# A General Framework for Brain–Computer Interface Design

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***Abstract*—The Brain–Computer Interface (BCI) research community has acknowledged that researchers are experiencing difficulties when they try to compare the BCI techniques described in the literature. In response to this situation, the community has stressed the need for objective methods to compare BCI technologies. Suggested improvements have included the development and use of benchmark applications and standard data sets. However, as a young, multidisciplinary research field, the BCI community lacks a common vocabulary. As a result, this deficiency leads to poor intergroup communication, which hinders the development of the desired methods of comparison. One of the principle reasons for the lack of common vocabulary is the absence of a common functional model of a BCI System. This paper proposes a new functional model for BCI System design. The model supports many features that facilitate the comparison of BCI technologies with other BCI and non-BCI user interface technologies. From this model, taxonomy for BCI System design is developed. Together the model and taxonomy are considered a general framework for BCI System design. The representational power of the proposed framework was evaluated by applying it to a set of existing BCI technologies. The framework could effectively describe all of the BCI System designs tested.**

***Index Terms*—Assistive technology, brain–computer interface (BCI), direct-brain interface (DBI), EEG, framework, functional model, taxonomy.**

## I. INTRODUCTION

THE CONCEPT of a direct Brain–Computer Interface (BCI) has emerged over the last three decades of research as a promising alternative to existing interface methods. The ultimate goal of this research is to create a specialized interface that will allow an individual with severe motor disabilities to have effective control of devices such as computers, speech synthesizers, assistive appliances, and neural prostheses. This type of interface would increase an individual's independence, leading to an improved quality of life and reduced social costs.

BCI research is a multidisciplinary field integrating researchers from neuroscience, physiology, psychology, engineering, computer science, rehabilitation, and other technical and health-care disciplines. As a result, there have been several varied approaches to the design of BCIs reported over the last three decades.

The variance in BCI designs was seen in the range of technologies presented at the First International Meeting of Brain–Computer Interface Technology [1]. In a review of this meeting [2], Wolpaw *et al.* emphasized that many attendees had difficulty comparing existing BCI technologies. They concluded that the development of objective methods for comparing BCI designs and evaluations was essential for fostering further development and for synchronizing multinational collaborative research programs. However, the terms used to describe BCI designs (as seen in [1] and [3]) are diverse and inconsistently used among different research groups. This lack of common language impedes the development of objective methods of comparison. There is, therefore, a critical need for a common vocabulary. Such a development would greatly aid intergroup communication and would facilitate the development of standard objective methods of comparison.

One of the principle reasons for the lack of common vocabulary is the absence of a common functional model of a BCI System.[1] Although a consensus among researchers for the need of a functional model is not well documented, the issue is generally recognized in the scientific community. Such a model could be an important reference, not only for researcher-to-researcher interaction, but also for communication to persons in related fields and professions.

This paper proposes a new functional model for BCI System design. The new model is presented in Section II, along with several comments related to its application. From this model, taxonomy for BCI System design is proposed in Section III. Together, the model and taxonomy represent a general design framework for BCI Systems. In Section IV, the representational power of the framework is demonstrated when it is applied to a selection of published BCI System designs. The value of the model and suggestions for future developments are summarized in Section V.

The proposed framework has evolved from a study of BCI literature and work in related fields, including pattern recognition, assistive technology development, and Human–Computer Interaction (HCI) [4]–[8]. This work has been influenced by the set of functional component definitions presented at the First International Meeting of Brain–Computer Interface Technology [2].

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[1]Although the term "BCI system" is not universal, it is considered to be the best term to represent the collection of all BCI components. A definition of a BCI system is presented later in Section II.

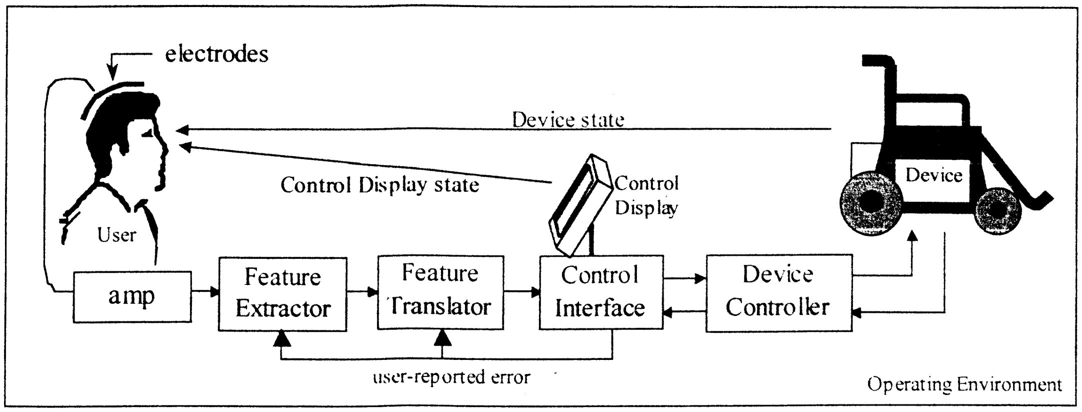


Fig. 1. Proposed functional model of a BCI System.

## II. Functional Model of a BCI System

The proposed functional BCI System model is presented in Fig. 1. The figure depicts a generic BCI System in which a person (the User) controls a Device in an operating environment (e.g., a powered wheelchair[2] in a house) through a series of functional components.[3] The User monitors the state of the Device to determine the result of his or her control efforts. In some systems, the User may also be presented with a Control Display, which displays his or her control inputs within a semantic application-specific context. For this paper, the set of functional components between the User and the Device Controller will be considered BCI interface technology, or simply BCI technology. (Even though a User could potentially control multiple Devices with combinations of interface technologies in various environments, the functional model in Fig. 1 has been restricted to one Device, one interface technology, and one operating environment to simplify the presentation.) Like other interface technologies, a BCI technology is developed to help a target population with specific abilities perform certain tasks with a Device within an operating environment.

The function of each component of the proposed model is discussed in Table I and related feedback loops are defined in Table II. As will be demonstrated subsequently, our choice of boundaries between the functional components will facilitate objective comparisons between two (or more) BCI technologies, and between BCI technologies and other non-BCI user-interface technologies. (Note, the functional model as presented in Fig. 1 does not incorporate the hardware and software components used for BCI System customization or evaluation. Discussion of this specialized hardware and software and their relation to the functional model is beyond the scope of this paper.)

The component definitions and the functional boundaries between components were selected to meet several design objectives:

1) The components in the model should be a minimal but sufficient set to effectively represent existing and future BCI Systems.
2) The boundaries between the functional components should align as much as possible with existing research disciplines (such as pattern recognition, assistive technology development, and HCI) to maximize the use of existing knowledge and technology.
3) The boundaries between the functional components should align as much as possible with existing interface technology to facilitate comparisons between BCI technologies and non-BCI user-interface technologies.

The model in Fig. 1 does not show the external sensory stimulator used by some BCI Systems to evoke brain activity in the User. It was left out of this diagram to simplify the presentation. The model can be drawn as in Fig. 2 to show the external simulator as part of the Control Interface, with a stimulus synchronization signal sent to (or received from) the Feature Extractor. In some systems, the stimulator may be integrated into the Control Display. For the remainder of the paper, the functional model will be presented without the external stimulator.

We will now simplify the model to better illustrate how the new functional model facilitates the comparison of technologies. By treating the device-independent components (i.e., the electrodes, amplifiers, Feature Extractor, and Feature Translator) as a single entity, which we will call a BCI Control, the functional model reduces to the model depicted in Fig. 3. This new construct, the BCI Control, is analogous to a physical transducer such as a potentiometer or a switch. The output of the BCI Control, like that of a physical transducer, consists of either sequences of discrete states or a continuous signal.

By defining BCI Systems in terms of the components in Fig. 3, several advantages to this representation become apparent. First, BCI controls (with similar outputs) can be tested against each other using a common Control Interface. Second, BCI Controls can be tested against alternative controls, like electromyographic (EMG) switches and physical transducers (which have similar outputs) using a common control interface. Third, the abilities of a BCI Control design can be tested across a range of Control Interfaces (with a range of Devices, if desired). This perspective will lead naturally to the design and development of benchmark Control Interfaces.

