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ORIGINAL ARTICLE

Brain–computer interfaces for space applications

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Abstract Recent experiments have shown the possibility to use the brain electrical activity to directly control the movement of robots. Such a kind of brain–computer interface is a natural way to augment human capabilities by providing a new interaction link with the outside world and is particularly relevant as an aid for paralysed humans, although it also opens up new possibilities in human–robot interaction for able-bodied people. One of these new fields of application is the use of brain–computer interfaces in the space environment, where astronauts are subject to extreme conditions and could greatly benefit from direct mental teleoperation of external semi-automatic manipulators—for instance, mental commands could be sent without any output/latency delays, as it is the case for manual control in microgravity conditions. Previous studies show that there is a considerable potential for this technology onboard spacecraft.

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Abbreviations

AI	Artificial intelligence
ANN	Artificial neural networks
BCI	Brain–computer interface
CNS	Central nervous system
EEG	Electroencephalogram
EVA	Extra-vehicular activity
fMRI	functional magnetic resonance imaging
GCR	Galactic cosmic rays
HDT	Head-down tilt
IDIAP	Institute dalle-molle d'Intelligence artificielle perceptuelle
IVA	Intra-vehicular activity
LEO	Low-earth orbit
MEG	Magneto-encephalography
MMU	Manned manoeuvring unit
PET	Positron emission tomography
SAFER	Simplified aid for EVA rescue
SCR	Solar cosmic radiation
SPE	Solar particles events
SPR	Solar particle radiation
UV	Ultra-violet

1 Introduction

While communication between humans has been extensively developed and studied, communication between people and artificial systems and machines is at a relatively early stage. It was just 60 years ago that the state-of-the-art for computing communication required the use of punch cards. Although modern means of interfacing with a computer—such as keyboard, mouse or joystick—show a remarkable improvement, they remain unintuitive and unnatural. If we consider the ultimate goal of every human–computer interaction technology to be the minimisation of the gap between the human's cognitive models of what they want to accomplish and the computer's understanding of the user's intended task, Brain–Computer Interfaces (BCI) seem to be the straightforward answer.

Scientists have speculated for decades on the possibility of a direct interface between a brain and a machine. The basic ideas were put forward in the 1970s, and some initial experiments were carried out—basically analysing the brain's electrical activity generated in response to changes in gaze direction [1]. Our understanding of how the brain works has increased since, and the recent years have seen the development of prototypes based on these and other principles, showing the possibility to use the brain electrical activity to directly control the movement of robots.

Such a kind of brain–computer interface is a natural way to augment human capabilities by providing a new interaction link—i.e. an additional communication channel—with the outside world and is particularly relevant as an aid for paralysed humans, although it also opens up new possibilities in human–robot interaction for able-bodied people.

One of these new fields of application is the use of BCIs in the space environment, where astronauts are subject to extreme conditions and could greatly benefit from direct mental teleoperation of external semi-automatic manipulators or robotic agents. For instance, mental commands could be sent without any output/latency delays, as it is the case for manual control in microgravity conditions. Previous studies performed by the authors indicate that there is a considerable potential for this technology onboard spaceships [2].

This chapter will offer an insight into the state-of-the-art of BCI technologies and review the challenges posed by the space environment and the effects that it could have for the implementation of BCI systems. We then critically analyse the requirements for a successful implementation of a BCI system to be used in space and the possible showstoppers that could interfere with this implementation. To conclude, we propose the systems that we believe are the most promising for a successful integration into space applications, and finally we present our vision of what these applications may be, far in the future… or maybe not so far?

2 Background

2.1 Brain–computer interfaces

A BCI is, broadly speaking, any device that can monitor brain activity and translate a person's intention into actions, such as moving a robotic arm or selecting a letter from a virtual keyboard. Different intended actions or mental tasks produce different patterns of brain activity. Being able to distinguish them is at the core of BCIs.

A typical BCI system has a simple architecture, as shown in Fig. 1. The first step consists on the acquisition of the brain signals to be monitored, the nature of which will determine the instrumentation to be used. Once acquired, the signals are conditioned and converted to digital format for further processing. To be sure that the information comes strictly from brain signals, these may be filtered to eliminate unwanted artefacts (e.g. large-amplitude ocular movement signals). The extraction of the relevant features and their classification according to previous models will give information on the action intended by the user. Underlying all the process is a carefully designed application-dependant protocol that specifies the choice of mental tasks to be performed and stimulus parameters (i.e. information presented to the user at every moment).

