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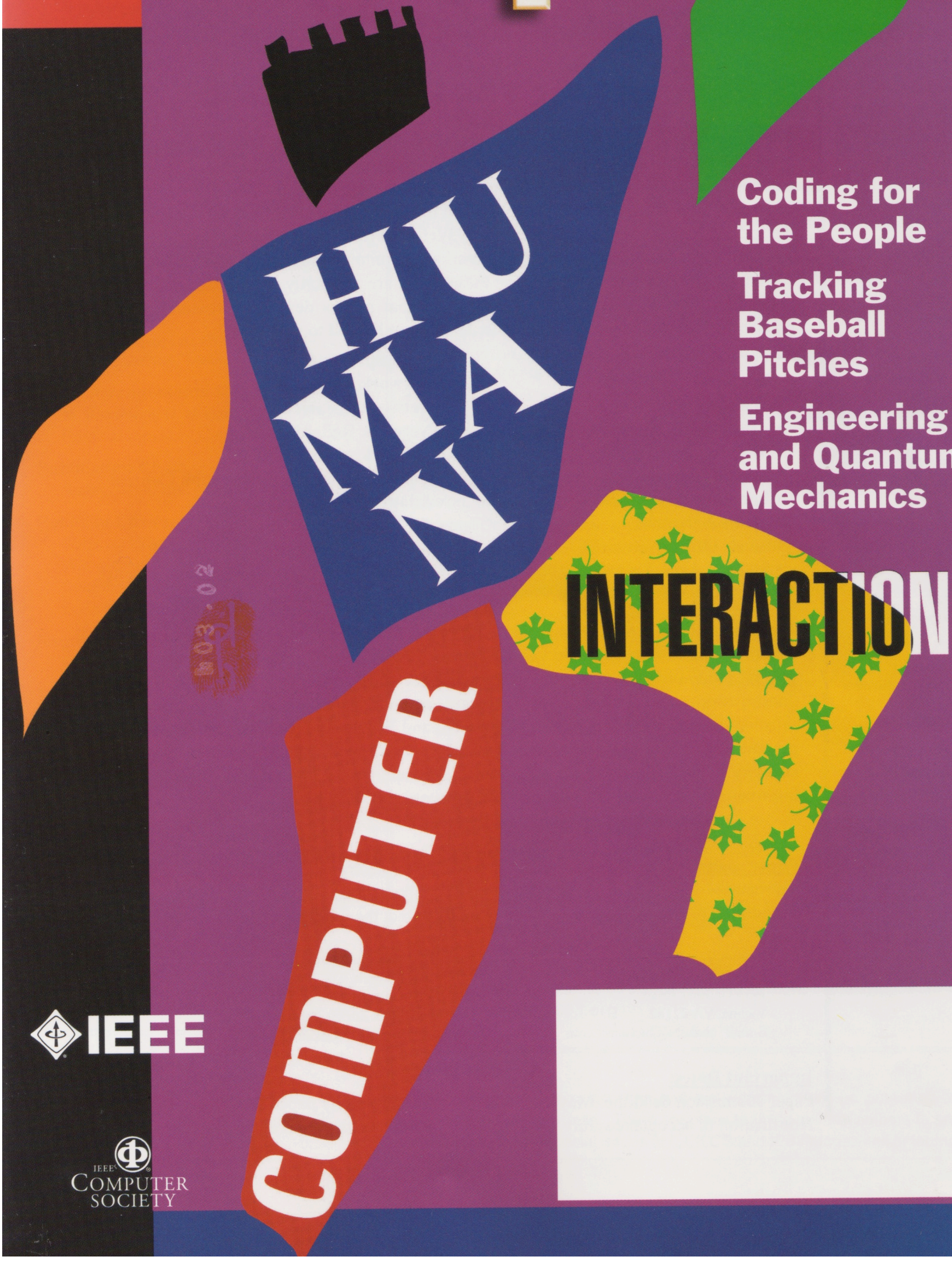

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Electrophysiologically Interactive Computer Systems

Combining computing with physiological sensing technologies will transform human-machine interaction and usher in a wide range of new applications.

