, V5, and V6. These six measure the cardiac electrical current in an anterior-posterior aspect with regard to the heart. For measurement of EKG we will be using the V3 and V4 positions at the chest.

The following figure shows the placement of these leads:



- One ground electrode will be placed on bony area (clavicle, for example).
- Electrodes will be secured with surgical tape.

Time: estimated 5 minutes

7) The respiration rate will be measured utilizing a band placed around the subjects abdomen or chest.

8) Dermal skin measurements will be performed utilizing surface electrodes on the finger.

9) EMG electrodes will be applied to upper trapezius (between the shoulder blade and the neck) as shown in the following figure::

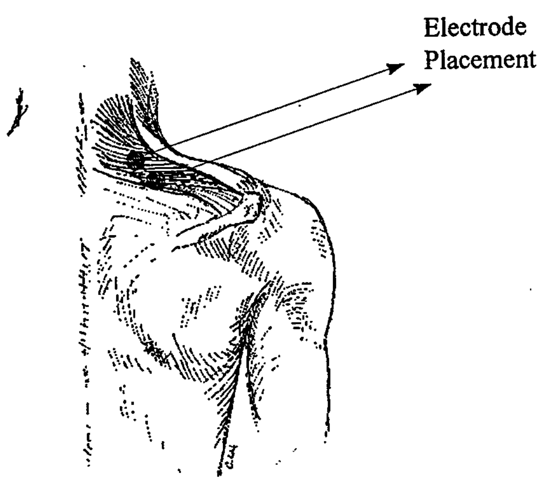


Figure 77: EMG location of the Upper Trapezius
(From Boston University Neurology, Joe F. Fabre, M.D., ©1997)

- Optimal location for electrodes are determined by resisting subject's shoulder elevation while feeling for the flexing trapezius muscle in the back of the neck area. (which will be demonstrated by the experimenter.)
- Area is marked with pen

- Skin is cleaned with alcohol swab and allowed to dry
- Electrodes are placed and secured with surgical tape.

Time: estimated 4 minutes

10) EOG electrodes will be applied to the face as shown in Figure 78:

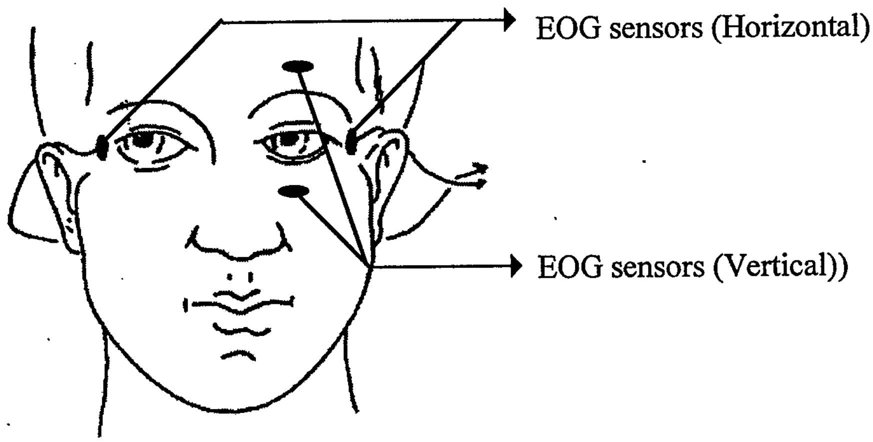


Figure 78: Typical Placement of EOG Sensors for Lateral & Vertical Eye Movements (From McGuigan, F.J. (1979) Psychophysiological measurement of covert oral behavior: A guide for the laboratory. Hillsdale, NJ: Lawrence Erlbaum Associates).

- Skin will be cleaned on each side of the eyes and above/below the dominant eye, using alcohol.
- Four electrodes will be placed and secured with tape.

Time: estimated 3 minutes

11) The EEG cap will be placed on the subjects head with electrode positions based on the International 10-20 System (*Figure* 79). Simply, the Electrodes are placed on the scalp at points that are 10 and 20 percent of the distance from the lines of the nose to the back of the head (nasion to the inion in *Figure* 79), and from the left to the right mastoid points (just behind the ear.)

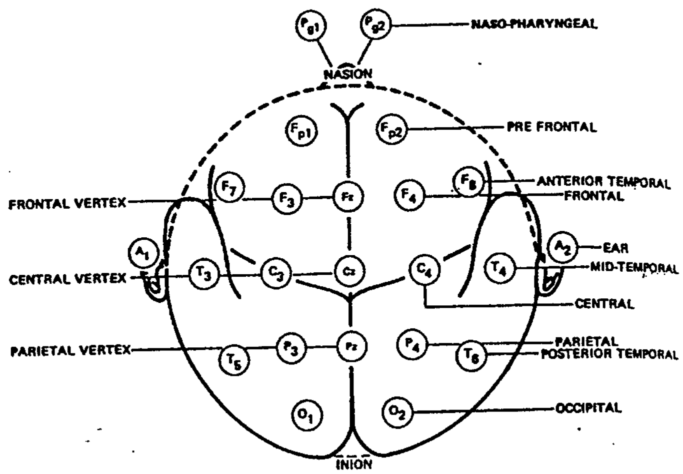


Figure 79: Electrode Locations in the International 10-20 System (From Hippocrates Project NYU School of Medicine, 1992-present)

The procedure for placing the cap on the subject is as follows:

a) Before placing the EEG cap on the subject the neck strap and chin strap are loosened
b) the cap is placed on the subjects head so that the ears fit comfortably through both ear loops
c) The front tab is adjusted so that it is positioned at the nasion and taped in position
d) Chin and neck strap are adjusted so that they are centered on the chin
e) The EEG cap is checked to ensure that the placement is symmetrical
f) The hair is parted and the skin under the biosensor sockets is prepped using a cotton swab with a water alcohol mix.
g) The biosensors are then put into place

12) The eye tracker will be placed on the subject's head over the EEG cap, adjusted for comfort, proper imaging of eye, and the correct cameras field of view.

    Time: estimated 5 minutes

13) Wires will be secured with tape and connected to the physiological monitor.

    Time: estimated 2 minutes

14) All signals will be verified.

    Time: estimated 15 minutes

15) The EMG signal will be calibrated

- Shoulder elevation of subject in upright posture will be resisted by holding hand down with arm along side of the body.

- After complete relaxation of shoulder subject will be asked to build up elevation force within 1-2 seconds and maintain maximum exertion for two seconds.
- Data will be recorded simultaneously, starting while subject is fully relaxed, one second before exertion.