[2]Although the Device is depicted as a powered wheelchair, it can be any device, such as a computer, a speech synthesizer, a neural prosthesis, or any object in the User's environment, such as a television or light.

[3]Component names have been selected to best identify the component's function. Many of the names used for the components have a history of use in other fields, such as assistive technology development and pattern recognition.

TABLE I
DEFINITION OF FUNCTIONAL COMPONENTS

| Component | Functional Description |
|---|---|
| User | The User is the person controlling the Device in the BCI System. The User intentionally modifies his or her brain state in order to generate the control signals that operate the BCI System. |
| Electrodes | The electrodes convert the User's brain state into electrical signals. Several types of electrodes (e.g., scalp, inter-cranial and intercortical) have been used in various configurations. See Table IV for specific examples. (Note, even though the term electrodes implies electrophysiological measures of brain activity, it will be used in this work to represent the mechanisms, electrophysiological or non-electrophysiological, that transform the User's brain state into electrical signals.) |
| Amp | The amplifiers amplify and bandpass filter the electrical signals from the User's brain. |
| Feature Extractor | The Feature Extractor transforms the amplified signals into feature values that correspond to the underlying neurological mechanism used by the User for control. (To be consistent with terminology used in the pattern recognition community, the output of the Feature Extractor will be referred to as a feature vector [4].) For example, if the User controls the power of their mu and Beta rhythms, a Feature Extractor can be designed to continually generate a feature vector containing the power spectral estimates of the User's mu and Beta rhythms. |
| Feature Translator | The Feature Translator translates the feature vector into logical (device-independent) control signals. For example, a Feature Translator may produce a 2-state discrete output[a]. By our definition, these logical output states would be independent of any semantic knowledge about the Device or how it is controlled. |
| Control Interface | The Control Interface translates the logical control signals from the Feature Translator into semantic control signals that are appropriate for a particular type of device. This mapping may be instantaneous (i.e., its output is calculated directly from the current logical control signal input) or by integrating inputs over time. For example, the Control Interface to a stereo volume control may translate a 2-state discrete input from the Feature Translator directly into "volume up" and "volume down" control signals. An alternative design may monitor the 2-state input over time and assign its output state based on the temporal behaviour of the input.<br><br>The semantic mappings in Control Interfaces are usually dynamic and not static. (These maps may be internally sequenced or synchronized with the Device Controller state.) For example, dynamic semantic mappings are seen in systems that allow the User to navigate through a series of menus to reach the final output. The advantage of interchangeable (or dynamic) semantic maps is that the User can produce a wide variety of semantic control signals with a limited set of logical control signals.<br><br>As depicted in Fig. 1, the Control Interface may have a Control Display[b]. The role of the Control Display is to display the interpretation of the User's control signals within a semantic context. As an example, the Control Display may depict a virtual keyboard |

[a] Many existing BCI Systems map the electrical signals onto discrete control signals, not continuous control signals. For these systems, the Feature Translator is often referred to as the Feature Classifier or simply the Classifier.

[b] The term Display is a bit of a misnomer because the User feedback from the Control Interface may not be visual. It may be aural or tactile for example.

The development of benchmarks would be extremely valuable, enhancing the community's ability to objectively compare BCI technologies. Possible benchmark Control Interface designs include one or more virtual keyboard designs, a menu system, and a mouse emulator (one- and two-dimensional).

Based on the simplified model, we can clearly differentiate the control signals present in a BCI System. As illustrated in Fig. 4, there are four principal control signals within this model: User control signals, logical control signals, semantic control signals, and physical control signals.

The revised model also provides an excellent context for building multimodal systems with BCI and non-BCI controls. Such a system is depicted in Fig. 5.

The User, although drawn as a simple static form in Figs. 1–3, is a highly variable component in this model. There are many psychological and intrinsic factors that influence the

TABLE I (Continued)
DEFINITION OF FUNCTIONAL COMPONENTS

| | |
|---|---|
| | and the User's control signals may be seen as movements of a cursor over this keyboard. The User monitors this display and dynamically adjusts his or her brain state to achieve the desired response. In BCI Systems where the Control Interface output is based on the User's output over time, a Control Display is required. For Control Interfaces that provide a direct mapping of logical input to semantic output, the Control Display is optional.<br><br>For systems that use an external stimulator, the stimulator is driven by the Control Interface. Stimulus synchronization signals are sent to the Feature Extractor in order to synchronize feature extraction. |
| Device Controller | The Device Controller translates the semantic control signals from the Control Interface into physical control signals that are used within the Device. It also controls the overall behaviour of the Device. For example, the Device Controller is responsible for initializing and resetting the Device when required.<br><br>Device Contollers may be implemented in variety of forms, ranging from fixed hardware and software specifically designed for a Device to a generic computer with programmable software and configurable hardware. The Device Controller may reside inside the Device or be a separate object connected to the Device. |
| Device | There is an unlimited range of Devices that can be used in a BCI System. Researchers have used computers, speech synthesizers, neural prostheses, and other objects in the User's environment such as televisions and lights. These devices are usually physical (that is, they physically exist in our environment), but they can also be virtual, existing only on a computer monitor. |
| Operating Environment | The term Operating Environment refers to the physical environment (e.g., walls, floor surfaces, ambient temperature, and noise) and objects and people in the environment. These environmental factors are usually controlled or constrained in a laboratory setting. |

User's output and integration of feedback. The User's abilities, their mental and physical state, the task being performed, and physical and social factors in the operating environment all have a significant impact on the User and thus affect the functioning of a BCI System. For example, the usefulness of a particular system design is extremely dependent on the User's internal processing methods and various human factors (such as motivation, engagement in the activity, task meaningfulness, and response to stress and fatigue). Although these factors are difficult to quantify, it is extremely important for system designers to characterize their target population, potential activities or tasks, and target operating environments as well as possible. Designs that effectively incorporate these contextual factors will have better success when they are taken from the laboratory and used in the real world. As a reference, Cook and Hussey [9] provide a comprehensive overview of perception, cognition, psychosocial factors, and motor control (using Bailey's Information Processing model of the Human Operator [10]) and discuss how they relate to the design of assistive technology systems.

### A. Comparison to Previous Work

The proposed functional model is an extension of the informal model described in [2]. This model has never been formally defined, so the specific function of the components are sometimes difficult to interpret and apply, especially for BCI Systems that do not control a computer. Our interpretation of this model is shown in Fig. 6.

We chose to rework this model for several reasons. First, the function of the translation algorithms component is extremely general. The Translation Algorithms component appears to contain all translation algorithms in the system, which includes algorithms for feature-to-logical-control translation, logical-control-to-semantic-control translation, and semantic-control-to-physical-control translation. This definition precludes the model segmentation, which, as shown previously, facilitates objective comparison of BCI and non-BCI technologies and supports multimodal BCI System designs. Second, the function of the Application component is vaguely defined. This could lead to confusion for those attempting to apply the model to BCI Systems. Third, the component name "Application" implies algorithms used in a computer to control a computer monitor. This name makes it awkward to describe BCI Systems that control devices other than computers. Fourth, the model does not define all the principle feedback paths in a BCI System. Specifically, the separation between Control Display state feedback and Device state feedback is not delineated. Fifth, comments about the model state that the Control Display state feedback is a required feature of a BCI System. This is not true for some BCI System designs [11]–[13], as seen in Table IV.

