REVIEW ARTICLE

USE OF BRAIN-COMPUTER INTERFACES UNDER EXTREME ENVIRONMENTAL CONDITIONS

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Introduction*:* Brain-computer interfaces (BCI) are devices that enable transmission of signals outside the nervous system without engaging muscles. One of the fields in which BCI can be used is aviation and astronautics. However, the way of assessing the utility of BCIs under specific conditions of flight and outer space is controversial. This review aims to present the limitations of future use of brain-computer interfaces under extreme environmental conditions as well as to indicate the direction for further research that could overcome these limitations.

Methods: Systematic review.

Results: In the first part, we present basic information on the subject of brain-computer interfaces and how they work as well as characterize invasive and noninvasive methods of registering brain activity in such devices. Subsequently, we describe the most popular types of brain-computer interfaces in terms of their differences regarding the speed of information processing, mechanisms and time needed to master their use. Then, we propose the ways in which brain-computer systems could be used in aviation and astronautics and describe the basic conditions under which they could be used in natural environments. We also analyze the influence of extreme environments on the physiological and psychological functioning of people.

Conclusion: Considering the difficulties in using BCI systems under extreme environmental conditions, we propose specific methods and conditions under which studies should be performed in order to provide reliable assessments of the utility of brain-computer interfaces in aviation and astronautics.

Keywords: brain-computer interfaces, EEG, extreme environment, psychophysiology, ergonomics

INTRODUCTION

Brain-computer interfaces (BCI) are systems that transform the activity of the central nervous system into actions of external tools that substitute, restore, enhance, supplement or improve natural ways of communication of people with the environment without any use of neuromuscular and hormonal pathways [72].

The steering of a brain-computer interface is based on the principles of neurophysiological feedback (neurofeedback, NF). The users learn to control their own physiological reactions by observing the changes that are induced in the device that is being steered [12]. The activity of the brain can be recorded with different methods of neuroimaging. There are methods that detect metabolic changes in the central nervous system (CNS) such as functional magnetic resonance (fMRI) [30, 56, 61, 62, 73] or functional near-infrared spectroscopy (fNIRS) [11, 42,63]. Brain-computer interfaces can also be based on devices that detect the bioelectrical activity of the brain. This can be done invasively with the use of electrodes implanted directly in the tissue [19, 20] or placed on the cortical surface [32, 57, 68]. In noninvasive methods such as magnetoencephalography (MEG) [4, 6, 36] or electroencephalography (EEG) [23], the physical barrier of the organism is preserved. The latter method, i.e. EEG, is used in approximately 60% of all research brain-computer interfaces. It is used commonly due to a low cost of use and a good ratio of temporal resolution to spatial resolution [23].

Over the last 25 years, the interest in creating new brain-computer interfaces has been constantly growing [22]. With an expanding interest in this method, the number of its possible applications is also growing. Some of the uses of BCIs include hand prostheses [51], wheelchairs [21], applications that improve communication [47] and virtual reality [32]. The majority of these applications are dedicated to people who have either completely lost their ability to communicate with the environment because of disease [28, 35] or have this ability limited to a significant extent [40, 45, 46, 68].

Some of the applications of BCIs can also be used by healthy people, for instance, in order to steer a car [2], a humanoid robot [3], a drone [29] or an aircraft [17] (Fig. 1). However, the speed of information exchange in the fastest available brain-computer interfaces ranges only from a few to a dozen bits per minute [44]. The effectiveness of this method is therefore significantly lower in comparison to the control with the use of limbs (96-198 bit per minute) or eye movements (ca. 60 – 222 bits per minute) [9]. This is insufficient in order for BCIs to substitute the contemporary ways of steering vehicles under normal environmental conditions.