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Interactive systems research is beginning to breach the barrier between human and machine. Direct brain-computer communication is an emerging reality, subject to its own research agenda,[1] and researchers are developing intelligent, affective technologies that will allow computers to comprehend and respond to users' changing emotional states.[2] Advanced sensing capabilities facilitate these emerging applications, which are evolving beyond deliberate user manipulation of electromechanical devices to employ an increasingly important computer input source—subtle human physiology.

Throughout the twentieth century, medical engineers developed technologies to gain access to the subtle echoes of the human body's internal workings. Modern physiological data detection relies on the direct application of sensors to the body's surface. Different sensors collect various types of data, such as heart and respiration rates, peripheral body temperature, skin conductance, muscle contraction, and electrical brain activity. Transduction, amplification, and filtering of detected physiological signals provide a useful data stream for a wide range of exciting interactive applications.

EPICS

As Figure 1 shows, electrophysiologically interactive computer systems (EpICS) combine physiological sensing technologies with interactive computer applications. These systems support a diverse range of monitoring and training disciplines including systems design and evaluation, medical diagnostics and rehabilitation, hazardous awareness monitoring, psychophysiological conditioning, dynamic interface reconfiguration, and affective computing. EpICS provide interesting usability metrics and form the backbone of brain-computer interfaces, prosthetics, and other hands-free control technologies.

We have identified two basic EpIC systems. Monitoring EpICS quantify or measure an electrophysiological signal of interest against some scale. Examples include the direct measurement of blood pressure or body temperature or continuous monitoring of heart rate, respiration rate, or brain activity over a specified period of time. Training EpICS feed back physiological information to a subject in real time to enable operant conditioning or instrumental learning of control to occur—a process commonly known as biofeedback.

Monitoring EpICS

Monitoring EpICS are open-loop systems that detect physiological information from a subject and relay it to a human expert or a computer with advanced processing capabilities for analysis. Affective computers[2]—literally, systems that know how users feel—are one exciting application of integrated monitoring technologies. Developing sys-

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tems that display intelligent behavior has long been a goal in artificial intelligence research. Daniel Goleman's[3] thesis that largely unconscious emotional cues influence intelligent human-to-human exchanges has led MIT researchers to consider how to augment computers to gather user data from which they can deduce emotional status. Physiological parameters that are good indicators of arousal, such as heart rate and skin conductance, are proving to be integral data sources for emotional-state-related interactive computer systems.

Identifying optimal mixes of operator and system functionality is a vital part of many control systems' interfaces. Cognitive psychologists involved in the design and evaluation of such interfaces have developed a suite of techniques for assessing the amount of mental effort involved in performing operational tasks. Researchers have been monitoring physiological characteristics known to be responsive to cognitive loading since the late 1980s. However, the cumbersome nature of existing monitoring equipment has limited practical use of this evaluation tool to the laboratory setting—not ideal for applications such as testing the effects of a flight deck on users during the course of normal operation.

The ability to continually observe the physiologic reactions of system operators such as automobile drivers, pilots, and assembly line workers is one useful application of monitoring EpICS. Most forms of modern, computer-rich transportation are configured to rely, to some extent, on human operators to perform tasks vital to their continued safe operation. A system with embedded monitoring capabilities could automatically react if its human operator became incapacitated.

Psychological states such as stress, high anxiety, boredom, absorption, fatigue, or inattention can be detrimental to performance and potentially dangerous. NASA's Alan Pope[4] and his team are developing integrated monitoring systems to help identify the physiological signatures of these and other *hazardous awareness states*. We know that the experience of stress and anxiety for prolonged periods of time has a profound and detrimental impact on the health and well-being of the developed world's population. New physiological detection technologies let individuals use personal computing devices to passively monitor stress responses.