Time: estimated 2 minutes

16) Eye position will be calibrated.

- Subject will gaze at fixed points while eye image (and EOG data) are collected.
- Accurate eye tracking will be verified by asking the subject to look at the specific locations.

Time: estimated 5 minutes

17) The subject will be seated at the workstation and cables will be attached and arranged for minimal obstruction. All signals will be re-verified prior to beginning the tests.

Time: Up to 10 minutes

18) The subject will then perform the series of tasks while all data is measured from start to finish. After each task, the subject will be asked to fill out a short form reporting on their mental and physical states. A session will consist of several different task runs with rest periods between. Each rest period will last approximately 3 minutes.

The order in which the subjects perform the different task types (number recall, Sternberg and tracking tasks) will be randomized. Future experiments will also involve interfaces that combine multiple tasks into a single interface. The exact interface parameters and configurations to be tested is variable, and will be determined in the future.

Time: up to 120 minutes

Post-Test

19) At the end of the experimental procedure the test participant's cognitive workload and stress levels will be collected with the NASA TLX and the SRE forms. These forms will be filled out by the subject once the last test has been completed.

Time: estimated 10 minutes

20) After completion of the entire procedure, the eye tracker, electrodes, and lead wires will be removed, and the subject will be allowed to fully recuperate for up to 30 minutes, under supervision, to monitor if any complications arise from the testing (i.e. dizziness, tiredness etc.).

21) The subject will be de-briefed and given a point of contact for follow-up on individual performance or results of the study.

Time: estimated 5 minutes

Total Time: up to 3 hours

The subject's participation will involve 1 to 3 visits (on different days) of approximately 3 hours each.

Purpose of the procedure or treatment:

The goal of this project is to develop a system that will facilitate real-time measurement of human performance in multi-task environments. This will be performed through the measurement and analysis of psychophysiological-based signals, subjective data and direct observation. The physiological data will provide insight into mental workload, stress, and the visual cues used during a multi-task situation.

Benefits, risks, discomforts and precautions:

There is no real direct benefit to you. Benefits of this study will mostly be realized by the Army through the development of a cognitive workload and performance measures. There will be a potential benefit of the study for possible expansion into future projects at CSC. All data gathered will also serve to enhance the system for use as a scientific research tool. This project will also support future commercialization of the system which may provide significant benefits to a variety of human factors research.

The risk associated with this set of experiments is minimal. This project has minimum risk since the potential harm is not greater, considering probability and magnitude, than those tasks ordinarily encountered in your daily life or during the performance of routine psychological tests.

Please be assured that the MMDS is safe. The MMDS will be optically linked to the recording computer. This provides a de-coupling from the electrical components of the computer, thereby eliminating the possibility of you receiving an electrical shock while the MMDS is attached.

Although all instrumentation is non-invasive, you may feel discomfort from using the eye tracker as well as the E-net EEG cap. If this occurs you will be asked if you wish to continue, delay, postpone or discontinue the study.

There is some possibility you will develop simulator-sickness like symptoms which range from slight eye strain and dizziness. The simulator sickness like symptoms may happen when wearing the HMD or eyetracker.

Any incidents of simulator sickness will be followed up by a 1 hour observation period during which time we do not wish you to continue. This is to preclude any potential flashback effects of simulator sickness which have been known to occur in rare cases.

Due to the investigational nature of this study there may be other risks that are currently unknown. If any unforeseen risk(s) arise from the project the IRB committee will be informed immediately.

Procedure For Injuries:

For medical emergency or any personal injury to you:

- Report any injuries to the Investigator as soon as possible.
- The Investigator will report any injuries to the IRB Committee as soon as possible
- An injury report must be made as soon as possible to Cybernet System Corporation's Human Resource office.
- Cybernet Systems Corp. will follow all OSHA procedures.

Criteria for participation in this study:

I am being invited to participate because:

- I am between the ages of 20 and 45.
- I am not pregnant.
- I am volunteering for this experiment
- I do not have any neurological disorders that I am aware of.
- I do not have any allergy to alcohol, electrode gel or tape that I am aware of.

Anticipated duration of subject's participation (including number of visits):

Your participation will involve 1 to 3 visits of approximately 3 hours each.

General Conditions

1. Should you consent to participate in this research, your identity will be kept confidential. A copy of the informed consent documentation will be made available to you as well as the sponsoring agency.
2. All forms of research- whether routine or experimental involve some minor risk of injury. In spite of all precautions, you might develop dizziness and or lethargy from participating in this project. If such complications arise, the researchers will provide you with assistance for obtaining proper rest.
3. If in the event you develop medical complication as a result of the project medical treatment will be available. However, you will not be provided with reimbursement for medical care other than what your insurance carrier may provide, nor will you

receive other compensation. CSC has made no provisions for payment of costs associated with injury resulting from participation in this project. The researchers will assist you in obtaining appropriate follow-up medical treatment but this study does not provide compensation for additional medical or other costs.

4. You will be told of any new findings that may influence your willingness to continue to participate in the project. Your participation in this project may be terminated by the project investigator if in his/her judgment it is inadvisable for you to continue.
5. If you would like to discuss your rights as a research subject and or your participation in this study with a CRC representative who is not part of this study, please call Cybernet at 734-668-2567 and ask for Paulette Hodge, Human Resources Manager.
6. Should you agree to participate in this research you may change your mind at any time. Refusal to participate will not harm your relationship with the facility and staff, nor will it prejudice further relations.
7. COSTS: Subject compensation will not be provided to the subjects. Time lost and traveling expenses may be provided to subjects outside CSC.

I hereby acknowledge that the Investigator ______________________ has provided information about the procedure described above, about my rights as a subject, and he/she has answered all questions to my satisfaction, I understand that I may contact him/her at Phone No. (734) 668-2567 should I have additional questions. He/She has explained the risks described above and I understand them; he/she has also offered to further explain all possible risks or complications.

I have read the description of the project study and general conditions or it was read to me by: ______________________. Anything I did not understand was explained to me by : ______________________, any questions I had were answered by: ______________________.

I understand that, where appropriate, the U.S. Army may inspect records pertaining to this study. I understand further that records obtained during my participation in this study that may contain my name or other personal identifiers may be made available to the sponsor of this study, the U.S. Army. Beyond this, I understand that provisions have been made to protect my privacy and to maintain the confidentially of data acquired through this research project.

I understand that I am free to withdraw my consent and participation in this project at any time after notifying the project director without prejudicing future care. No guarantee has been given to me concerning this procedure.

I have not given up any of my legal rights or released the investigator, the study sponsor, the facility or its agents from liability for negligence.