TABLE II
DEFINITION OF PRINCIPLE FEEDBACK PATHS WITHIN A BCI SYSTEM

| **Information** | **Feedback Paths** |
|---|---|
| Device state | The Device state is fed back to the User through one (or more) sensory channels. The User correlates changes in Device state with their control attempts. This information is used by the User to adjust his or her output.<br>The Device state may be fed back to the Device Controller if the Device supports this type of output. This information is used to keep the Device Controller synchronized with the Device. |
| Control Display state | In many systems, the Control Display state is fed back from the Control Interface to the User through one (or more) sensory channels. This information is used by the User to dynamically adjust his or her output. |
| Device Controller state | The Device Controller state is fed back from the Device Controller to the Control Interface. This information is used to synchronize the semantic mapping of the Control Interface to the state of the Device controller. |
| User-reported errors | If the Feature Extractor or the Feature Translator is adaptive, user-reported errors can be fed back from the Control Interface to the Feature Extractor or the Feature Translator so that they can modify their function. |
| User state | The User's self perception of his or her state is an internal source of information fed back to the User. For example, the User may notice changes in energy, fatigue, frustration, interest in the task, or body pains and may adapt his or her control to this new state. Attempts are usually made in laboratory studies to control or limit the User's state. |
| Environmental state | The state of the physical environment and the people and objects in the environment are fed back to the User through one (or more) sensory channels. The amount of feedback is usually constrained in a laboratory setting, by limiting changes in the Operating Environment. |

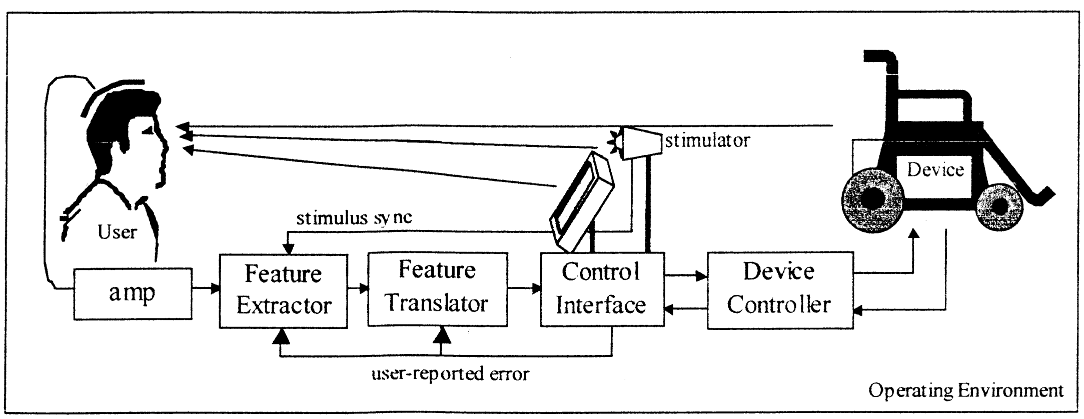


Fig. 2. Version of the functional model of a BCI System depicting external stimulation source.

*B. Input Device Emulation*

For researchers who are interested in input device emulation, the revised model of Fig. 3 can be further simplified to the model shown in Fig. 7. In this model, the BCI Control and the Control Interface have been combined into a single input device, a BCI Input Device. Vanderheiden and others have emphasized input device emulation as an important design criteria for assistive technology [5]–[7]. As the field of BCI research matures, the issue of device emulation will become more significant. Viewing the BCI Control and Control Interface as a single input device facilitates BCI designs that emulate standard input devices.

The perspective offers several advantages. First, this model can be used as a reference for testing a BCI Input Device against other BCI Input Devices using a common Device Controller. Second, it can be used to test BCI Input Devices against other user interface technologies (including other input device emulators) using a common Device Controller. Third, the abilities

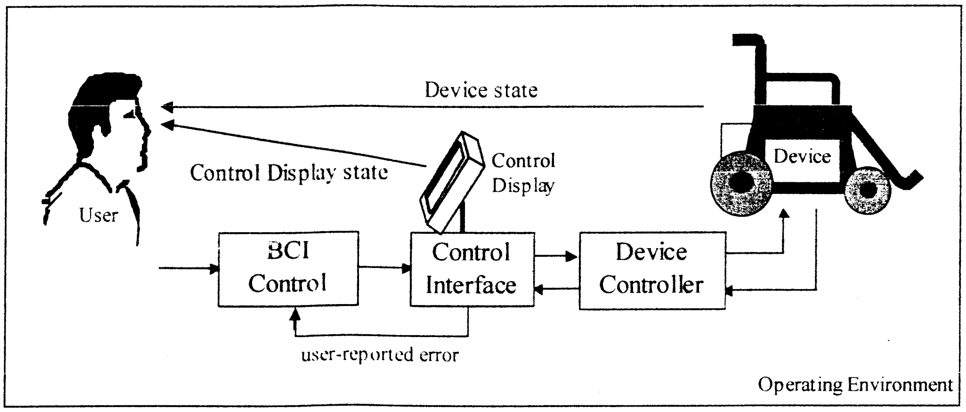


Fig. 3. Simplified version of the functional model.

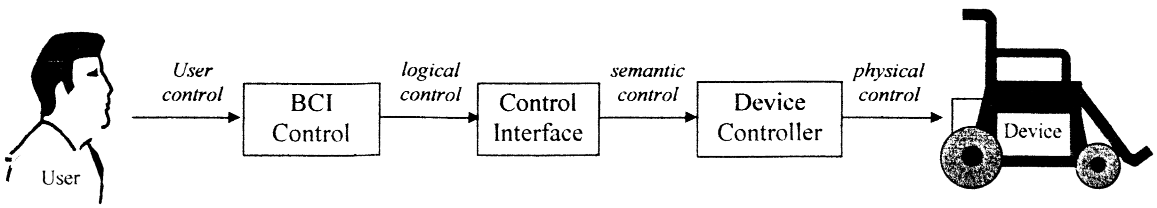


Fig. 4. Feed-forward control signal paths in the simplified version of the functional model.

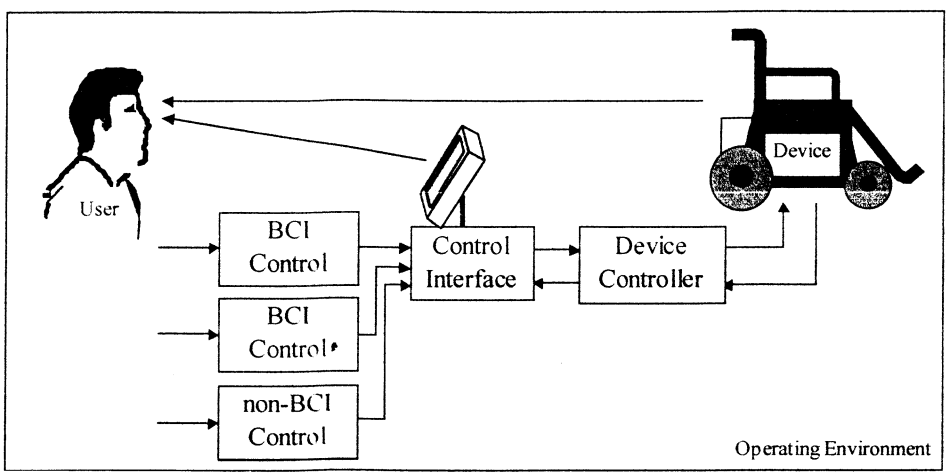


Fig. 5. Multimodal BCI System. (Note that the User-reported error feedback path has been left out to simplify the presentation.)

of a BCI Input Device can be tested across a range of Device Controllers.

The discussion of common Device Controllers should inspire the development of benchmark Devices and Device Controllers for testing BCI Input Devices with other BCI and non-BCI technology. Suggestions for benchmark Devices and Device Controllers have included a personal communications device, an environmental controller, and a personal entertainment device. These benchmarks could be custom-built or selected from many off-the-shelf devices.

### C. Interfacing With Computers and Virtual Devices

Interfacing BCI technology to a computer is a special case of BCI System design that deserves discussion. Computers can be used to implement Devices in one of the following three ways:

1) as the Device;
2) as a prototype of a physical Device;
3) displaying a virtual Device in a virtual world.