Training EpICS

In contrast to monitoring EpICS, training EpICS are closed-loop biofeedback systems that detect physiological changes and relay them back to the subject audibly or visibly in real time. The interfaces to physical rehabilitation biofeedback systems, for example, amplify weak muscle signals, encouraging patients to persevere when there is no visible physical response to therapy. Interfaces to existing biofeedback applications range from interactive 2D graphical tasks—in which muscle signals, for example, are amplified and transformed into control tasks such as lifting a virtual dumbbell—to real-world physical tasks such as manipulating radio-controlled toys.[5]

Beyond physical therapy, healthcare providers are increasingly using brain-wave biofeedback or neurofeedback as part of the treatment of a growing range of psychophysiological disorders such as attention deficit/hyperactivity disorder (ADHD), post-traumatic stress disorder, addictions, anxiety, and depression. In these applications, surface-mounted electrodes detect the brain's electrical activity, and the resulting electroencephalogram (EEG) is presented in real time as abstract images. Using this data in reward/response-based control tasks generates increased or reduced activity in different aspects of the EEG spectrum to help ameliorate these psychophysiological disorders.

Biofeedback also is playing an increasingly important role in more mainstream computer applications, including hands-free human-machine interaction.[6] The most obvious use of such technology is to help disabled individuals interact with their environment. Advanced prosthetic arms, for example, are electrophysiological interactive com-

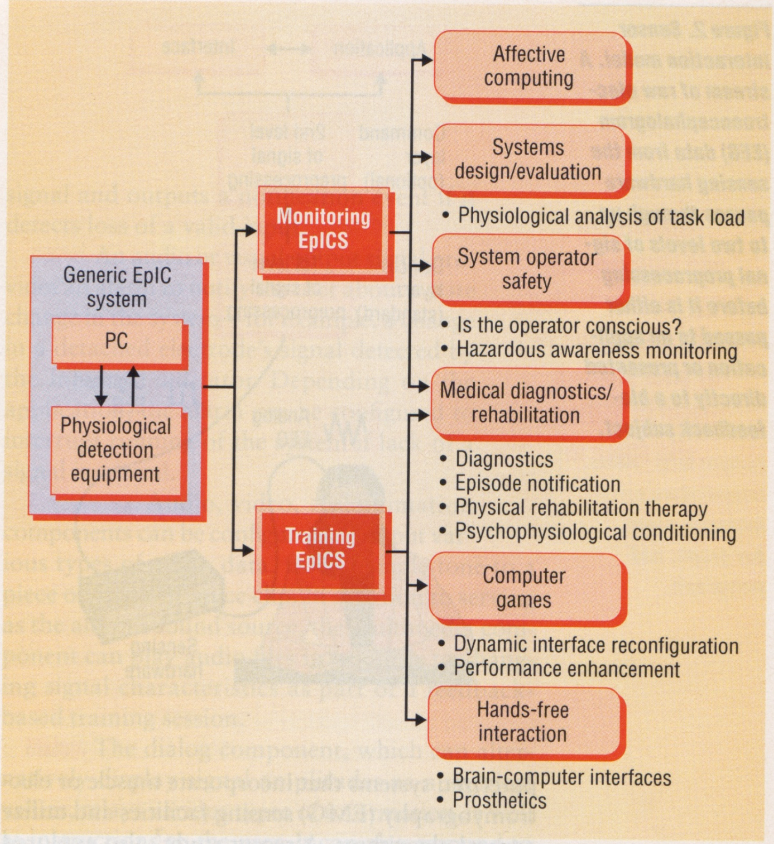

Figure 1. Electrophysiologically interactive computer systems. EpICS collect information regarding a subject's physiological functioning and make it available in real time to a computer system.