I have read and fully understand the consent form. I sign it freely and voluntarily. On this basis I consent to participate in this experimental study. I have been informed that a copy of the consent form will be given to me.

I certify that I am/am not (circle one) participating in another research project at this time, and have discussed the implications of such activity with the project investigators of this project. In consideration of this understanding, I voluntarily agree to participate in this research at CSC.

Print Name ______________________________

Date:____________ **Time** _____**AM** **Signed**______________________
PM **(subject)**

Witness ________________________ ______________________________
(person authorized to consent for subject, if required)*

***For subjects who may not be capable of providing informed consent the signature of a legal representative is required.**

I certify that I have personally overseen the completion of all blanks in this form and explained them to the subject or his/her representative before requesting the subject or his/her representative to sign it.

Signed______________________________ **Date:** ______________
(Signature of Project Director or his/her Authorized Representative)

Witness: ______________________________ **Date:** ______________

Location: ______________________________

____

____

____

____

7.3.4.6 Subject Consent to be Videotaped Form

Project # 303_1 (IRB 0004-1)

Video Consent

With your permission, you will be videotaped during each session of this research. Your personal information will not be recorded on the videotape and confidentiality will be strictly maintained. These tapes will be labeled only with a code number, which will be kept in the investigator's files. The videotapes will be kept in a secured cabinet by the Principal Investigator (PI) of this study. However, you should be aware that the showing of these videotapes may result in others being able to recognize you. These videotapes will be shown under PI's direction to the other investigators, associates, and other professionals.

The tapes will be used to support data analysis and to obtain brief excerpts and to illustrate Cybernet's findings in scientific publications or at professional meetings.

If you agree to participate in this study, your signature on this video consent form grants the investigator(s) permission to retain the videotapes for this purpose. However, you have the right to review the videotapes and to request that all or any portion of the tapes be erased.

I give permission to be videotaped for this research project, for the purposes of CSC research, and for presentations at scientific meetings under the conditions described.

Print Name ______________________________

______________________________ Signature ______________ Date

7.3.4.7 Results

This experiment had a pool of six (6) subjects. Complete data was not collected from Subject 2 because the subject requested the experiment be aborted part way through due to discomfort of the EEG cap. In subsequent experiments measures were taken to make the EEG cap more comfortable. With data from only 5 subjects it was deemed difficult to draw statistically significant conclusions. However, described below are the results from one subject which provide indications that there are potential psycho-physiological indicators of individual subject workload. In our analysis looked for potential indicators of cognitive workload based on frequency band analysis of the EEG and other measures. The following tables and figures show results and generalized indications from one particular subject. Similar trends were seen in other subjects.

Figure 80: Power Ratio Alpha/Beta

Electrode Pair	Easy Recall Task	Hard Recall Task	Slow Tracking Task	Fast Tracking Task
O2-P4	6.69	1.84	2.21	2.02
P3-P4	4.22	3.52	7.50	2.74
O1-P4	2.28	1.10	2.01	1.14
T6-P4	12.80	3.65	2.66	4.49
C4-P4	2.10	1.54	2.03	1.66

Figure 81: Power Ratio Theta/(Alpha+Beta)

Electrode Pair	Easy Recall Task	Hard Recall Task	Slow Tracking Task	Fast Tracking Task
O2-P4	0.56	0.55	0.49	0.82
P3-P4	0.14	0.13	0.12	0.32
O1-P4	0.44	0.26	0.41	0.32
T6-P4	0.86	1.15	1.83	1.57
C4-P4	0.43	0.49	0.48	0.57

Figure 82: Effect of Increased Workload in the Tracking Task

Parameter	Effect of increased workload	Comments
Beta / (Alpha + Theta)	Possible increase	Some electrodes
Beta / Theta	Possible increase	Some electrodes
Alpha / Beta	Decrease	
Left / Right – alpha, beta, delta	Possible decrease	
OP / CT - delta	Decrease	
Other parameters	No significant change	

Figure 83: Effect of Increased Workload in the Sternberg Task

Parameter	Effect of increased workload	Comments
Beta / (Alpha + Theta)	Increase	Except random cases (4, 5) and case of greatest # digits (3). May be due to two opposing effects.
Beta / Theta	Increase	Same as above
Alpha / Beta	Decrease	
Left / Right – Beta/(Alpha+Theta)	Possible decrease	
Left / Right - Beta/Theta	Large increase for fast presentation (case 8)	Others unchanged
OP / CT - Beta/(Alpha+Theta)	Decrease	
OP / CT - Beta/Theta	Large increase for fast presentation (case 8)	Others unchanged
Other parameters	No significant change	

Figure 84: Effect of Increased Workload in the Number Recall Task

Parameter	Effect of increased workload	Comments
Beta / (Alpha + Theta)	Increase	Strong effect due to increased # digits. Minimal effect due to timing demand.
Beta / Theta	Increase	
Alpha / Beta	Decrease	
Left / Right – %Beta	Decrease	Timing demand only
OP / CT -- % Gamma	Increase	
OP / CT -- % Beta	Decrease	Timing demand only
Other parameters	No significant change	

Workload rating for each task was assessed using subjective evaluation methods. The table below contains the results of the NASA TLX "Task Load Indicator" as determined from a subject's self-reported stress and workload levels. After an individual task, the subject is asked to rate the task and his performance based on a scale of 0-100 in terms of how important a particular factor was in performing successfully on that task. Weights of importance are computed, and a 'Total Workload' value is obtained. The higher this value, the greater the amount of cognitive workload the task placed on the subject. We have also provided a column for subject reported 'Stress' for comparison.

Figure 85: NASA TLX Results for Self-Evaluated Workload and Stress of Individual Tasks