There is a variety of methods to monitor brain activity, broadly classified as invasive and non-invasive. Most non-invasive BCI systems use electroencephalogram (EEG) signals, i.e., the electrical brain activity is directly recorded from the surface of the scalp, the main source of which is the synchronous activity of thousands of clustered cortical neurons. Although measuring the EEG is a relatively simple and non-invasive method, it does not provide detailed information on the activity of small brain areas and is characterised by noisy measurements and small amplitudes in the range of a few micro-volts.

Besides electrical signals, neural activity produces other types of signals that could be used in a BCI, such as magnetic and metabolic. Magnetic activity can be recorded

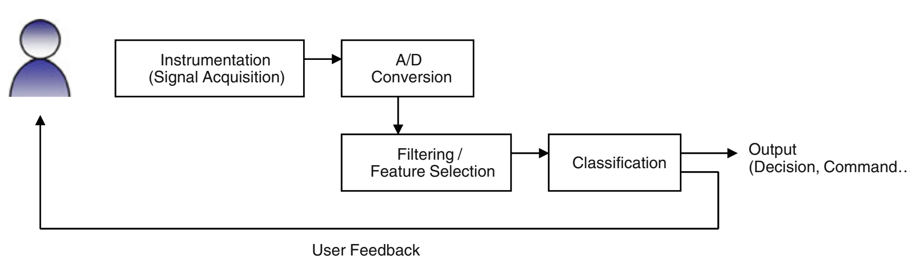

Fig. 1 The elements of a brain–computer interface

with magneto-encephalography (MEG), while metabolic activity (reflected in changes in blood flow and the blood oxygenation level) can be observed with functional Magnetic Resonance Imaging (fMRI), Positron Emission Tomography (PET) and optical imaging. However, these alternative techniques require very sophisticated devices that can only be operated in special facilities, making impractical their use for prototyping and practical implementation.

Invasive BCI systems measure the activity of single neurons from microelectrodes directly implanted in the brain. Although these techniques can provide signals that are less noisy than EEG signals and with higher spatial resolution, they still require surgical operations. In some cases, scar tissue might form from the surgical operations, impacting the strength of the electrical signal (as it implies changes of electrical impedance) and requiring repeated surgical treatments to maintain the signal strength. In a series of experiments with rats and monkeys, researchers have monitored different areas of the cortex related to execution and planning of movements, and from a real-time analysis of the neural activity, have been to determine the animal's movement intentions [3, 4], predict the monkey's hand trajectory [5, 6] and to drive a computer cursor to desired targets [6, 7]. The first steps towards invasive approaches in humans have been made, and one of the patients was eventually able to drive a cursor and write messages.

Partially invasive (or semi-invasive) BCI indeed reduce the risk of surgery infection and the formation of scar tissue as they are implanted inside the skull but on top of the brain surface. The signal strength and recognition is weaker than in the case of invasive BCIs and is still susceptible to noise, but this control option is suggested to be more powerful and stable than using non-invasive BCIs [8].

Nevertheless, we believe that a non-invasive approach promises a more direct impact for our society in the long term, both because it does not require surgical operations and it has a more favourable public perception. It is, in addition, more suitable for space applications as it needs shorter time for qualification and it is safer, especially from the perspective of the astronauts. In particular, and as discussed earlier, we will concentrate in BCIs using electrical brain signals as measured by EEG.

2.2 EEG-based brain–computer interfaces

2.2.1 Signals

In the presence of certain external stimuli (e.g. flashed images and lights), the EEG exhibits a strong characteristic signal, the so-called evoked potential, which reflects the immediate and automatic responses of the brain to those external stimuli. Evoked potentials are, in principle, easy to pick up with scalp electrodes and have been used in the context of BCIs [9–14]. The necessity of external stimulation does, however, restrict the applicability of evoked potentials to a limited range of tasks. In our view, a more natural and suitable alternative for interaction is to analyse components associated with spontaneous "intentional" mental activity. This is particularly the case when controlling robotics devices.

Spontaneous BCIs are based on the analysis of EEG phenomena associated with various aspects of brain function related to mental tasks carried out by the subject at his/her own will. Such a kind of BCI can exploit two kinds of spontaneous brain signals, namely slow potential shifts or variations of rhythmic activity. It should be noted that eye movements and breathing might cause considerable artefacts in slow potentials, while muscular tension—in face and neck—can generate artefacts in higher frequencies. Also, EEG rhythms have response latencies of about 0.5 s, whereas other EEG components have response latencies of two or more seconds.