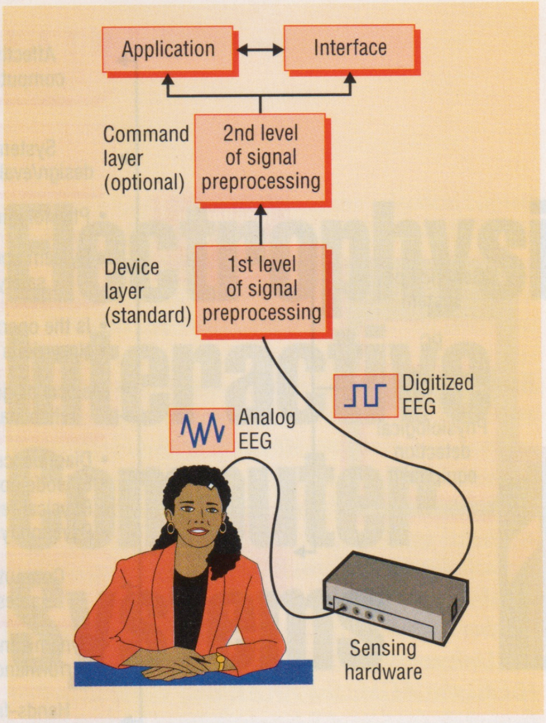

Figure 2. Sensor interaction model. A stream of raw electroencephalogram (EEG) data from the sensing hardware passes through up to two levels of signal preprocessing before it is either passed to an application or presented directly to a biofeedback subject.

puterized systems that incorporate muscle or electromyography (EMG) sensing facilities and utilize control algorithms. A recent study[7] also explored the use of EMG feedback as a means of providing interaction in mobile computing applications. Computer games are currently an engaging interface technique for therapeutic neurofeedback, and the potential for enriching computer game play with biofeedback information is clear.

SUPPORTING EPICS DEVELOPMENT

As with other classes of interactive systems, the lack of available development support tools has limited research into human-machine interaction based on detectable physiological information. Therefore, we undertook development of a set of components to collect signals from physiological sensing hardware and use them to drive various applications.

Sensor interaction model

Due to their ad hoc nature, the EpICS available when we undertook our project three years ago did not clearly separate user interfaces from the underlying applications. Because development tools for a particular class of interactive system are usually based on one or more conceptual models of interaction appropriate to that system class, our first task was to identify a high-level model for EpICS. Our original inspiration was Grant R. McMillan's structural coupling paradigm for nonconventional controllers,[8] from which we derived the model shown in Figure 2.

The generic sensing hardware can consist of any number of actual physiological sensors. Some commercial devices detect data corresponding to a single physiological parameter, while other, multichannel, devices simultaneously detect and relay multiple parameters. A certain amount of primary preprocessing of physiological signals occurs within the hardware itself—thus, for example, a blood pressure monitor converts physical pressure from an air-filled cuff into electrical pressure. Transduction is followed by amplification of the signal, analog-to-digital signal conversion, and feature extraction. This last stage is achieved through hardware and software filtering.

In our model, software support for primary signal preprocessing resides on the *device layer* along with the capabilities for retrieving data from the hardware itself. It is important that the level of preprocessing be specific to the sensing hardware used.

Applications that use physiological signals as interaction parameters require further processing of signal streams to determine what, if any, action to take based on the signals' current state. For example, sophisticated brain-computer control-specific EpICS rely on neural networks or other adaptive algorithms to process EEG components in a bid to recognize particular thoughts or actions the system could use as control commands. However, this level of signal processing is not a requirement of all sensing-based applications. In biofeedback-based systems, for example, the first level of signal processing provides data in a format suitable to that particular application's interface. A second *command layer* is thus optional. Once the system has preprocessed the signals, it passes them on either directly to the interface or to become part of a larger, multimodal application.

Development tools

Once we had identified an interaction model, we were ready to design our development support tools. We decided that the most flexible solution would be component based and use an existing set of tools. Our components would monitor and present electrophysiological signals and also exploit the signals to cause interaction with other applications.

Our toolkit consists of a set of components developed as individual JavaBeans atop a PC-based multichannel physiological sensing device with a Windows interface, manufactured by MindPeak (http://www.mindpeak.com/index.html). This is a five-channel device suitable for detecting any combination of heart, brain, muscle, and skin conductivity data. A dynamic link library, equivalent to our model's device layer, provides access to the device's functionality. A Java/native translation layer between the JavaBeans and the biofeedback hardware ensures the independence of implemented components. Thus, using our toolkit with another physiological sensing device would only require replacing the software device layer.

The toolkit, which is available online along with related development software (http://www.comp.lancs.ac.uk/computing/users/allanson/web/EpICSProject/), includes the following components.

