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Brain-Computer Interfaces used for Virtual Reality Control

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***Abstract*— Brain-Computer Interfaces (BCIs) are *non-muscular channels for sending messages and commands to the external world*. Historically, BCIs were developed with biomedical applications in mind, such as restoring communication in completely paralyzed individuals and replacing lost motor function. More recent applications have targeted non-disabled individuals by exploring the use of BCIs as a novel input device for entertainment, gaming and virtual reality (VR) control. This paper acquaints readers with the necessary background knowledge on BCIs and outlines the usefulness of VR to enhance BCI performances.**

Keywords: Brain-Computer Interface, Electroencephalogram, Virtual Reality, Augmented Reality, Bionics.

I. INTRODUCTION

Many studies have demonstrated that humans can use signals from the brain not only to restore communication in patients with locked-in-syndrome or control of neuroprosthesis in patients with spinal cord injury, but also to navigate in virtual environments, manipulate virtual objects or control computer games [1, 2, 3, 4]. On the one side, virtual reality (VR) is a powerful feedback medium that makes users more engaged and motivated, and is able to shorten Brain-Computer interface (BCI) training times [5, 6]. On the other side, VR can be used to realize and test scenarios that are too dangerous or too difficult to perform in reality, as for example to investigate motorized wheel chair control by thought with disabled users.

One of the first who combined VR and BCI technologies was Bayliss in 2003 [7]. Bayliss' group introduced a VR smart home in which users could control different appliances using evoked brain potentials. The results of the experiment showed that immersive feedback based on a computer game can help people learn to control a BCI based on imagined movement more quickly than mundane feedback. Recently, Leeb et al. [5] reported on exploring a smart virtual apartment using a motor imagery-based BCI, and Holzner et al. [8] on an experiment for smart home control using a visual attention-based BCI. Both studies reconfirmed the finding that VR enhances the motivation and shorten the training.

In this paper, we introduce novel readers to the field of brain-computer interfacing, define important concepts and terms, and discuss the usefulness of VR to enhance BCIs technology.

II. DEFINITION AND BASIC PRINCIPLES OF A BCI

A BCI is a "...new non-muscular channel for sending messages and commands to the external world" [1] and must fulfil the following three requirements:

- At least one brain signal that the user can intentionally modulate must provide input to the BCI,
- the digital signal processing and pattern recognition must occur online and real-time, and output a communication or control signal, and
- the user must obtain goal-directed feedback, about the success or failure of the control.

As a consequence of these requirements each BCI is a *closed-loop system* with two adaptive controllers *the user's brain* and the *BCI* itself.

BCIs can be differentiated into two categories: Exogenous or stimulus-dependent BCIs are based on external stimulation and focused attention to selected stimuli. Endogenous BCIs require the user to perform mental tasks as e.g. motor imagery, mental arithmetic or mental rotation.

In the case of exogenous BCIs, phase-locked changes in the brain signal (evoked potentials) are processed; In the case of endogenous BCIs non-phase locked changes in brain rhythms are analyzed and classified. These changes are mentally induced and known as event-related desynchronisation (ERD) and event-related synchronization (ERS) [9]. Summarizing, we can differentiate between BCIs using predefined mental tasks and classifying induced brain activitiy (Figure 1 upper panel), while the others are based on sensory stimulation (e.g. visual) and classifying evoked potential changes (Figure 1 lower panel).

A. Exogenous or Stimulus-Dependent BCIs

P300 BCIs and steady-state visual evoked potentials (SSVEP) BCIs belong to the class of exogenous BCIs. The P300 is the positive component of the evoked potential that may develop about 300 ms after an item is flashed. The user focuses on one flashing item while

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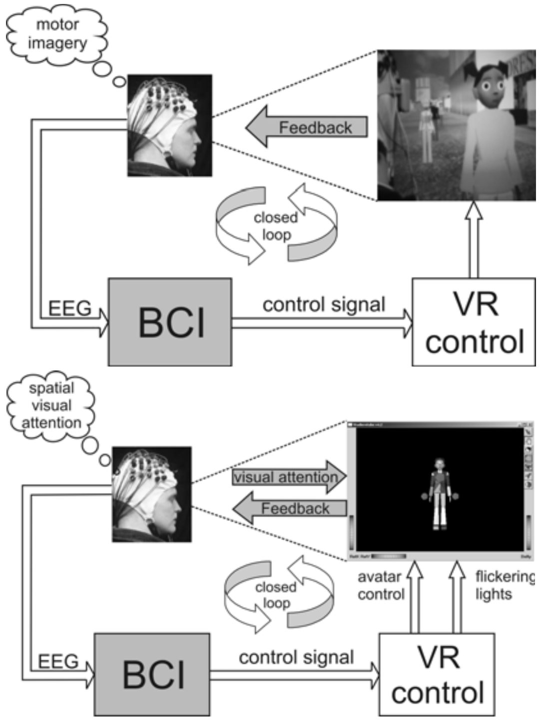