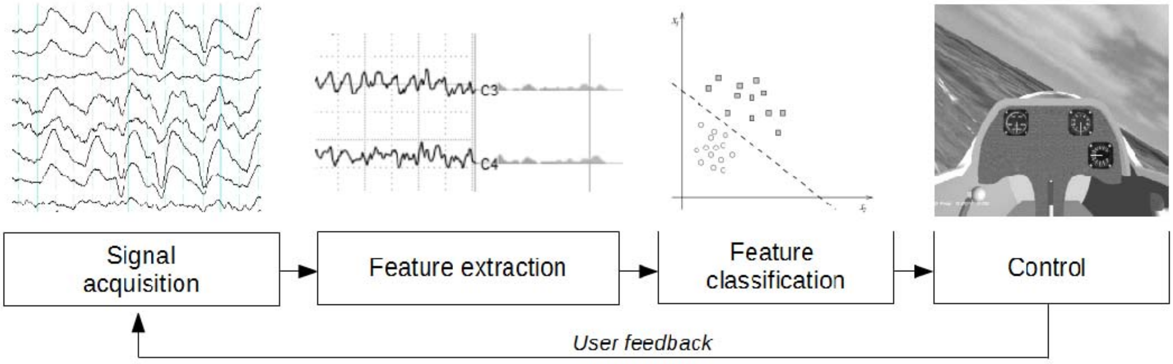


Figure 1. Diagram showing the processing of signals in a brain-computer interface. The registered single (e.g. EEG) is transformed in order to extract changes in frequencies and spatial localization typical for a give system. A classification algorithm assigns signal changes to the reactions of the device. Finally, the real-time changes in the recordings are transformed into responses of the application or device, for instance, into parameters of flight in a flight simulator. The users, by observing the reactions caused by their activity, can modify their activity instantly based on the principles of feedback.

Research on alternative ways of communication with machines without the use of muscle control is carried out also in the view of extreme environments in which this type of control could be hampered by unfavorable environmental conditions. Such conditions can be found during flight [39] or in astronautics [38]. Therefore, there a proposals to use brain-computer interfaces in the fields of astronautics where the activity of people has always been supported by other monitoring and assisting devices. However, it is rarely underscored that current BCI systems have a low effectiveness of communication [9]. In the context of the use of BCI systems in aviation and astronautics, an important issue, that is often overlooked, is the influence of the environment on physiological and psychological mechanisms. This influence can limit the possibility of using specific BCI types in aviation and astronautics [15]. Although some attempts to use BCIs to steer drones or simulators have been made [17, 29], there are serious doubts regarding the fact if the obtained results can be utilized outside the laboratory.

In this context, in the subsequent parts of this article, we evaluate the possibility to use selected BCI systems in aviation and astronautics. We will discuss advantages and disadvantages of particular types of brain-computer interfaces that could be used under the specific conditions of flight and space journey. We also describe the tests of brain-computer interface that have been performed under extreme environmental conditions.

Main types of brain-computer interfaces

In order for a given biological signal to be used in brain-computer interfaces, it has to be clearly recorded, repeatable and easy to modulate. In the case of the most common EEG-based interfaces, several such phenomena have been observed [75]. Some of them are passive, which means that they represent the brain's reaction to stimuli. This type of interface is based on searching for EEG features that are associated with a given property of the presented stimulus, e.g. the frequency of stimulus display. There are also active interfaces that utilize the brain's reaction associated with an intentional action, e.g. an imagined movement or performance of arithmetic calculations. Moreover, there are intermediate interfaces that are both partially passive and active, and they are referred to as reactive systems. In this case, similarly to passive interfaces, the relation between the presented stimulus and its correlate in the signal is looked for. It should be stressed that this correlate is produced as a result of a cognitive reaction of the users who directs their attention to a particular object. The different types of brain-computer interfaces differ in terms of speed of information processing, ergonomics and times needed to master control over the interface [44].