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	STRESS
Weights	5	1	4	2	2	1		
STERNBERG 1	25	15	30	90	40	35	37	20
STERNBERG 2	45	37	43	80	43	51	48.73333333	35
STERNBERG 3	55	25	45	85	40	40	51.33333333	25
STERNBERG 4	45	30	60	80	30	40	50.33333333	25
STERNBERG 5	55	30	45	75	37	52	50.73333333	30
STERNBERG 6	55	30	60	80	40	60	56.33333333	45
STERNBERG 7	53	40	70	65	42	55	56.93333333	50
STERNBERG 8	45	40	80	90	55	51	61.73333333	55
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	2	1	3	4	0	5		
RECALL 1	10	20	25	80	25	40	42.33333333	35
RECALL 2	40	40	52	64	45	52	52.8	35
RECALL 3	70	55	82	25	90	95	67.73333333	65
RECALL 4	40	35	45	60	40	57	51.66666667	47
RECALL 5	46	34	52	62	48	58	54.66666667	43
RECALL 6	60	45	64	40	68	86	63.13333333	66
RECALL 7	65	53	62	44	72	87	65.33333333	75
RECALL 8	45	40	52	60	40	61	55.4	53
RECALL 9	52	41	61	71	59	47	56.46666667	52
RECALL 10	57	46	68	62	63	54	58.8	63
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	1	4	1	3	5	1		
TRACKING 1	15	25	25	90	55	5	46	5
TRACKING 2	15	15	15	97	24	34	35.66666667	7
TRACKING 3	26	34	25	82	35	25	42.2	8
TRACKING 4	8	8	14	98	15	7	28.66666667	7
TRACKING 5	13	20	14	93	14	15	31.4	13
TRACKING 6	23	30	22	78	33	19	38.86666667	19
TRACKING 7	46	49	36	57	52	58	51.13333333	41

For the following, slightly more detailed analysis, it is important to note that the task # (Recall 1, Recall 2, etc.…) indicates the relative difficulty: as the task number increases, the difficulty of the task increases as well.

The below figure demonstrates the total EEG Theta band power for all the listed tasks. It was indicative of all tasks to show repressed EEG power from baseline (non-moving, non-stimulated, eyes open). In the below example we can see that as difficulty increases in both the Recall and Tracking tasks, EEG Theta activity is further suppressed. Results for the Sternberg tasks may at first appear anomalous, but remember that Sternberg 1-3, 4 & 5, and 6-8 are separate sub-groupings. Looking at this we notice a decrease in activity across tasks 1-3, a stable level of activity for tasks 4 & 5 (our random cases), and decrease in activity for tasks 6-8.

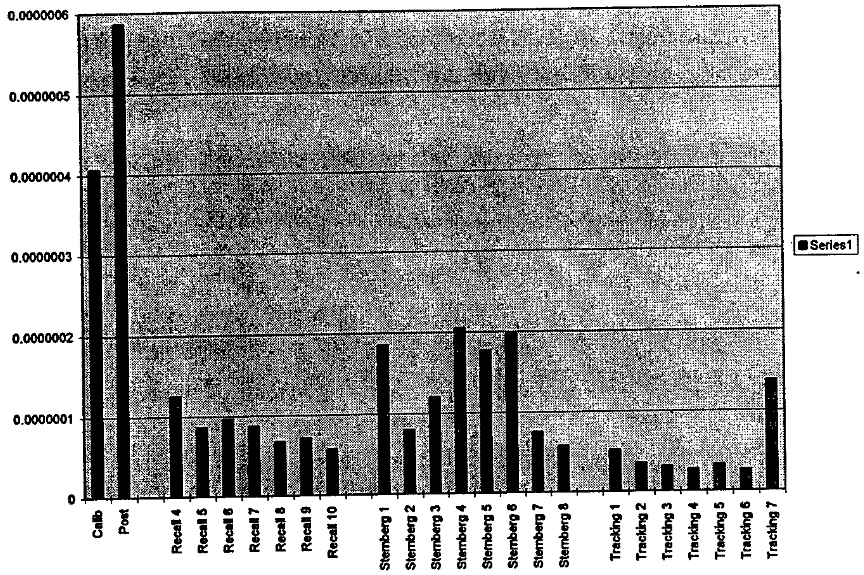


Figure 86: EEG Theta Band Power

The next figure below displays the % that the Theta band represents in terms of total EEG power. Here we can see similar trends to what was shown above. As workload increases for the Recall and Tracking tasks, Theta activity is suppressed. However, for the Sternberg tasks, as workload increases (tasks 1-5) % Theta increases. The interesting cases are Sternberg tasks 6-8, where % Theta activity decreases. These tasks increased workload by decreasing the amount of time the subject had in which to function. This suggests that mental workload due to cognitive factors, and mental workload due to time constraints may have separate physiological indicators. Tracking task 7 is considered to be anomalous, possibly caused by a poorly seated electrode or wire connection.

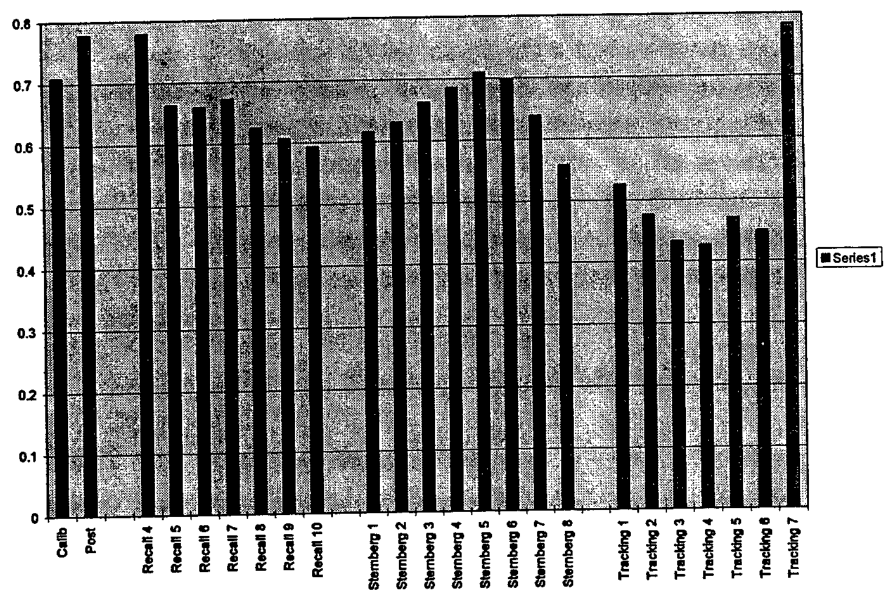


Figure 87: EEG %Theta Power

The figure below is a plot of heart rate Vs workload (for all tasks). You can see that there is a general trend for heart rate to increase as workload increases.