A computer (implying the computer and monitor) would be considered the Device when it is used for customized or generic activities, such as a word processor or e-mail and Internet access. The internal hardware and software controlling the computer would be considered the Device Controller. When a computer is used as a physical Device prototype, it is configured with the necessary hardware and software to act as a physical device; one that performs a set of functions in response to certain inputs. For example, the computer could function as an environmental controller. (It is assumed that such a prototype could be repackaged in specialized hardware and software, if desired.) In this role, the computer (including the monitor) can be considered the Device, and the internal control hardware and software would be part of

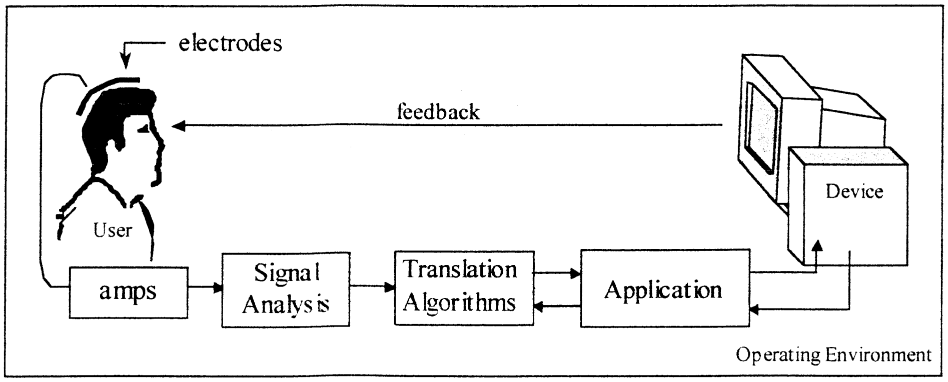


Fig. 6. Previous functional model of a BCI System.

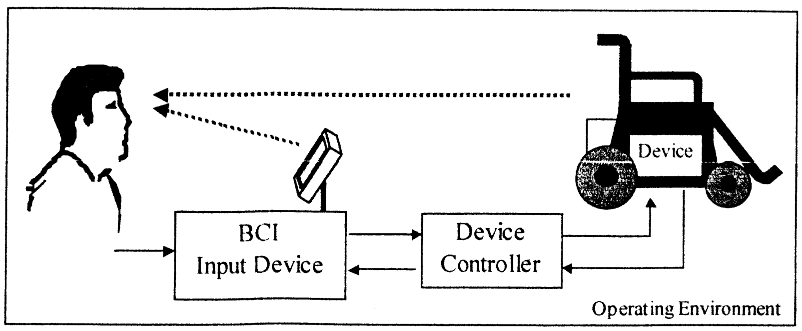


Fig. 7. View of the functional model suitable for Input Device emulation.

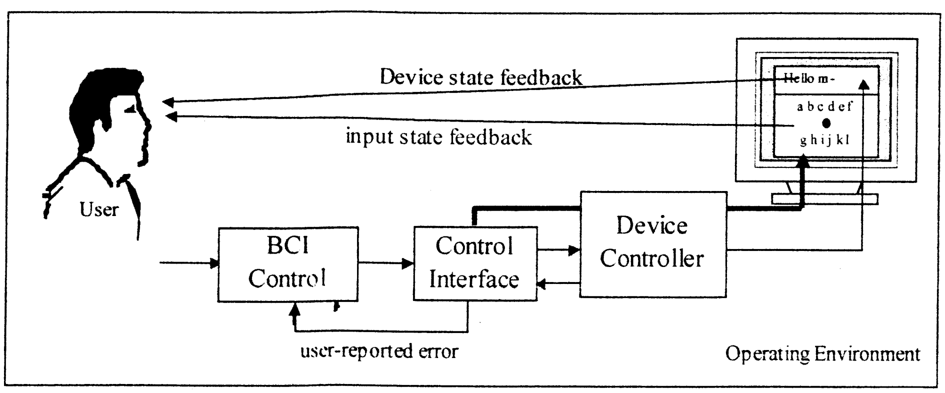


Fig. 8. Dedicated BCI System with Control Display state feedback built into the Device Controller.

the Device Controller. When a computer is used to display a virtual Device, the virtual Device is considered the Device, and the software controlling the virtual Device would be the Device Controller.

### *D. Building Control Displays Into Devices*

It is possible to build the Control Display into the Device. This approach has been used by a few researchers [14], [15]. As shown in Fig. 8, this arrangement is usually implemented with a computer but can be implemented with any Device that supports an extra channel for information feedback.

There are some advantages to this approach. The most obvious is the cost and space savings of using less equipment (e.g., one display, instead of two). A second advantage, assuming visual feedback, is that the User only monitors one device, rather than two separate displays. However, there are drawbacks to this design approach. First, the Control Display feedback may limit or obscure the Device state feedback. Another limitation is that the User is now dependent on the Device to present the Control Display. Assistive device designers have demonstrated that building dedicated interface systems of this type is generally a poor design choice [6], [7]. A preferred design would support input device emulation.

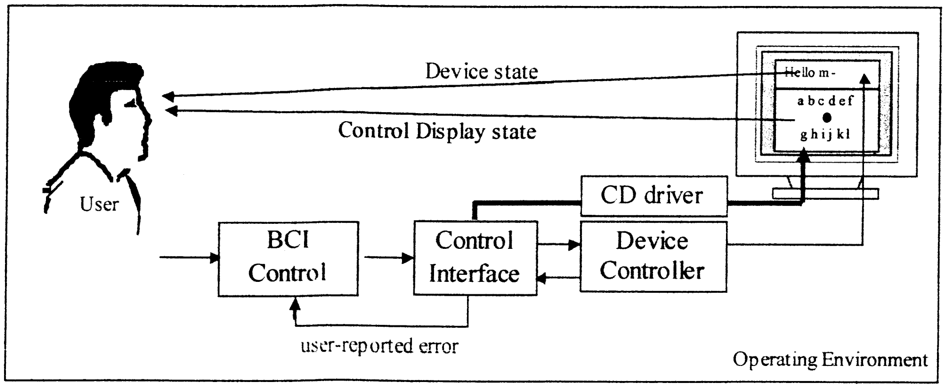


Fig. 9. Dedicated BCI System demonstrating modular design. The module named "CD driver" represents a component designed to drive the Control Display on the Device monitor.

TABLE III
TAXONOMY FOR BCI SYSTEM DESIGNS

| Item | Terms | Definition |
|---|---|---|
| Target Population: | description: | description of the people for which the BCI System is designed, including their abilities, skills, functional limitations and psychological state. |
| | needs: | description of the Users' personal goals or needs being addressed by the system (e.g., need to communicate with caregivers). |
| Target Tasks: | description: | description of the tasks the system is designed to facilitate (related to the Target Populations' needs). |
| Target Operating Environment(s): | description: | description of where the BCI technology will be used. Includes physical and social characteristics. |
| BCI Control: | neuro. mechanism: | description of the neurological mechanisms or processes that the User uses to generate the User control signals |
| | input: | description of electrical signal source and amplification |
| | user control: | defines whether the user control signal is intermittent or continuous |
| | feature extraction: | description of the methods used to create the feature vector |
| | feature translation: | description of the methods used to translate the feature vector into logical control signals |
| | outputs: | description of the number of outputs and their characteristics |
| Control Interface: | inputs: | description of the number of inputs and their characteristics |
| | semantic translation: | description of how the logical-control inputs are translated into outputs with semantic meaning for the Device being controlled |
| | outputs: | description of the number of outputs and their characteristics |
| | Control Display: | description of the Control Display (if present) |
| | stim. mechanism: | description of the external stimulator control mechanism (if present) |
| | On/Off mechanism: | description of On/Off mechanism |
| Device: | description: | a general description of the Device |
| | state feedback: | description of how the Device state is fed back to the User |
| Device Controller: | inputs: | description of the number and type of inputs |
| | functional desc: | description of how the semantic control inputs are mapped onto physical control signals |

Regardless of the disadvantages, this approach may seem appropriate for test environments with cost and space constraints. It may also be appropriate for specific Users who have extremely limited mobility and will only work with one device (usually a computer). Nevertheless, even in these circumstances, the mechanism that drives the Control Display should be kept separate from the Device Controller as shown in Fig. 9. This is general modular design practice, and it will maximize one's ability to compare and reuse the interface technology.

## III. A TAXONOMY FOR BCI SYSTEM DESIGN

The functional model presented in the last section implies the basic taxonomy shown in Table III. Most of the items and terms are obvious from the functional model definitions. Two terms, "User Control" (in the BCI Control) and "ON/OFF mechanism" (in the Control Interface) are new and will be described in the following two subsections.

The first three items listed in Table III, Target Population, Target Tasks, and Target Operating Environment(s), provide the context for a BCI System design. These items compel BCI technology designers to understand and incorporate related factors into their designs. These three items also facilitate the interpretation and use of published designs.