Figure 1. Principles of endogenous BCI systems without external stimulation (upper panel) and exogenous or stimulus-dependent BCI systems with external stimulation (lower panel). Motor imagery is the most common mental strategy for BCIs which does not rely on external stimulation to generate the necessary brain activity. BCIs that do rely on external stimulation to elicit brain activity typically involve spatial visual attention.

ignoring the other stimuli. Whenever the target stimulus flashes, it yields a larger P300 than the other possible choices. P300 BCIs are typically used to spell but have been validated with other tasks such as control of a mobile robot or a smart home [8]. Steady-state evoked potentials (SSEPs) occur when sensory stimuli are repetitively delivered rapidly enough that the relevant neuronal structures do not return to their resting states. The user has to focus on one of several stimuli, each of which flicker at a different rate and/or phase. Typical SSVEP BCI applications are control of spelling systems, avatars or computer games [10, 11].

The main advantages and disadvantages of P300 and SSVEP BCIs are: They require minimal training, can be set-up easily and very fast, can be realized with only one EEG channel and can achieve a high information transfer rate (ITR) of up to 60 bits/min. The main disadvantage however, is that those systems require permanent attention to external stimuli which may be fatiguing for some users.

B. Endogenous BCIs

The endogenous BCIs are known as sensorimotor rhythm (SMR), mu, beta or ERD BCIs and rely on the detection of mentally induced amplitude changes in sensorimotor (mu and central beta rhythms) and/or other brain oscillations [1, 2, 4, 12]. The most common mental strategy is motor imagery which results in a somatotopically organized activation pattern, similar to that observed when the same movement is really executed. In particular, hand and feet motor imagery affects sensorimotor EEG rhythms in ways that allow a BCI to detect such changes online and generate a reliable control signal.

The SMR or ERD BCI can operate in two different modes: the input data are either processed in a predefined time window of a few seconds each following cue stimuli (synchronous or cue-based BCI), or continuously by sample-by-sample (asynchronous or self-paced BCI). In a synchronous protocol the user is instructed to perform the mental task after each cue; the EEG processing is time-locked to externally-paced cues that are repeated in intervals of several seconds because the onset of motor imagery is precisely known. No cue is presented in the asynchronous mode. Hence, the system is continuously available for control, allowing users to freely decide when they wish to generate a control signal. The output (control) signal of a BCI can be either the result of the user`s intended control (IC) or not-intentionally (NIC) generated. In the latter case, the resting state activity, undefined mental tasks (thoughts) or artifacts may be erroneously classified as correct. Such an asynchronous BCI is more complex and demanding for developers, even though it may be easier for the user.

The main advantages and disadvantages of SMR or ERD BCIs are: They are independent of any stimulation and can be operated at free will. The ITR is between 20 – 30 bits/minute. For a good performance multichannel EEG recordings are necessary. The main disadvantage, however, is that the training is very time-consuming, can last many weeks and months in patients. Moreover not all users are able to obtain control of their brain waves after intensive training. ERD-based BCIs have been used to control the steering of a virtual car or the take off of a virtual spaceship [13, 14].

III. THE IMPORTANCE OF BCI FOR VR TECHNOLOGY

The increasing availability of VR technology has awakened increasing interest in using BCI applications in virtual environments (VEs). BCI systems may overcome an important limitation of VEs, which is that one has to use interfaces like mouse or keypad for e.g. navigating through a VE [15]. BCIs offer the promise of hands-free and more intuitive VE control through imagination of hand or foot movement by using an *endogenous* BCI paradigm (Figure 1, upper panel). In the case of an exogenous or *stimulus-dependent* BCI-VR systems

(Figure 1, lower panel), the users can control appliances in the VE by simply directing their eye gaze and/or focus of attention towards the desired element as e.g. looking at the TV to switch it on or looking at the door to open it.

One of the great advantages of immersive virtual environments (VE) is that they can be used for rehearsal of scenarios or events that are otherwise too costly or even impossible in physical reality. One example is the prototyping and testing of systems for BCI-based prosthesis control, another is to investigate wheel chair control through thought. For a tetraplegic person who is wheel chair-bound, training in VEs is especially attractive. A new fields to benefit from VR technology is that of restoration of movement after stroke [16]. Patients can learn e.g. to realize object-related grasping with a virtual hand controlled by a motor imagery-based BCI.

IV. VR AS EFFICIENT FEEDBACK MEDIUM IN BCI RESEARCH

Each BCI system is a closed loop system (see Fig.1) whereby feedback is a very important component as it provides the user with information about the efficiency of his/her strategy and success or failure of the control. It was shown that immersive VR feedback can enhance the mental effort and result in a better performance when compared to simple PC feedback with a moving bar [17]. VR feedback can not only enhance the classificabilty of brain patterns, but also modify emotional experiences and enhance cardiovascular responses. Large heart rate responses in the order of several beats per minute are e.g. a prerequisite to realize a hybrid BCI with simultaneous EEG and ECG processing and the enhancement of the overall BCI performance [12].

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