Active BCI

In recent years, more than a half of publications in the field of brain-computer interfaces deals with active interfaces [23]. The majority of them utilizes the so-called sensorimotor rhythms (SMR). This is a type of activity that is observed over the areas of the sensorimotor cerebral cortex [52]. It is registered in three frequency ranges, μ (8-12 Hz), β (18-30 Hz) and γ (30 - 200+ Hz), although the limits of these ranges are determined individually [54]. During the performance of a motion as well as during an observed or imagined movement, the power of SMR signal decreases; this phenomenon is termed event-related desynchronization (ERD) [48]. After completion of the movement or during periods of relaxation, an opposing phenomenon takes place, and this is referred to as event-related synchronization (ERS) [48]. Both ERD and ERS take place during movements of individual fingers, hands, feet or tongue [50, 54]. As regards hand movements (real or imagined), ERD/ERS is more pronounced in the contralateral electrodes [52]. The difference in ERD/ERS power between ipsilateral and contralateral electrodes can be used in brain-computer interfaces and translated, for instance, to movements of the cursor on the screen [72].

The effectiveness of SMR-BCI-driven control depends on individual predispositions and can be influenced by variables such as lack of attention during performance of tasks [13]. The task of simulating one's own movements is difficult for people with a poor ability to imagine sensorimotor phenomena [67]. Devices based on sensorimotor waves are characterized by moderate effectiveness (~3 signs per minute) and need to be preceded by training sessions [70]. At the same time, the process of steering objects by imaging movements is natural and therefore the devices can be used long-term [12].

Brain-computer interfaces that are based on sensorimotor rhythms have been tested in hypergravity (1.8 g) and zero gravity (0 g) during parabolic flights. Therefore, it can be supposed that this type of BCI could be used in astronautics [39]. Successful attempts to control vertical movements of an aircraft in a flight simulator and to control flight parameters of a quadcopter (up/down/right/left) have been made with the use of SMR-BCI [17, 29]. Some interesting data on the use of SMR-BCI have been provided by the experiments conducted by Vecchiato and co-workers [66]. The participants in those experiments controlled a flight simulator with the use of brain-computer interfaces and at the same time they performed other tasks that engaged attention and vigilance. Although the effectiveness of control fell in comparison to the control condition, the participants were able to steer the simulator with an increased cognitive burden.

Passive BCI

Passive brain-computer interfaces are characterized by the highest efficacy of information transmission (up to 60 – 100 bits per minute), and their advantages include no necessity for long-term training and a high resistance to artifacts [44]. Passive BCIs are based on the so-called steady state evoked potentials (SSEP). Similar to other event related potentials (ERP) that are studied in psychophysiological experiments, SSEPs are EEG patterns that are correlated with particular stimuli or events. In contrast to ERPs, where characteristic positive or negative potential deviations of the EEG signal are looked for, in SSEP, the patterns that are correlated with stimuli can be found in specific rhythmic oscillations that are similar in frequency to the oscillations of the presented stimulus. In the case of SSEP, the stimuli are not single events but rather systematically repeated events with a specific interval [12]. An increase in the power of signal within a particular frequency range or its derivative (i.e. harmonic or subharmonic frequency) is correlated with the occurrence of a stimulus that have been displayed with a similar frequency [1].

The stimuli that can be used in SSEP-BCI can have various modalities. Most commonly, visual stimuli are used (steady-state visual evoked potentials – SSVEP) [12]. There are also steady-state somatosensory evoked potentials (SSSEP) that are induced by touch [41] as well as auditory steady-state evoked potentials (ASSEP) induced by sounds [24].

Despite the obvious advantages of SSEP-BCI, they require constant focusing of attention of the proper stimulus, which can cause exhaustion of the user and limit the time of a single BCI session [43]. Moreover, the relatively unnatural way of presenting the stimuli (in the case of SSVEP it involves a high-frequency flashing) can increase the risk of an epileptic seizure [1]. Although an SSVEP-BCI has been tested in flight simulators in a horizontal plane [38], there are no data on the effectiveness of this technology under extreme conditions, e.g. in hypergravity or zero gravity.

Reactive BCI

Reactive interfaces combine the features of both active and passive interfaces, as they use changes in the P300 component depending on focusing of attention on the presented stimuli. The P300 wave is a component with a positive deviation that can be seen 250-750 ms after stimulus presentation. It is best seen in the electrodes located in the central-parietal areas [60]. The presence of P300 wave is associated with the fact of anticipating a stimulus (visual, auditory, sensory) or with directing attention towards a new element in a set of known elements [12]. The tasks that can elicit the P300 wave require the user to direct attention towards the target stimulus and to ignore the remaining elements that can be described as noise.