### A. BCI Control: User Control

Some BCI Controls in the literature [16], [17] have been designed to recognize when the User is in a passive, observing state as well as in an active control state. (The passive state occurs when the User is just watching the Device and not actively trying to control it.) These controls have been designed for use in environments where (with the system turned on) the User can intermittently control the Device when they desire. For these control designs, one output state is reserved to indicate that the User is in a passive state. BCI Controls that do not support a passive User state expect the User to be continually producing (active) control signals.

The User Control attribute of a BCI Control defines whether the BCI Control supports intermittent user control or continuous user control.

### B. Control Interface: ON/OFF Mechanism

For a truly independent unsupervised system, Users require a mechanism to turn the system on and off. No automated mechanism has been reported to turn BCI Interface Devices on and off. All techniques reported in the literature are manually turned on and off by the researcher or an assistant running the study. Developing an automated switch to turn the system on is recognized as a difficult problem. Such a switch has to differentiate between all possible innate brain states and the system ON state. In practical terms, the mechanism will probably be implemented in the future as a sequence of commands, where each step in the sequence confirms the User's intent to turn the system on.

Turning the system off is assumed to be one of the control options available to the User once the system has been turned on.

## IV. Application of the Framework

To illustrate the usefulness of this framework, the taxonomy defined in Section III was used to describe a representative set of BCI approaches. The results are summarized in Table IV. The presentation is chronological, and the information presented is limited to the descriptions found in the cited references. Note that this table is not intended as a comprehensive review of all BCI designs and evaluations. Example techniques were selected to test the ability of the framework to adequately describe the range of BCI System designs and evaluations seen in the literature. In some instances where multiple references to a BCI technology existed, the most widely cited works were used.

Note, in some studies, only a BCI Control design is evaluated. These off-line studies, which do not define a Control Interface or a Device, will be referred to as an "off-line evaluation of a BCI Control design." Other studies evaluate a BCI Control with a Control Interface (i.e., a BCI Input Device) with no Device attached. We will refer to these studies as an "on-line study of a BCI Input Device design."

### A. Comments on the Application of the Functional Model

Overall, the model and taxonomy seem able to effectively represent the designs of all the BCI Systems reviewed. The application of the taxonomy identifies many similarities and differences across the designs. For example, the BCI Control designs of [12], [14], [15], and [20] all have a single, continuous control output. This information is useful if one is looking for a continuous controller. The identified techniques could be evaluated using a common Control Interface to determine the most suitable design for a given application. As another example, the various Control Interface designs of [14], [15], and [20] all emulate a keyboard. We could study these designs in order to develop a common (benchmark) "virtual keyboard" Control Interface.

During the application process, we observed several issues that require further comment.

While the Target Population and Target Tasks were reasonably well defined (at a high level), few studies explicitly defined their Target Operating Environment. This is an important oversight in these works, since the evaluation results cannot be accurately interpreted without an explicit definition of the operating context.

The identification of the majority of the BCI Control elements (i.e., neurological mechanism, input, user control, signal recording methodology and feature extraction methodology, and output) was relatively straightforward to interpret from the literature. The Feature Extractor components were easily identified, since the output of the Feature Extractor was a feature vector that represented the underlying neurological mechanism.

In several cases, the division between Feature Translation algorithms and Control Interface algorithms (that is, the division between Device-independent and Device-dependent algorithms) was not obvious from the written report. To address this issue, three objective guidelines were used to interpret the reported methods and separate the Feature Translation algorithms from the Control Signal Translation algorithms. The guidelines were as follows.

Guideline 1: Feature Translation algorithms do not receive feedback of Device state, whereas Control Interface algorithms can receive this type of feedback.

Guideline 2: The Feature Translation (Classification) algorithms for BCI Controls only produce logical outputs. Any assignment of semantic value to a particular class is considered part of the Control Interface. As an example, Wolpaw *et al.* [20] employed semantic mapping in their Control Interface to map the five possible output levels from their BCI Control onto various (User-specific) movement amounts and directions.

TABLE IV
SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Vidal [11] 1977** | | |
| Target Population: | description: | not explicitly defined – text implies the general population. (This study seems to be a general evaluation of a technology without a specific application.) |
| | needs: | not explicitly defined |
| Target Tasks: | description: | not explicitly defined – text implies general control of computers or prosthetic devices |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | single-trial Visual Evoked Potential (VEP) evoked by a strobed checkerboard |
| | input: | EEG recorded over occipital cortex |
| | user control: | continuous |
| | feature extraction: | the feature vector was produced by Wiener filtering the time-locked input signal followed by step-wise discriminant procedure to reduce feature vector dimensionality |
| | feature translation: | Bayesian classifier with outlier rejection |
| | outputs: | a single output, equivalent to a 4-position switch |
| Control Interface: | inputs: | a single 4-state input |
| | semantic translation: | a static mapping of the 4-state input onto 4 directions: up, down, right or left |
| | outputs: | a single output, representing one of four directions: up, down, right or left |
| | Control Display: | none |
| | stim. mechanism: | strobed checkerboard superimposed on the Device output (shared display) |
| | On/Off mechanism: | manual |
| Device: | description: | a virtual token within a virtual maze on a computer screen |
| | state feedback: | visual feedback of token position within the maze |
| Device Controller: | inputs: | a single input, coded direction: up, down, left, right |
| | functional desc: | the controller moves the token in one of four directions based on the input signal. |
| **Farwell & Donchin [18] 1988** | | |
| Target Population: | description: | individuals who cannot use any motor system to communicate. |
| | needs: | ability to communicate with family, friends and/or caregivers and/or control appliances in their environment |
| Target Tasks: | description: | create text messages, synthetic speech or control signals by selecting letters, words, commands from a menu on a computer monitor |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | P300, evoked by flashing symbols on computer screen |
| | input: | EEG at Pz referenced to linked mastoids |
| | user control: | continuous |
| | feature extraction: | 36 feature vector were produced, one for each cell of the 6x6 menu on the Control Display. When a row of the menu was flashed, a 600 ms window of the input signal (time-locked to flash) was added to all the feature vectors corresponding to cells in that row. Similarly for column flashes. |
| | feature translation: | the feature vectors (representing signal averages) were continually ranked (using a variety of methods) and either a correlation/threshold was used to select a cell, or the highest ranked cell was selected after a fixed length of time |
| | outputs: | a single output, equivalent to a 36-position, momentary-on switch |
| Control Interface: | inputs: | a single, 36-state input |
| | semantic translation: | a configurable mapping of input to one of 36 letters or commands |
| | outputs: | a single output, representing one of 36 letters or commands available for selection |
| | Control Display: | a 6x6 square menu on a computer screen with a single letter or command in each cell |
| | stim. mechanism: | randomly strobed rows and columns of the square menu. Strobe synchronization is sent to the Feature Extractor. |
| | On/Off mechanism: | manual |
| Device: | description: | a text box on a computer screen |
| | state feedback: | visual feedback of contents of text box |
| Device Controller: | inputs: | a single input, coded letter or command |
| | functional desc: | if a letter, the controller displays the letter in the text box. If a command (such as Backspace or Send), the controller executes the command. |

Guideline 3: Algorithms that perform feature scaling and bias adjustment, such as those seen in [23], are considered to be part of the Feature Translator because they only modify the Feature Extractor outputs.

In certain works where the output of a BCI Control was a continuous set of $N$ discrete values, the BCI Control could be interpreted as either a digital continuous control (with $N$ levels of quantization) or a continuously sampled $N$-position switch. In these cases, the following guideline was used:

Guideline 4: The BCI Control is described as a (digital) continuous control (with $N$ levels of quantization) if the $N$ discrete values are an ordered set. Otherwise, it is considered a $N$-position switch.

In several works, the hardware processing (such as amplification and filtering) was treated as separate from the software algorithms. For the purposes of modeling these systems, there is no value in differentiating between amplifier systems, custom hardware, firmware running on custom hardware, or software algorithms running in a generic computer. The following guideline was used during the application of the framework:

Guideline 5: Within a BCI System, all signal processing, whether implemented in hardware or software, can be viewed as signal processing algorithms, regardless of physical implementation.