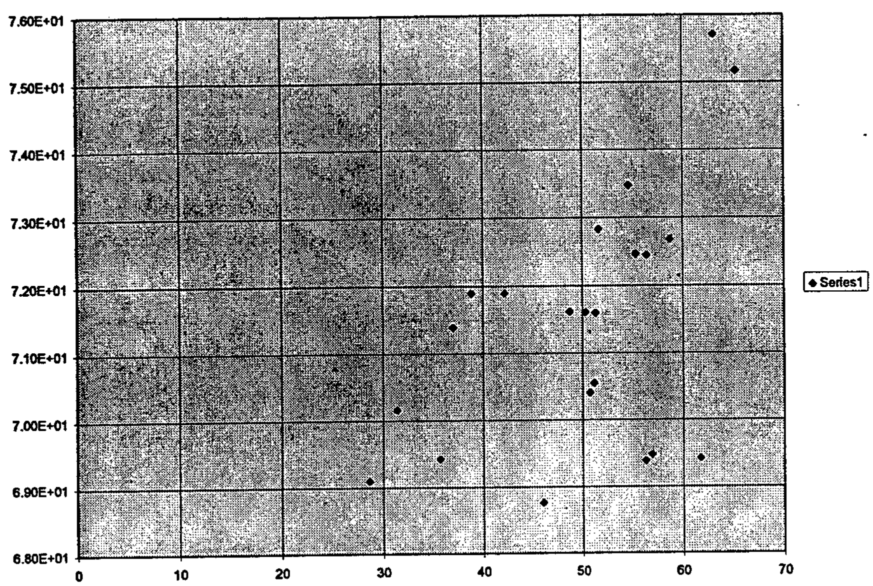


Figure 88: Heart Rate Vs Workload

7.3.4.8 Discussion

Because of the small subject pool, it was determined that there was not enough data collected to provide for any statistically valid conclusions. However, as the above selected results show, there are many potential indicators of cognitive workload.

The next step in a study of this sort would be to examine the data for the strongest possible indicators, then refine the experimental procedure for speed and enhanced data collection around those parameters. A collection of roughly 10 parameters would be chosen, along lines for strength of signal and repeatability across the subject pool. The experimental tasks provided in the next experiment should better reflect the workload parameters we are interested in examining, as well as producing the types of cognitive workload that we have determined are the most interesting to study.

7.3.5 Experiment 2 - Tetris, Reading, Mensa

7.3.5.1 Background

By varying cognitive workload, we can effect changes in Task Performance (for both cognitive and physical ability) and Physiological Measures. By varying physical workload, we can effect changes in Task Performance (for both cognitive and physical ability) and Physiological Measures. Having categorized these changes and resulting patterns, we can look for these changes and patterns as signs of degrading cognitive and physical performance. In addition, based on the parameters designed in the experiments, we can use our knowledge of those parameters to analyze specific work environments to provide a 'Degradation Number' to the environment. This 'Degradation Number' would be an indicator of how strongly that operational environment would adversely effect operator performance.

This experiment was developed both to provide the HPBMS with a comprehensive 'real' scenario under which to test the functionality of the system after upgrades and improvements had been made following the previous set of validation experiments. In keeping with the goals of the previous experiment, and building on the results of data analysis, new computer interface tasks (and other cognitive tasks) were developed for use. These new tasks would be more engaging both in terms of hand-eye activity as well as keeping the subject continuously cognitively challenged. They were designed to move away from the more memory related tasks of the first experiment.

Problems encountered with the previous set of tasks were that they were boring. Subjects indicated that their boredom and lack of cognitive enthusiasm was a possible contribution to errors.

7.3.5.2 Hardware Setup

This experiment required an enhanced version of the standard HPBMS. The additional hardware pieces were: video camera, extra TV and VCR pair (for recording and synchronizing the video camera output), and a computer and monitor on which to run the interface experiments. This computer served as the 'subject's station'. The 'subject's station' and 'experiment's station' has been explained previously.

The 16 channel physiological monitor was used to record 16 channels of EEG, and the 8 channel monitor was reserved for life signals and an event marker switch. For more information on the exact EEG and other signals monitored, please see the experimental procedure below.

7.3.5.3 Experimental Parameters

Experimental tasks can be designed along 3 major variables: time constraints, cognitive difficulty, and separation of attention (based on the number of tasks needing to be processed at a single time - multitasking).

While temporal constraints can greatly effect performance, in an effort to limit the number of variables present in the experiment, those constraints have been removed in favor of being able to more strongly characterize cognitive workload effects and separation and demands of attention. Several new tasks were introduced for this experiment. The following identifies the parameters of interest for these tasks.

<u>Tasks:</u>
Tetris

Gaze Location = where the subject is looking and how long they look at certain locations will be key in determining where their focus of attention is: preview box (cognitive functions), keyboard (physical functions), 'waterfall area' (cognitive functions).
Time = to task completion
Variables = # of games running simultaneously
# of lines to be completed in each Tetris screen
Importance values (for multiple game scenarios only)
Win Conditions = complete X number of lines in a single game
complete X number of lines in each of A simultaneously running games
Multiple games, where each has an importance value associated with it (completion of X
lines is the goal here as well)
Performance = number of lines completed vs. Importance value vs. Number of lines required

Brain Teasers (Mensa Test)
Gaze Location = given the nature of the task, gaze location could be irrelevant
Time = to complete the teaser
Variables = difficulty level of the puzzles
# of puzzles
Win Conditions = to solve the puzzle
Performance = time to complete the puzzle vs. Correctness vs. Puzzle difficulty

Phone Interruptions
Gaze Location = time spent looking at certain locations while engaged in conversation
Time = time is likely to be irrelevant in this task or time to write down the information supplied
Variables = number of calls per time period
amount of information asked or supplied for record
difficulty of information supplied or questions asked
length of time of phone calls
Win Conditions = to accurately record all information given over the phone
to accurately answer all questions asked over the phone
Performance = time to answer questions/record information vs. Correctness of answers or Accuracy of recording vs. Variability of calls

7.3.5.4 Procedure

The experimental procedure for this experiment was exactly the same as for the one previously described (see Section 7.3.4.4) with the exception that a different set of tasks was performed. The following outline describes the tasks that were performed:

<u>1. Collect data while the subject reads a passage of text ("ReadBase")</u>

The subject was asked to sit in a chair, relax, and read aloud the text on a sheet of paper. The passage took approximately 5 minutes to read

<u>2. Collect data while the subject performs the compensatory tracking task ("TrackBase")</u>

The subject performed the same tracking task seen in the previous set of experiments, using the default parameter values

<u>3. Collect data while the subject plays a game of Tetris ("TetrisBase")</u>

The subject played a single game of tetris (standard computer game involving the placement of falling bricks of different shapes and orientation). The task lasted as long as the subject could keep the game from ending.

<u>4. Collect data while the subject solves a set of brain teaser questions ("MensaBase")</u>

The subject was asked to answer as many of the questions correctly as possible within the alotted 10 minutes of time. They were not given any feedback as to how much time was remaining. The questions were taken from a Mensa Test Puzzle book.