The brain-computer interfaces based on the P300 component are characterized by the following features – a high validity (up to 95% of correct assignments), high speed of transmitting information (20 – 25 sign per minute) [44] and requirement of prior training [60]. There are, however, serious limitations of P300-based BCIs. Because ERP components have a small voltage, they are difficult to extract from signal noise [34]. Therefore, it is necessary to repeat the procedure many times in order to identify the relevant changes in EEG recordings. Moreover, reactive, P300-based BCIs are influenced by user-dependent factors such as the ability to sustain attention and direct vision in specific directions. Both of these abilities decline with time [5]. The P300 wave can also be influenced by gradual habituation during a long session with the device, and this makes the placement of subsequent stimuli more and more difficult [60]. P300-based BCIs can be additionally influenced by other ERPs that are detected simultaneously [1]. Although the P300 component has long been regarded as a correlate of attentional processes that can be monitored during flight [27], there are no experimental data on the use of P300-based BCIs in such conditions.

Potential applications of BCI in aviation and astronautics

Coffey and co-workers [10] name three areas in which BCIs can be used in astronautics. These are as follows: (I) modification of interactions between the user and the device that is being steered; (II) objective measurement of ergonomics and utility of designed systems; (III) gathering of data on functioning of the user during various tasks performed under extreme conditions. For instance, the engagement of the user's attentional processes could be evaluated during the performance of difficult procedures in outer space. Data on neuronal correlates of attentional processes, such as the P300 component, could provide an additional safety control that could reduce the risk of mistakes associated with exhaustion or cognitive burden.

A list of requirements for BCI systems to be used under extreme condition, such as microgravity, was put forward by De Negueruel and co-workers [15]. First, a brain-computer interface used under extreme conditions should be based on *a noninvasive method of registering brain activity*, as performing tasks under such conditions is associated with an increased health risk for the user. Second, BCI systems should be *relatively reliable*, as repairs or exchange of elements cannot be carried out under extreme conditions. Third, obviously, BCIs should be characterized by a *high effectiveness and sensitivity of the applied solutions*. The authors also emphasize the *ease of use* as a decisive property, because the potential users cannot count on external help, and the tasks performed by them will take place in environments that limit their movements. Moreover, the directions of research that could enable the use of BCIs under extreme condition have also been proposed [37]. According to the author's, an emphasis should be put on the following areas – ability of a constant synchronization of the interface with the state of the user, searching for markers of higher cognitive and emotion functions, improvement of spatial resolution, methods of displaying feedback information and device ergonomics.

The usefulness of BCI systems used under extreme condition should also be evaluated in terms of the potential factors that could interfere with their function. This applies especially to the changes in the physiological and psychological state of users that are seen during flight and space journey.