Polygraph. Both monitoring and training EpICS traditionally present physiological signal data as real-time polygraphic traces. The polygraph component dynamically plots a trace for each data stream, which signifies a signal's changing amplitude.

Bar graph. Viewing combinations of signals is desirable in certain clinical biofeedback applications. For example, ADHD training protocols can involve simultaneous training of multiple bands of activity filtered out of a stream of EEG data. The bar graph component can display any combination of physiological signals. The height of each bar changes in real time in direct response to its associated signal's changing amplitude.

Graduated scale. A sliding pointer moves along a graduated scale to represent the amplitude value of a single EEG or other signal.

Slider. A sliding scale allows visually setting data values. For example, if a given physiological signal is serving as a switch, this slider can indicate the threshold—the amplitude value above and below which the switch state changes from off to on.

Switches. The system sets a switch when the signal amplitude rises above the threshold value. A latching switch is unset when the amplitude drops below this value and rises above it once again; a nonlatching switch is unset as soon as the signal drops below the threshold value.

Timer. Clinical EEG feedback training may encourage a subject to raise a signal's amplitude and maintain it for as long as possible. To emulate this, we added a timer component that inputs notification events, such as a signal's amplitude going above its threshold. Another event, such as the signal amplitude dropping below its threshold, will subsequently stop the timer. The timer also outputs notification events to indicate when it has been started and when it has stopped.

Integrity indicator. Determining whether input signals from the physiological sensing hardware are valid is necessary to maintain system integrity. Commercial systems rely on a user to spot when an electrode has become displaced and a signal lost. An integrity indicator periodically checks a signal and outputs a notification event if it detects loss of a valid input.

Alarm. An audio or visual output signal provides an alarm to notify the user about a state change in the system—for example, a change in a detached electrode's signal detected by the integrity indicator. Depending on the application, the alarm can be configured to interrupt running of the system if lack of a signal is critical.

Multimedia. Audio, video, and animation components can be configured to output various types of audio data, from a single tone to a piece of music or voice clip. In addition to serving as the alarm's sound source, the multimedia component can play audio files in response to changing signal characteristics as part of a feedback-based training session.

Dialog. The dialog component, which can alternatively display signal amplitudes as numerical values, relays various types of information as well as instructions to the user. It can also respond to integrity indicator notification events and other instances requiring information about the occurrence of some error.

3D environment. A simple 3D environment visualizes objects that respond to changes in physiological data.

Archiving. This component retrieves signals as a stream of data values and then writes them out to a text file. The system compiles the archived signal data into a list of comma-separated value pairs that correspond to a time stamp added by the archiving component and a floating-point number that represents the signal data point's magnitude value. This formatting enables direct importation of an archived file into a data analysis package such as Microsoft Excel.

Input/output. All components used in a training or application environment register interest in one or more physiological data signals. The I/O component processes the data it receives from the sensing hardware and notifies components when it receives a signal in which they have registered interest.

Multimedia components can output various types of audio data, from a single tone to a piece of music or voice clip.

CREATING EPICS

To assess our toolkit's suitability for supporting EpICS development, we used it to prototype and build a real-world application—a training system for a controlled psychological investigation into the role of signal presentation in EMG biofeedback.[9] As part of an ongoing study by members of Lancaster University's Psychology Department into strategies for avoiding the onset of migraine