<u>5. Collect data while the subject plays two simultaneous games of Tetris ("2Tetris")</u>

The subject played 2 games of Tetris at once with the goal of maximizing total score. The two screens of Tetris were setup on the screen side by side, with a 1cm gap between them. The subject had to use the mouse to switch control between the two screens. The task continued until both games were completed.

<u>6. Collect data while the subject manages multiple different tasks simultaneously ("Multask")</u>

This collection involved the simultaneous operation of a tracking task, a game of tetris, and the addition of interrupting phone calls that demanded cognitive attention. The phone calls arrived very 30 seconds (roughly) and the subject was required to answer the phone as quickly as possible and answer the question posed by the caller. Questions involved simple mathematical operations and recall of previously stated nonsense information. This tasks lasted a total of 6 minutes. If for some reason the Tetris game ended during this time, a new game was immediately begun and noted in the experiment log.

<u>7. Collect post experiment resting data ("PostMult")</u>

At the end of the experiment, 5 minutes of data was collected while the subject rested in a chair with eyes open.

7.3.6 Analysis

The experiment had a pool of three (3) subjects. Data was not collected from one of the subjects because the experiment was aborted due to system difficulties. Described below are the results from one subject which provide indications that there are physiological indicators of individual subject workload.
Below are a selection of some of the data plots used in the analysis which most strongly suggest physiological indicators that should be examined further in future experiments. The data for the subject playing two games of Tetris at once was lost due to a battery failure with the physiological monitors.

Below is a graph of the EEG channels in the Alpha frequency band. All levels are depressed from the reading task ('ReadBase') except for the brain teaser task ('Mensabase'). It is apparent that EEG in the Alpha band is related to strong cognitive workload - during the Mensa test, the most cognitive challenging of all the experimental tasks, EEG in the Alpha band was the highest. Following the trend from most cognitively challenging to the least, we find that 'Multask', with it's phone calls and questions was the next most challenging, then down to playing Tetris, and lastly to the Tracking task, which required no or little cognitive thought at all, being mostly a hand-eye coordination task.

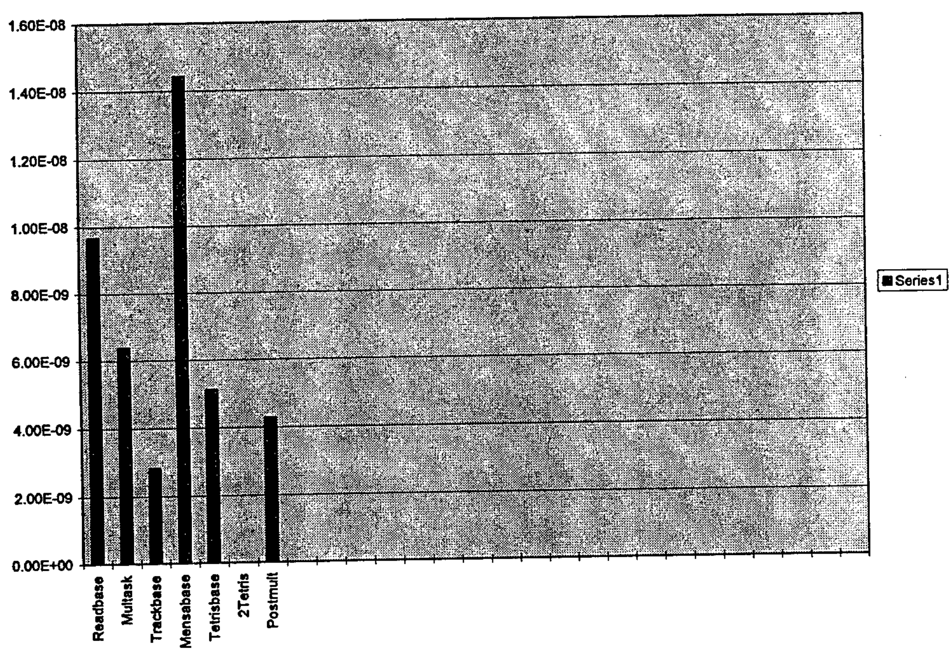


Figure 89: EEG Power Levels in the Alpha Band

This data demonstrates that in times of strong cognitive workload, the EEG Alpha band will likely be a strong indicator of that workload, and possibly even of cognitive burnout. (This would need to be evaluated in future experiments.)

The data plot below shows the subject's average heart rate across the different experimental trials. With an increase in task cognitive difficulty, the subject experiences an increased heart rate.

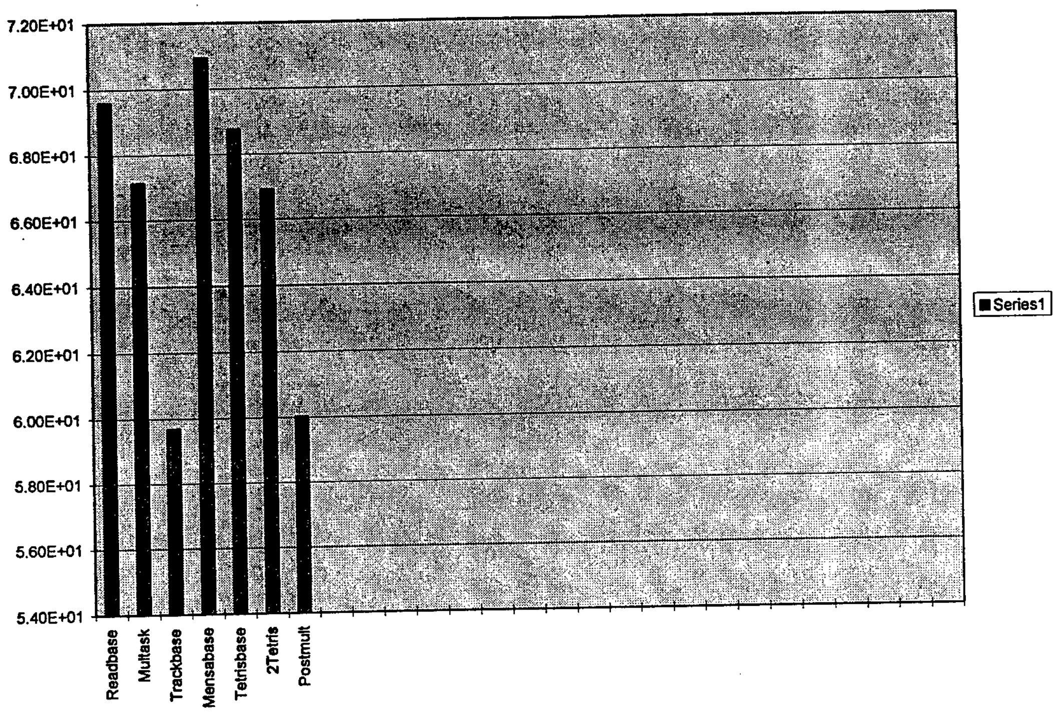


Figure 90: Subject Heart Rate

The table below contains the results of the NASA TLX "Task Load Indicator" as determined from a subject's self-reported stress and workload levels. After an individual task, the subject is asked to rate the task and his performance based on a scale of 0-100 in terms of how important a particular factor was in performing successfully on that task. Weights of importance are computed, and a 'Total Workload' value is obtained. The higher this value, the greater the amount of cognitive workload the task placed on the subject. We have also provided a column for subject reported 'Stress' for comparison.