## V. DISCUSSION

The proposed framework addresses the fundamental need for objective methods to compare BCI technologies. As demonstrated in Section IV, the framework provides us with a common language for describing BCI technology and BCI Systems. The

TABLE IV (*Continued*)
SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Keirn & Aunon [19] 1990** | | |
| Target Population: | description: | individuals with severe physical disabilities |
| | needs: | ability to communicate with surroundings |
| Target Tasks: | description: | generate predefined commands by spelling codewords (based on a limited alphabet) |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | differences in lateralized spectral power levels related to various cognitive tasks |
| | input: | EEG recorded over parietal and occipital regions |
| | user control: | continuous |
| | feature extraction: | three feature vectors were generated using three methods: two spectral power estimation methods (FFT and AR spectral estimation) followed by band-pass filtering in four frequency bands; and a method that used AR coefficients of signals in four frequency bands. |
| | feature translation: | Bayesian quadratic classification of power or AR coefficient features |
| | outputs: | a single output, equivalent to a 5-position switch |
| Control Interface: | … | n/a (off-line evaluation of a BCI Control design) |
| Device: | … | n/a (off-line evaluation of a BCI Control design) |
| Device Controller: | … | n/a (off-line evaluation of a BCI Control design) |
| **Wolpaw et al [20] 1991** | | |
| Target Population: | description: | individuals with severe motor disabilities or communication problems |
| | needs: | ability to communicate and/or control a prosthetic device |
| Target Tasks: | description: | control of one or more prosthetic devices (such as augmentative communications devices) by moving a cursor to select icons on a computer monitor. |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | active control of mu rhythm power |
| | input: | EEG recorded from bipolar electrode anterior and posterior to C3. |
| | user control: | continuous |
| | feature extraction: | the feature vector was produced by calculating the EEG power spectrum (FFT) with 3Hz resolution. Power value centered at 9Hz was used as amplitude of mu rhythm. |
| | feature translation: | linear discrimination of mu rhythm power with heuristic thresholds into 5 levels |
| | outputs: | a single output, equivalent to (digital) continuous control (with 5-levels of quantization) |
| Control Interface: | inputs: | a single, continuous control input |
| | semantic translation: | the input was mapped over time onto a 2-state output. To achieve this, the 5-level input was mapped onto a 1-dimensional cursor by one of five preset directions and magnitudes. Over time, the cursor reached a target at the top or bottom of a computer screen. Since this study did not use a Device or Device Controller attached to the output of the Control Interface (i.e., it was an on-line study of a BCI Input Device design only), the outputs related to "cursor at the top" and "cursor at the bottom" were not mapped to specific semantic values. |
| | outputs: | a single 2-state output (no specific semantic meaning assigned) |
| | Control Display: | a 1-dimensional cursor was visible on a computer monitor. The cursor position indicated how close it was to one of the two possible selections at the top or bottom of the screen. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | … | n/a (on-line study of a BCI Input Device design) |
| Device Controller: | … | n/a (on-line study of a BCI Input Device design) |
| **Sutter [21] 1992** | | |
| Target Population: | description: | individuals with severe motor disabilities (e.g., locked-in syndrome) |
| | needs: | ability to communicate with surroundings |
| Target Tasks: | description: | create text messages or synthetic speech by selecting letters, words and editing commands from a menu on a computer monitor |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | steady-state VEPs evoked by alternating symbols on computer screen |
| | input: | EEG recorded over occipital cortex, and (in one subject) from and intercranial electrode array |
| | user control: | continuous |
| | feature extraction: | the feature vector was the single-trial, time-domain signal time locked to the VEP stimulus |
| | feature translation: | the time-domain signal was correlated with templates related to 64 possible responses. Switch state was selected when one of the time-averaged correlation values exceeded a threshold. |
| | outputs: | a single output, equivalent to a 64-position, momentary-on switch |
| Control Interface: | inputs: | a single, 64-state input |
| | semantic translation: | configurable mapping of input to one of 64 letters or commands |
| | outputs: | a single output, representing one of 64 letters or commands available for selection |
| | Control Display: | a 8x8 square menu on a computer screen with a single letter or command in each cell |
| | stim. mechanism: | randomly strobed cells within the square menu. Strobe synchronization is sent to the Feature Extractor. |
| | On/Off mechanism: | Manual |
| Device: | description: | the device contains a text box on a computer screen and a speech synthesizer |
| | state feedback: | visual feedback of contents of text box, and aural feedback of speech synthesizer output |
| Device Controller: | inputs: | a single input, representing a coded letter or command |
| | functional desc: | if a letter, the controller displays the letter in the text box and/or sends it to the speech synthesizer. If a command (such as Backspace or Send), the controller executes the command. |

functional model defines the minimal set of components required to describe BCI System designs, a characterization that should not constrain future designs.

As discussed in Section II, the functional model has many features. The model is useful for describing BCI Control and BCI Input Device prototypes as well as complete BCI Systems. It is flexible; it can represent a range of system configurations, including multimodal designs, and it supports any type of Device. It is scalable, that is, it supports three different levels of detail (see Figs. 1, 3, and 7). The model is suitable for describing BCI

TABLE IV *(Continued)*
SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Pfurtscheller [22] 1993** | | |
| Target Population: | description: | individuals with high-level spinal cord injuries |
| | needs: | ability to communicate or control appliances in their environment |
| Target Tasks: | description: | not explicitly defined – text implies control of one or more prosthetic devices |
| Target Environment: | description: | not explicitly defined – text implies general living or working environments |
| BCI Control: | neuro. mechanism: | active control of mu event-related desynchronization (ERD) |
| | input: | EEG recorded over sensory-motor cortex. |
| | user control: | continuous |
| | feature extraction: | the feature vector was generated by filtering the input signal to 8-12 Hz. Then the result was squared as an estimate of instantaneous mu power. Five consecutive power estimates of mu power related to event-related desynchronization (ERD) were bundled into a five-dimensional feature vector. |
| | feature translation: | one-nearest neighbor (1-NN) classification, using reference vectors selected with a learning vector quantization method known as LVQ. |
| | outputs: | a single output, equivalent to 2-position switch |
| Control Interface: | inputs: | a single, 2-state input |
| | semantic translation: | the 2-state input was mapped onto a 2-state output: move left or move right. Since this study was an on-line study of a BCI Input Device design, the outputs related to "move left" and "move right" were not mapped to specific semantic values. |
| | outputs: | a single 2-state output (no specific semantic meaning assigned) |
| | Control Display: | a 1-dimensional cursor was visible on a computer monitor. The cursor position, by moving to the left or the right of the screen, indicated which of the two possible selections was made. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | … | n/a (on-line study of a BCI Input Device design) |
| Device Controller: | … | n/a (on-line study of a BCI Input Device design) |
| **Wolpaw et al [23] 1994** | | |
| Target Population: | description: | individuals who are paralyzed or have other severe movement disorders |
| | needs: | ability to communicate and control their environment |
| Target Tasks: | description: | control of one or more prosthetic devices (such as augmentative communications device) by moving a cursor to select icons on a computer monitor. |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Controls: | neuro. mechanism: | active control of distributed mu rhythm power |
| | input: | EEG recorded across sensory-motor cortex using bipolar electrodes at FC3-CP3 and FC4-CP4. |
| | user control: | continuous |
| | feature extraction: | the feature vector was generated for each of the two EEG inputs. Specifically, the square root of signal power in a 5Hz (or 4Hz) band centered at 10Hz (or 12Hz) was calculated for both inputs. The mu rhythm signal power was estimated for both inputs using a Fast Fourier Transform (FFT). |
| | feature translation: | The sum of power level features was mapped (using an adaptive, linear transform) to vertical movement and the difference of power level features was mapped to horizontal movement. |
| | outputs: | two outputs, equivalent to a 2-dimensional (digital) continuous control |
| Control Interface: | inputs: | two (digital) continuous control inputs |
| | semantic translation: | the first input was mapped to horizontal cursor displacement. The second input was mapped to vertical cursor displacement. Over time, the cursor reached one of the four corners of a computer screen. Since this study was an on-line study of a BCI Input Device design, the outputs related to "cursor at the top, left", "cursor at the bottom, left", etc, were not mapped to specific semantic values. |
| | outputs: | a single, 4-state output |
| | Control Display: | a 2-dimensional cursor was visible on a computer monitor. The cursor position indicated how close it was to one of the four possible selections in the four corners of the computer screen. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | … | n/a (on-line study of a BCI Input Device design) |
| Device Controller: | … | n/a (on-line study of a BCI Input Device design) |

Systems with BCI and non-BCI interface technology. It provides an excellent frame of reference for the development of standardized testing components, specifically benchmark Control Interface designs and benchmark Device and Device Controller designs. The terminology and functional divisions chosen for the model align well with other disciplines (such as pattern recognition, assistive technology development and HCI). As a result, the research community can maximize use of existing knowledge and technology.