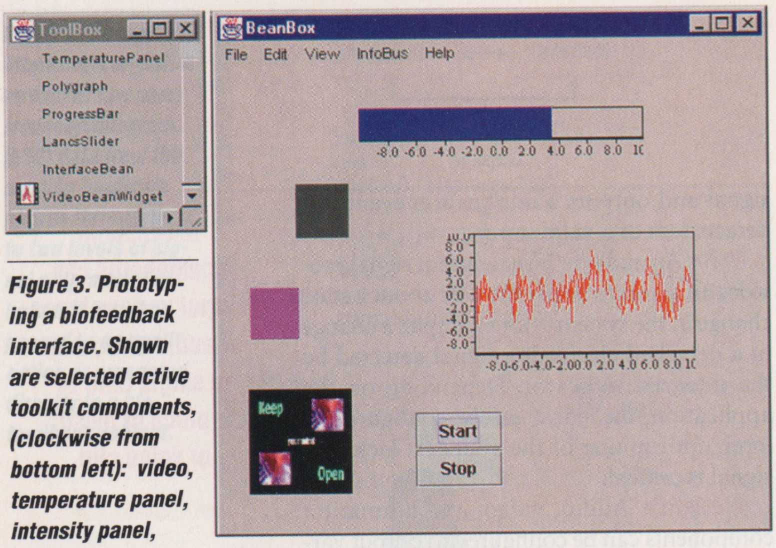

Figure 3. Prototyping a biofeedback interface. Shown are selected active toolkit components, (clockwise from bottom left): video, temperature panel, intensity panel, bar graph, and polygraph.

headaches, the application was designed to train individuals to reduce forehead muscle tension. The study's aim was to evaluate whether providing subjects with information about their current level of forehead muscle tension helped them learn how to relax those muscles more quickly or deeply than if they had received no feedback.

Prototyping interactive systems can be expensive, so we wanted to demonstrate that using the components was easy as well as rapid. We developed the components as JavaBeans, which can be introspected to make their methods explicit within a graphical environment such as Sun Microsystems' BeanBox (http://java.sun.com/products/javabeans/software/beanbox.html#top). As Figure 3 shows, we dragged the interface components into the BeanBox and graphically wired them together. We then connected the components to the sensing hardware using the input/output component. Once this connection is established, physiological data flows from the sensing device to the interface components, and they respond according to their predefined functionality.

By having someone unfamiliar with the toolkit's design and development—in this case, the psychologist in charge of the study—use the application, we hoped to establish the components' robustness. With the psychologist's input, it took approximately 5 minutes to construct a functional prototype of the biofeedback interface. The lead psychologist was particularly interested in

- the display options for feeding back EMG signal data to a subject;
- the effect of various timer intervals on the different display options; and
- support for archiving and data analysis.

The presence of a running simulation fueled discussion about other potential interface configurations, establishing further display requirements.

The study involved three groups of individuals. The control group received no physiological signal feedback information. A second group received audio feedback about the current level of tension in the forehead muscle group. One of the prototype's audio components presented the frontalis EMG signal's amplitude as a continuous tone, the pitch of which increased and decreased in relation to changes in muscle tension. The third group received visual feedback. Avoiding a traditional polygraphical representation, the study director chose the more abstract signal representation the prototype's 3D environment provided, with a levitating block corresponding to forehead EMG signal amplitude.

The changing characteristics of all participants' frontalis EMG signals were continuously monitored throughout each training session. The toolkit's archiving component stored the data for later offline analysis using a standard spreadsheet package. Wired subjects who were left alone to learn to use the feedback information to control the level of tension in their frontalis muscles experienced no difficulties understanding or using the system.

At the study's conclusion, the psychologist in charge indicated his satisfaction with the application, which he used unsupervised and without technical assistance. He especially liked the toolkit's flexibility in signal presentation, including the ability to present signal feedback within a 3D virtual environment. As one biofeedback proponent[10] acknowledges, however, individuals have definite preferences for presenting physiological information that may lead to differences in training outcomes. This is a subject still awaiting investigation.

The development of electrophysiologically interactive computer systems will enable creation of truly personal computers—systems that read and understand their users' signatory physiology. EpICS will transform our interactions with machines as well as help us learn more about our psychophysiological selves. Our work demonstrates that creating such systems is fairly easy with the right kind of support. The sensor interaction model we adopted was quite general, and the components we developed required no more than a desktop PC and off-the-shelf sensing devices.

The interfaces we can build have thus far been limited to generic EpICS applications that incorporate only basic signal preprocessing. At present we are establishing the requirements of as wide a range of potential sensors as possible with a view to providing software support for integrating different combinations of sensors into interactive applications. Our hope is that this will enrich those tools involved in advanced, second-level signal preprocessing. In addition, we are extending the components to support development of one specific EpICS application—biofeedback-based direct brain-computer interaction—in conjunction with researchers in the Department of Cognitive Neuroscience and Behaviour at London's Imperial College School of Medicine. ■

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