Physiological and psychological functioning in hypergravity and modified gravity

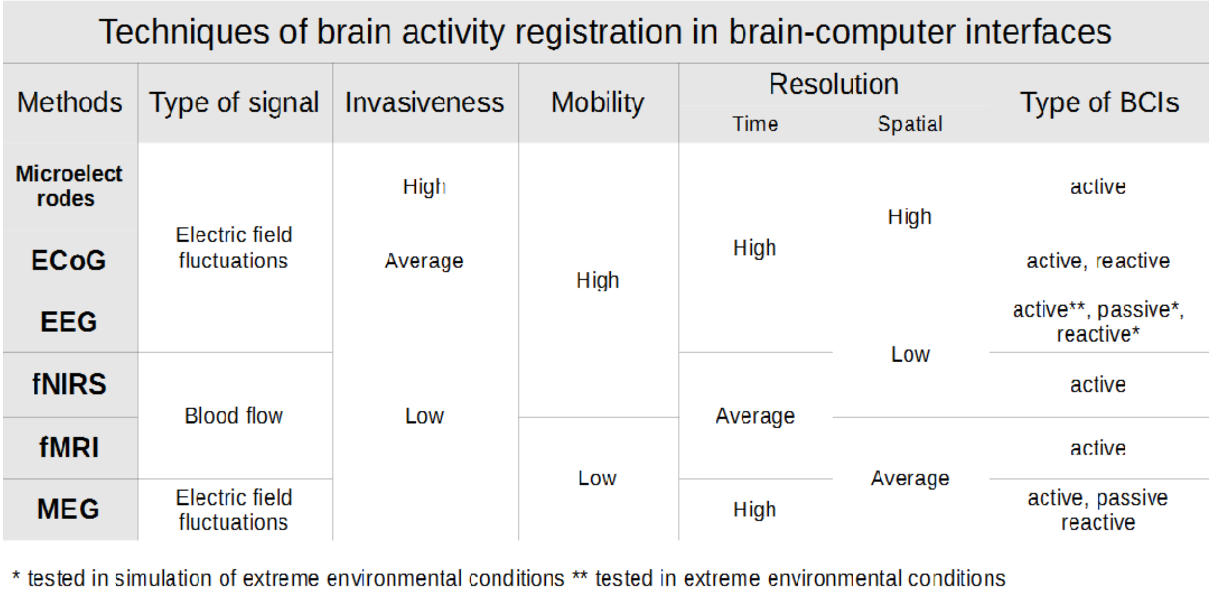
In the fields of medicine, aviation and astronautics psychology, a number of factors that influence the physical and psychological function of people during flights and space journeys have long been identified [65, 14, 31, 64]. The most common factors include hypergravity, acceleration, changes in gravity, noise, changes of body orientation in space, time pressure and changes of atmospheric pressure. They result in physical and psychological symptoms such as stress, decreased concentration of attention, disorientation, cognitive overload, disturbance of circadian rhythms, disorders of the vestibulum and difficulties in movement control. Some of the above-mentioned factors can influence the effectiveness of selected types of brain-computer interfaces that could be used in aviation and astronautics [37, 10, 15]. Therefore, studies that investigate the mechanisms associated with particular BCI types used during real or simulated flights or space journeys provide the most useful data.

An active BCI based on sensorimotor rhythms within the μ and β frequency ranges has been tested in experiments similar to natural conditions. [53]. In an experiment carried out during a parabolic flight, it was observed that the amplitude of waves in the β range decreases during microgravity and increases in hypergravity [59]. An increase in the power of waves of the 10 Hz frequency (the μ range of 8 – 12 Hz) was also observed during decreased gravity [7]. Therefore, the changes in environmental conditions can modify SMR waves in a way similar to the ERD/ERS phenomenon during an imagined movement. Being in microgravity for a long time can also influence the activity of structures engaged in motor control. In a case study of an astronaut who returned from space after 169 days, during which time he lived in microgravity, it was shown that the functional connectivity (studied by fMRI) between cerebellum and motor areas, engaged also in the modulation of sensorimotor waves, was decreased [16]. Functional resonance imaging experiments have also shown that, after being exposed to microgravity, other structures related to initiation of movements, motor coordination and kinesthetic perception had decreased activities [14]. Moreover, it has been shown that people who experience microgravity have difficulties in planning goal-directed movements [64], and the process of imaging such movements is utilized by SMR-BCIs [43]. This is an argument against the use of this type of brain-computer interfaces under extreme conditions.

In the case of reactive and passive BCI systems that use the P300 components and steady-state potentials, attentional processes and working memory influence the effectiveness of device control [25, 57]. Lia and co-workers [31] observed a decreased activation of the anterior cingulate cortex (ACC) after microgravity stimulation. ACC is associated with shifting and directing of attention. In another experiment with reduced gravity, such working memory deficits were not noted [73]. However, the decrease in cognitive function (including working memory) during flights can be related to stress that is difficult to recreate under laboratory conditions [73]. At the same time, the characteristics of the P300 potential are similar when it is induced during microgravity and normal gravity [26]. There are no studies on the steady-state potentials under conditions of modified gravity or under other extreme environmental conditions such as increased g-force. The usefulness of reactive and passive BCI systems is therefore still to be investigated.