As with any assistive technology, this proposed functional model can be placed within the high-level context of the Modified Institute of Medicine (IOM) Model of disability [27]. For readers who are familiar with this model, the User is the *person* who interacts with his or her *environment*. The components between the User and the Device Controller are part of the *assistive technology* that improves the User's *functional abilities*. Devices that are common appliances, such as TVs, computers, phones, and lights, would be considered part of the User's *physical environment,* whereas Devices, such as wheelchairs, neuroprosthetics, environmental control systems, and speech synthesizers, would be considered part of the *assistive technology*. Other items and people in the operating environment are considered part of the User's *physical and social environment*.

As the first formally defined framework for BCI System design, this work provides a valuable design reference that could greatly aid intergroup communication and the comparison of technologies. If accepted by the research community, the framework will foster technology development and advance the development of standardized testing environments. It would also provide an excellent basis for synchronizing multinational col-

TABLE IV *(Continued)*
SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Pfurtscheller [24] 1994** | | |
| Target Population: | description: | not explicitly defined – reference to previous study identifies the Target Population as individuals with high-level spinal cord injuries |
| | needs: | not explicitly defined – reference defines need to communicate or control their environment |
| Target Tasks: | description: | not explicitly defined – reference implies control of one or more prosthetic devices |
| Target Environment: | description: | not explicitly defined – reference implies general living or working environments |
| BCI Control: | neuro. mechanism: | active control of spectral power of several frequency bands related to finger, toe and tongue movement EEG recorded over sensory-motor cortex |
| | input: | continuous |
| | user control: feature extraction: | the feature vector was produced by calculating spectral power of several frequency bands related to finger, toe and tongue movement. The instantaneous signal power was estimated from the input signals using four, narrow band-pass filters (between 8 and 40 Hz). Eight consecutive power estimates (1/4 second) were bundled into an eight-dimensional feature vector. |
| | feature translation: | one-nearest neighbor (1-NN) classification, using reference vectors selected with LVQ |
| | outputs: | a single output, equivalent to a 2-position switch |
| Control Interface: | … | n/a (off-line evaluation of a BCI Control design) |
| Device: | … | n/a (off-line evaluation of a BCI Control design) |
| Device Controller: | … | n/a (off-line evaluation of a BCI Control design) |
| **McMillan and Calhoun [12] 1995** | | |
| Target Population: | description: | able-bodied pilots |
| | needs: | hands-free control of various secondary functions in an airplane |
| Target Tasks: | description: | control roll (e.g., left or right) of a motion-based simulator |
| Target Environment: | description: | airplane cockpit simulator |
| BCI Control: | neuro. mechanism: | magnitude of steady-state VEP evoked by 13.25Hz strobe light |
| | input: | EEG recorded from bipolar electrode between $O_1$ and $O_2$. |
| | user control: | continuous |
| | feature extraction: | the feature vector was generated by band-pass filtering the bipolar EEG (centered on 13.25 Hz), followed by signal amplification and power level estimation. |
| | feature translation: | linear discrimination with two heuristic thresholds and dwell time period. Feature values between thresholds, mapped to first state. Feature values over upper threshold for dwell period mapped to second state. Feature values under lower threshold for dwell period mapped to third state. |
| | outputs: | a single output, equivalent to (digital) continuous control (with 3-levels of quantization) |
| Control Interface: | inputs: | a single, 3-level continuous control input |
| | semantic translation: | the 3-state input was statically mapped onto values of "no roll", "roll left", and "roll right" |
| | outputs: | a single output representing one of three states: no roll, roll left, roll right |
| | Control Display: | none |
| | stim. mechanism: | strobed light |
| | On/Off mechanism | manual |
| Device: | description: | a cockpit roll simulator |
| | state feedback: | visual feedback of simulator roll indicator and proprioceptive feeling of physical roll |
| Device Controller: | inputs: | a single input, indicating direction of roll |
| | functional desc: | roll the simulator left or right if input is "roll left" or "roll right". Do nothing if input is "no roll". |
| **Pfurtscheller et al [25] 1997** | | |
| Target Population: | description: | individuals with severe motor disability (e.g., locked-in syndrome or high-level spinal cord injury) |
| | needs: | ability to communicate, control appliances in their environment, and/or move one or more of their paralyzed limbs (through functional electrical stimulation) |
| Target Tasks: | description: | control of one or more prosthetic devices (such as an augmentative communications device or neuroprothesis) by moving a cursor to select icons on a computer monitor. |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | active control of alpha and beta rhythm power related to imagined hand movements |
| | input: | EEG recorded over sensory-motor cortex |
| | user control: | continuous |
| | feature extraction: | the feature vector was generated by estimating signal power from two user-specific signal inputs and two user-specific frequency bands. These estimates were calculated four times over a period of 1 second. The 16 power features (within each second) were bundled into a 16-dimensional feature vector. |
| | feature translation: | one-nearest neighbor (1-NN) classification, using reference vectors selected with LVQ. |
| | outputs: | a single output, equivalent to a 2-position switch |
| Control Interface: | inputs: | a single 2-state input |
| | semantic translation: | the input signal mapped onto a 2-state output: move left or move right. Since this study was an on-line study of a BCI Input Device design, the outputs related to "move left" and "move right" were not mapped to specific semantic values. |
| | outputs: | a single 2-state output (no specific semantic meaning assigned) |
| | Control Display: | a 1-dimensional cursor was visible on a computer monitor. The cursor position, by moving to the left or the right of the screen, indicated which of the two possible selections was made. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | … | n/a (on-line study of a BCI Input Device design) |
| Device Controller: | … | n/a (on-line study of a BCI Input Device design) |

laborative research programs. Even if not wholly accepted by the BCI community, it can serve as a stable reference around which to discuss the community's needs.

Our hope is that this paper will stimulate discussion in the research community, and, as a result, the proposed model and taxonomy will continue to evolve. For instance, over time, the