	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	STRESS
Weights	3	0	1	5	4	2		
MULTASK ALL	92	22	68	91	90	73	87	54
MUL - TETRIS	91	5	34	83	83	63	78.66666667	33
MUL - PHONE	28	3	48	72	38	73	52.66666667	43
MUL - TRACK	28	8	48	64	48	43	48.66666667	17
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	4	0	2	5	3	1		
2 TETRIS	83	3	74	84	63	42	75.4	18
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	4	0	1	4	4	2		
MENSA	73	2	57	73	57	57	65.53333333	38
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	3	0	2	5	4	1		
BASE TETRIS	73	3	44	62	67	63	63.2	48
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	4	0	3	4	3	1		
BASE TRACK	24	2	12	13	12	4	14.93333333	4
	Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	TOTAL WORKLOAD	
Weights	5	0	2	3	4	1		
BASE READING	38	3	22	24	24	8	27.33333333	12

Figure 91: NASA TLX Index

7.3.7 Discussion

Because of the small subject pool, it was determined that there was not enough data collected to provide for any statistically valid conclusions. However, as the above selected results show, there exist potential indicators of cognitive workload.

The next step in a study of this sort would be to examine the data for the strongest possible indicators, then refine the experimental procedure for speed and enhanced data collection around those parameters. A collection of roughly 10 parameters would be chosen, along lines for strength of signal and repeatability across the subject pool. The experimental tasks provided in the next experiment should better reflect the workload parameters we are interested in examining, as well as producing the types of cognitive workload that we have determined are the most interesting to study.

7.3.8 Appendix of Experimental Questionnaires

7.3.8.1 Demographic Data Sheet

Project # 303_2 (IRB 0004-1)

ID: ____________________

Demographic Data Sheet
PERSONAL QUESTIONNAIRE

Please provide us with the following information, so that we can better evaluate our data and protocols. Circle the choice that applies:

Are you a willing volunteer for testing ?	**Yes**	**No**
Have you been a volunteer for an experiment before ?	**Yes**	**No**
Do you wear glasses and/or contacts ? If so, which one(s) ______________	**Yes**	**No**
Do you wear corrective lenses for reading ?	**Yes**	**No**
Are you void of all neurological disorders ? (i.e. epilepsy, Alzheimer's, etc.)	**Yes**	**No**
Are you pregnant (females only) ?	**Yes**	**No**
Do you have any allergy to alcohol or tape ?	**Yes**	**No**
Eye Dominance (if not known leave blank)	**left**	**right**

Have you recently hurt or injured any of the following? (Circle all that apply):

Left Hand	Right Hand	Legs	Head	Neck
Left Arm	Right Arm	Back	Eyes	Chest/Torso

Age ____

Years Computer Experience:

0 **1-3** **3-5** **5+**

Highest Degree Attained

H.S. Diploma
Bachelors Degree
Masters Degree
Ph.D.
Post-doctorate
M.D.
None

7.3.8.2 Satisfaction Survey

Project # 303_1 (IRB 0004-1)

Satisfaction Survey

Please help us evaluate our procedures by answering some questions about your experience. We are interested in your honest answers both positive or negative. Your name will be kept confidential we are looking at overall feedback and not individual responses. Please do not put your name on this form.

Circle the response that best fits your answer to the following questions:

1. How satisfied were you with the topics covered by the consent form and investigators?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

2. How satisfied were you with the amount of information supplied to you?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

3. How difficult was it for you to remain comfortable during testing?

- Very Difficult
- Somewhat Difficult
- OK
- Pretty Easy
- Not a Problem

4. How satisfied were you with the availability of staff when you needed help?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

5. Please rate your satisfaction with the investigator(s) in each of the following areas.

5a. Knowledge of the subject

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

5b. Preparation

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

6. Were you treated with courtesy and respect by CSC?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

7. How satisfied were you with the sensitivity of maintaining confidentiality?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

8. Generally, how satisfied were you with the helpfulness of this procedure in answering all your questions?

- Very Satisfied
- Somewhat Satisfied
- Neither
- Slightly Dissatisfied
- Very Dissatisfied

9. How many of the things you've learned through this study do you think you will use in everyday life?

- Most
- Some
- Only a Few
- None
- Don't Know

10. How much did you enjoy doing the experiment?

- Really Enjoyed
- Somewhat Enjoyed
- Neutral
- Did Not Enjoy
- Really Did Not Enjoy

10. Overall, was your visit to CSC a positive one?

- Very Positive
- Somewhat Positive
- Neutral
- Slightly Negative
- Very Negative

11. The thing I like best about the procedure is:

12. One thing I would change about the procedure is:

13. Additional comments about the procedure:

7.3.8.3 Long Form Self Report

Project # 303_1 (IRB 0004-1)

Long Form Self Report

ID: ____________________
PRE-EXPERIMENT

Please complete this form either answering the questions or placing an "X" on the measuring bars.

My PHYSICAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My MENTAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My OVERALL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

Please rate your overall stress level:

Low 10 20 30 40 50 60 70 80 90 High

The most tired/strained part of my body right now is (please circle one):

eyes head left arm right arm legs

left hand right hand chest stomach not really tired/strained

How comfortable are you in the following regions right now?
Head

Low 10 20 30 40 50 60 70 80 90 High

Arms

Low 10 20 30 40 50 60 70 80 90 High

Chest/Torso

Low 10 20 30 40 50 60 70 80 90 High

Legs

Low 10 20 30 40 50 60 70 80 90 High

Project # 303_1 (IRB 0004-1)

Long Form Self Report

ID: ____________________

POST-EXPERIMENT

Please complete this form either answering the questions or placing an "X" on the measuring bars.

My PHYSICAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My MENTAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My OVERALL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

Please rate your overall stress level:

Low 10 20 30 40 50 60 70 80 90 High

The most tired/strained part of my body right now is (please circle one):

eyes head left arm right arm legs

left hand right hand chest stomach not really tired/strained

How comfortable are you in the following regions right now?

Head

Low 10 20 30 40 50 60 70 80 90 High

Arms

Low 10 20 30 40 50 60 70 80 90 High

Chest/Torso

Low 10 20 30 40 50 60 70 80 90 High

Legs

Low 10 20 30 40 50 60 70 80 90 High

Project # 303_1 (IRB 0004-1)

Long Form Self Report

ID: ____________________

DEBRIEFING

Please complete this form either answering the questions or placing an "X" on the measuring bars.

My PHYSICAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My MENTAL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

My OVERALL fatigue is:

Low 10 20 30 40 50 60 70 80 90 High

Please rate your overall stress level:

Low 10 20 30 40 50 60 70 80 90 High

The most tired/strained part of my body right now is (please circle one):

eyes **head** **left arm** **right arm** **legs**

left hand **right hand** **chest** **stomach** **not really tired/strained**

How comfortable are you in the following regions right now?

Head

Low 10 20 30 40 50 60 70 80 90 High

Arms

Low 10 20 30 40 50 60 70 80 90 High

Chest/Torso

Low 10 20 30 40 50 60 70 80 90 High

Legs

Low 10 20 30 40 50 60 70 80 90 High

7.3.8.4 Short Form Self Report

(Note that for every experimental configuration, the subject was afterwards asked to fill out this form. The section listed under ID, currently 'STERNBERG 1' was changed to indicate the appropriate experimental trial.)

Project # 303_2 (IRB 0004-1)

Short Form Self Report

ID: ____________________
STERNBERG 1

Please rate the computer task by placing an "X" on the line that reflects the level of demand for each workload sub-category.

Mental Demand

Low 10 20 30 40 50 60 70 80 90 High

Physical Demand

Low 10 20 30 40 50 60 70 80 90 High

Temporal Demand

Low 10 20 30 40 50 60 70 80 90 High

Performance

Low 10 20 30 40 50 60 70 80 90 High

Effort

Low 10 20 30 40 50 60 70 80 90 High

Frustration

Low 10 20 30 40 50 60 70 80 90 High

Stress

Low 10 20 30 40 50 60 70 80 90 High

How bored were you with the previous task?

Not Bored 10 20 30 40 50 60 70 80 90 Very Bored

7.3.8.5 Task Form Self Report

Project # 303_1 (IRB 0004-1)

Task Form Self Report

ID: ____________________
STERNBERG

Please circle which scale was a more important contributor to workload for you in the previous computer tasks:

1. **Mental Demands** or **Frustration**
2. **Mental Demands** or **Performance**
3. **Mental Demands** or **Effort**
4. **Temporal Demands** or **Frustration**
5. **Physical Demands** or **Performance**
6. **Performance** or **Effort**
7. **Temporal Demands** or **Mental Demands**
8. **Physical Demands** or **Temporal Demands**
9. **Mental Demands** or **Physical Demands**
10. **Performance** or **Frustration**
11. **Physical Demands** or **Effort**
12. **Effort** or **Frustration**
13. **Temporal Demands** or **Performance**
14. **Physical Demands** or **Frustration**
15. **Temporal Demands** or **Effort**

How bored were you with the previous set of tasks?

Not Bored 10 20 30 40 50 60 70 80 90 Very Bored

Project # 303_1 (IRB 0004-1)

Task Form Self Report

ID: ____________________

RECALL

Please circle which scale was a more important contributor to workload for you in the previous computer tasks:

1. **Mental Demands** or **Frustration**
2. **Mental Demands** or **Performance**
3. **Mental Demands** or **Effort**
4. **Temporal Demands** or **Frustration**
5. **Physical Demands** or **Performance**
6. **Performance** or **Effort**
7. **Temporal Demands** or **Mental Demands**
8. **Physical Demands** or **Temporal Demands**
9. **Mental Demands** or **Physical Demands**
10. **Performance** or **Frustration**
11. **Physical Demands** or **Effort**
12. **Effort** or **Frustration**
13. **Temporal Demands** or **Performance**
14. **Physical Demands** or **Frustration**
15. **Temporal Demands** or **Effort**

How bored were you with the previous set of tasks?

Not Bored 10 20 30 40 50 60 70 80 90 Very Bored

Project # 303_1 (IRB 0004-1)

Task Form Self Report

ID: ____________________

TRACKING

Please circle which scale was a more important contributor to workload for you in the previous computer tasks:

1. **Mental Demands or Frustration**
2. **Mental Demands or Performance**
3. **Mental Demands or Effort**
4. **Temporal Demands or Frustration**
5. **Physical Demands or Performance**
6. **Performance or Effort**
7. **Temporal Demands or Mental Demands**
8. **Physical Demands or Temporal Demands**
9. **Mental Demands or Physical Demands**
10. **Performance or Frustration**
11. **Physical Demands or Effort**
12. **Effort or Frustration**
13. **Temporal Demands or Performance**
14. **Physical Demands or Frustration**
15. **Temporal Demands or Effort**

How bored were you with the previous set of tasks?

Not Bored 10 20 30 40 50 60 70 80 90 Very Bored

8. Future Opportunities

This Phase II effort produced a system and validated methodology for the comprehensive assessment of human performance in a wide range of human operator task environments. Now that this unique tool is available, there are extensive opportunities for further research, scientific study, and development. The developed system can facilitate research protocols and studies that were previously difficult, awkward, or ineffective. This is particularly true with regard to the combined, synchronized measurement of different types of performance related parameters. For instance, the ability to acquire brain wave activity and eye tracking data within an integrated, synchronized data collection system will be of tremendous value for a wide array of cognitive research studies.

Continued research and development efforts could help support the establishment and setup of new experimental protocols that take advantage of the developed system. Given, the focused goal of such an experiment, the system could be enhanced and tailored to meet very specific needs of the targeted protocol. For example, additional signal viewers, data analysis functions, and other custom "add-on" features can be readily developed to tailor the system performance to a given study or application. Cybernet has the expertise to support the establishment and execution of research protocols using the developed human performance measurement system.

In addition, there is significant opportunity to produce commercial products from the developed technology. Each individual component of the human performance based measurement system has product development plans already underway. For instance, the eye tracking technology is being integrated into a head-mounted display (along with voice recognition) for hand-free control of a wearable computer interface. The eye tracking technology also has product potential for medical applications. Furthermore, the physiological measurement system technology and related software is part of Cybernet's business plan for bringing medical data monitoring applications to the Internet.

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