CONCLUSIONS

In view of the above-mentioned articles and experiments, there are BCI systems that fulfill the largest number of usefulness criteria that decide on their employment in aviation and astronautics [15] (Fig. 2).



Techniques of brain activity registration in brain-computer interfaces

Methods	Type of signal	Invasiveness	Mobility	Resolution		Type of BCIs
				Time	Spatial	
Microelectrodes	Electric field fluctuations	High	High	High	High	active
ECoG		Average				active, reactive
EEG		Low			Low	active**, passive*, reactive*
fNIRS	Blood flow			Average		active
fMRI			Low		Average	active
MEG	Electric field fluctuations			High		active, passive reactive

* tested in simulation of extreme environmental conditions ** tested in extreme environmental conditions

Figure 2. Comparison of contemporary techniques of brain activity registration used in brain-computer interfaces. Properties of BCI systems that are relevant in extreme environmental conditions have been taken into account.

Among the methods of neuroimaging that are used in BCI, the noninvasive ones include EEG, MEG, fNIRS, and fMRI. However, only EEG and fNIRS are mobile enough to be used outside the laboratory. Both of these technologies are relatively *reliable* but are susceptible to artifacts induced by the user and the environment. With respects to EEG, artifacts are induced by muscle activity, eye movements and electric devices [34]. NIRS is based on the emission and detection of infrared light that goes through brain tissue and therefore it is resistant to changes of the electric field. However, NIRS measurements can be affected by other sources of light or metabolic processes other than brain activity. With the use of fNIRS, the changes in motor cortex activity during an imagined movement (similarly to SMR-BCI systems) as well as in frontal cortex during engagement of higher cognitive processes have been measured [62]. This method seems to be superior to EEG as regards monitoring of the state of the user; in this case, the communication with and steering of individual devices can be analogous to active BCIs, i.e. in a relatively free, cognitively absorbing way that requires prior training [63]. The criterion of *effectiveness* is met currently only by passive and reactive systems that use noninvasive electroencephalography [44, 60]. The postulated ease of use points towards passive and reactive systems, as they require from the user the least amount of learning. Moreover, in the case of EEG, the so-called "dry" electrodes that can be easily applied [55] and a possibility of wireless transmission [80] are emphasized.

A significant obstacle in verifying if brain-computer interfaces can be used in aviation and astronautics is the way in which experimental studies are performed in this field. The only kind of BCI that have been tested in hyper- and microgravity is an active interface based on sensorimotor wave modulation by an imagined movement [39]. At the same time, it is known that active BCIs require the largest amount of cognitive engagement on the side of the user, and they have a relatively low effectiveness of transmitting information [70]. Currently, it is hard to imagine that such interfaces could be used to control real vehicles outside the laboratory [29] or outside flight simulators [17]. BCIs based on passive (SSVEP) and reactive (P300) solutions have not been tested directly in experimental studies, although these BCIs have the greatest effectiveness and resistance to artifacts [44, 60]. They can also (P300) provide information on cognitive function during performance of tasks related to flight control; this can potentially increase the range of possible applications.

Data on the functioning of the nervous system and on the changes in EEG signal under the conditions of flight or space journey are gathered primarily in the laboratory. Although the changes in head position can imitate changes in gravity [60], it is difficult to model other physiological and psychological determinants that are relevant for BCI functioning. Experiments performed during parabolic flights seem to a relatively good solution [39], but experiments carried out, for instance, in centrifuges are lacking. Despite the costs and difficulties in performing such experiments, only ecologically valid studies could verify to what degree current brain-computer interfaces could assist the user under demanding environmental conditions.

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Study Design: Dariusz Zapała, Marta Jaśkiewicz, Marta Ratomska**,** Piotr Francuz **Data Collection:** Dariusz Zapała, Marta Jaśkiewicz, Marta Ratomska **Funds Collection:** Dariusz Zapała. The Authors declare that there is no conflict of interest.

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