TABLE IV *(Continued)*

SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Kennedy et al [14] 2000** | | |
| Target Population: | description: | individuals with "locked in syndrome" due to ALS or other pathology. |
| | needs: | ability to communicate with family, friends and/or caregivers and control appliances in their environment |
| Target Tasks: | description: | create text messages or synthetic speech by selecting letters, words, phrases from a virtual keyboard, or control environment or computers by selecting options from a menu system |
| Target Environment: | description: | not explicitly defined – Target Population implies BCI technology designed to be used from the bed in a person's bedroom or hospital room with family, friends and/or caregivers present. |
| BCI Control: | neuro. mechanism: | active control of neural group firing rate |
| | input: | signals recorded from two electrodes implanted within hand area of Primary Motor Cortex. |
| | user control: | continuous |
| | feature extraction: | the feature vector represented the neural group firing rate extracted from both signal sources |
| | feature translation: | Increases in neuronal firing rate resulted in increases in output level. Decreases in firing rate resulted in a zero output. |
| | outputs: | a single output, equivalent to (digital) continuous control (with 2-levels of quantization) |
| Control Interface: | inputs: | a single continuous control input |
| | semantic translation: | the input level was used to select one of 29 letters, words or commands from a wrap-around 2-D menu. The semantic mapping of the menu was configurable. A cursor was used to point to a cell in the 2-D menu. Input levels mapped to horizontal and vertical cursor speeds; larger inputs moved the cursor faster. Dwell time or external EMG switch used to select a menu item. |
| | outputs: | a single output representing one of 29 letters, words or commands |
| | Control Display: | a 2-D menu with a cursor. The cursor position reflected the culmination of inputs. The Control Display was displayed on computer screen shared with the Device. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | description: | a text box on a computer screen |
| | state feedback: | visual feedback of text box contents |
| Device Controller: | inputs: | a single input, representing a letter, word or command |
| | functional desc: | the controller displayed the letters (or words) in the text box. Commands were executed. |
| **Birbaumer et al [15] 1999** | | |
| Target Population: | Description: | individuals who are completely paralyzed (e.g., locked in syndrome) |
| | needs: | ability to communicate with family, friends and/or caregivers |
| Target Tasks: | description: | create text messages by selecting letters from a virtual keyboard |
| Target Environment: | description: | not explicitly defined – Target Population implies BCI technology designed to be used from the bed in a person's bedroom or hospital room with family, friends and/or caregivers present. |
| BCI Control: | neuro. mechanism: | slow cortical potentials (SCP) |
| | input: | EEG recorded over the Frontal Cortex |
| | user control: | continuous |
| | feature extraction: | the feature vector represented the amplitude of SCP waveform averaged over sliding window |
| | feature translation: | linear classification with heuristic threshold |
| | outputs: | a single output, equivalent to (digital) continuous control (with 2-levels of quantization) |
| Control Interface: | inputs: | a single, 2-level continuous control input |
| | semantic translation: | the 2-state input was used over time to select one letter from a set of 26 letters. The 2-state input was mapped directly onto a "move up" or "move down". These signals moved a cursor up or down the screen. The top of the screen represented half the alphabet, the bottom, the other half. Movement of the cursor to the top selected that half of the alphabet and similarly for the bottom. The selected set of letters was split, and cursor movement was repeated. This process continued until one letter was selected. |
| | outputs: | a single output representing one of 26 letters |
| | Control Display: | a binary keyboard with a cursor. The display presented half of a set of letters at the top, the other half at the bottom. The cursor position reflected the culmination of inputs. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | description: | a text box on a computer screen |
| | state feedback: | visual feedback of text box contents |
| Device Controller: | inputs: | a single input, representing a letter |
| | functional desc: | the controller displayed the letter in the text box |
| **Huggins et al [17] 1999** | | |
| Target Population: | description: | individuals with severe movement impairments |
| | needs: | self-paced control of appliances in their environment |
| Target Tasks: | description: | self-paced operation of one or more prosthetic devices |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | different voluntary movements or vocalizations (varied depending on patients' abilities) |
| | input: | ECoG recorded from the surface of the cortex at various locations. Number of electrodes varied from 16 to 126. |
| | user control: | intermittent |
| | feature extraction: | the feature vector was generated by filtering the amplified, time-domain ECoG signal between 0.05 and 100 Hz. |
| | feature translation: | the filtered, time-domain signal was correlated to template. The output was turned on if correlation values were greater than a heuristic threshold. |
| | outputs: | a single output, equivalent to a momentary-on 2-position switch |
| Control Interface: | … | n/a (off-line evaluation of a BCI Control design) |
| Device: | … | n/a (off-line evaluation of a BCI Control design) |
| Device Controller: | … | n/a (off-line evaluation of a BCI Control design) |

BCI research community will accumulate more data on the abilities of various BCI Controls in a range of applications. From this data, additional characteristics of BCI Controls and Control Interfaces will undoubtedly emerge that can be added

TABLE IV *(Continued)*
SAMPLE BCI SYSTEM DESIGNS DESCRIBED IN THE CONTEXT OF THE PROPOSED TAXONOMY

| | | |
|---|---|---|
| **Mason and Birch [16] 2000** | | |
| Target Population: | description: | individuals with severe movement impairments |
| | needs: | self-paced control of appliances in their environment |
| Target Tasks: | description: | self-paced operation of one or more prosthetic devices (such as robotic assistive appliances, computers or neural prostheses) |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | active control of single-trial, imagined movement-related potentials |
| | input: | EEG recorded over SMA and Primary Motor Cortex |
| | user control: | intermittent |
| | feature extraction: | the feature vector was calculated from windowed 1-4Hz EEG (over 1/8 second periods) using a custom spatiotemporal transform |
| | feature translation: | one-nearest neighbor (1-NN) classification, using reference vectors selected with LVQ. |
| | outputs: | a single output, equivalent to a momentary-on 2-position switch |
| Control Interface: | ... | n/a (off-line evaluation of a BCI Control design) |
| Device: | ... | n/a (off-line evaluation of a BCI Control design) |
| Device Controller: | ... | n/a (off-line evaluation of a BCI Control design) |
| **Kostov and Polak [26] 2000** | | |
| Target Population: | description: | individuals with severe motor disabilities who have no physical channel for control |
| | needs: | ability to communicate and/or control a prosthetic device |
| Target Tasks: | description: | control of one or more prosthetic devices by moving a cursor to select icons on a computer monitor. |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Controls: | neuro. mechanism: | not well defined – seems to be brain activity related to non-specific task-related (not movement-related) thoughts (such as "move cursor up" or "move cursor down") |
| | input: | EEG recorded across sensory-motor cortex using bipolar electrodes at FC3-CP3 and FC4-CP4. |
| | user control: | continuous |
| | feature extraction: | the feature vector was calculated from multiple channels of windowed EEG. Four AR coefficients per channel were combined into the final feature vector. |
| | feature translation: | an adaptive logic network (ALN) maps the feature vectors onto one of two (or four) states. |
| | outputs: | a single output, equivalent to a 2-position (or 4-position) switch |
| Control Interface: | inputs: | a single 2-state (or 4-state) input |
| | semantic translation: | the 2-state input was mapped onto discrete vertical cursor displacement. (The 4-state input was mapped to discrete horizontal and vertical cursor displacement.) Over time, the cursor reached a target at the top or bottom of a computer screen for 1-D cursor control, or targets at the four corners for 2-D cursor control. Since this study was an on-line study of a BCI Input Device design only, the outputs related to "cursor at target X" were not mapped to specific semantic values. |
| | outputs: | a single 2-state (or 4-state) output (no specific semantic meaning assigned) |
| | Control Display: | a 1-D (or 2-D) cursor was visible on a computer monitor. The cursor position indicated how close it was to one of the two (or four) possible selections at the top or bottom (or corners) of the screen. |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | ... | n/a (on-line study of a BCI Input Device design) |
| Device Controller: | ... | n/a (on-line study of a BCI Input Device design) |
| **Mason et al [13] 2000** | | |
| Target Population: | description: | individuals with severe movement impairments |
| | needs: | self-paced control of appliances in their environment |
| Target Tasks: | description: | self-paced operation of one or more prosthetic devices (such as robotic assistive appliances, computers or neural prostheses) |
| Target Environment: | description: | not explicitly defined – text implies general living or work environments |
| BCI Control: | neuro. mechanism: | active control of single-trial, imagined movement-related potentials |
| | input: | EEG recorded over SMA and Primary Motor Cortex |
| | user control: | intermittent |
| | feature extraction: | the feature vector was calculated from windowed 1-4Hz EEG (over 1/8 second periods) using a custom spatiotemporal transform |
| | feature translation: | one-nearest neighbor (1-NN) classification, using reference vectors selected with LVQ. |
| | outputs: | a single output, equivalent to a momentary-on 2-position switch |
| Control Interface: | inputs: | a single, 2-state output |
| | semantic translation: | the 2-state input directly mapped onto "change direction" or "do nothing" |
| | outputs: | a single output representing "change direction" or "do nothing" |
| | Control Display: | none |
| | stim. mechanism: | none |
| | On/Off mechanism: | manual |
| Device: | description: | a "pong"-style video game presented on a computer screen. The User had control of the direction of the center ball. |
| | state feedback: | visual feedback of the direction of ball movement |
| Device Controller: | inputs: | a single input, representing "change direction" or "do nothing" |
| | functional desc: | if the input is "change direction", toggle direction of a central ball between horizontal and vertical. |

into the taxonomy. For example, the following characteristics may be useful descriptors for BCI Controls: appropriate User populations, appropriate Control Interfaces, type and extent of User training required, retention of User training, and the constraints required on concurrent conventional sensory inputs and motor outputs. Additional characteristics of a Control Interface may include appropriate types of BCI Controls, required User sensory capabilities, and environmental constraints required for use. (Note that these suggestions are illustrative and not intended to be an exhaustive list.) The taxonomy may also be expanded to categorize aspects of BCI System evaluation.

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