2.2.2 Training

Some subjects can learn to control their brain activity through appropriate—but lengthy—training sessions in order to generate fixed EEG patterns that the BCI can then transform into external actions. An alternative to user training is to use machine-learning approaches to train the classifier embedded in the BCI. Most of these approaches are based on a mutual learning process where the user and the brain interface are coupled together and adapt to each other. This should accelerate the training time while the training efforts are reduced.

Typical tasks intended for subject training include positioning a cursor, tracking a moving object or selecting a target. Once these skills are acquired, the subject can progress to applications that perform real-world tasks such as communication, controlling the environment or moving robotic limbs. Incorporating rejection criteria to avoid making risky decisions is an important issue in BCIs. From a practical point of view, a low classification error is a critical performance criterion for a BCI; otherwise users can become frustrated and stop utilising the interface.

2.2.3 Synchronous versus asynchronous

EEG-based BCIs are limited by a low channel capacity, with most of the current systems having a channel capacity below 0.5 bits/s [15]. One of the main reasons for such a low bandwidth is that they are based on synchronous protocols. These facilitate EEG analysis since the starting time of mental states are precisely known. However, EEG-based BCIs are slow and normally recognise only up to four mental states independently of the number of electrodes used to acquire the measurement.

Other BCIs use more flexible asynchronous protocols where the subject can voluntarily change the mental tasks being executed at any moment without waiting for external cues [16]. The time of response of an asynchronous BCI can be below 1 s, although their accuracy is lower than for synchronous BCIs at the moment.

2.2.4 *Hardware*

Electroencephalogram signals are acquired with a portable acquisition system. Subjects wear a commercially available EEG cap with integrated scalp electrodes that cover the whole scalp and are located according to the 10/20 international system or extensions of this system to allow recordings from more than 20 electrodes (i.e., the 10/10 system) [17].

Electroencephalogram electrodes may bring many practical problems, such as sensitivity to electromagnetic radiation, difficulty to place and position, varying conductance, usually a limited number of channels and discomfort when used for a longer time.

New trends in the design of EEG measurement systems include miniaturization, battery-powered front-ends close to the patient, fibre optic data transfer to the computer in charge of signal processing and use of active electrodes. These have the property that the first amplifier stage is integrated within the electrode.

3 The case for BCIs into space

Space is a demanding environment, and space missions are among the most challenging endeavours undertaken by humankind. As it has been demonstrated during the almost 50 years of space age, a key factor for a successful space mission is a high degree of on-board autonomy, in particular when the spacecraft is travelling beyond Earth's orbit. For human missions, there are added requirements and constraints, and an efficient interaction between astronauts and space technology is a key factor. The question is in which context human spaceflight could benefit from BCI technologies.

Based on the unique advantages inherent to BCIs, we have identified a number of space applications that could benefit from the use of BCI technologies. Such applications range from critical and non-critical robotic applications to environment control, and even to monitoring astronauts' cognitive state. Looking farther into the future, we propose new applications based on features not yet fully investigated, like multitasking or human augmentation.

3.1 The advantages

Brain–computer interfaces are inherently advantageous when limited workspace and harsh environment prevent astronauts to manually send commands to external auxiliary artificial systems. BCIs bypass a direct interaction with the environment, thus allowing operations when the body of the astronaut is constrained.

The use of BCIs also suggests a new approach for the organisation of astronaut operations as multitasking could potentially be enabled. The capability of our cerebral activity to simultaneously perform different uncorrelated activities could be fully exploited by a machine that interprets commands directly from the astronaut's brain. One single astronaut could therefore perform several operations—his/her efficiency could be remarkably improved with strong impact on associated mission costs.

The capabilities of astronauts could be further improved as BCIs are envisioned to enable human augmentation. In addition to their own body, astronauts could also control external artificial systems that could be considered as their artificial appendages (invasive BCIs have already shown the feasibility of this feature).

An additional unique service that BCIs could enable would be a continuous monitoring of the health of the astronaut. Upon enabling a real-time check of brain functionalities, the post-processing of brain signals could give fundamental insights into the astronaut health state. Tiredness and loss of attention could be monitored to prevent inaccurate operations and erroneous commands.

An added benefit of the use of BCIs could be a theoretical faster control and easier command error correction. Differently from the other kind of interfaces, the nervous system is bypassed and signals could be sent without delay and distortion. However, much more research has to be done to quantify this unique advantage.

Taking into account these identified advantages, or unique characteristics of BCIs, we propose some scenarios in which BCIs could play an important role as a new technology onboard spaceships. It must be understood that these scenarios should be seen as a way of illustrating what a BCI could in principle do, but in no way do they reflect a roadmap or short-term applications as the technology readiness level is still quite low.

3.2 The scenarios

3.2.1 *Scenario 1: communications*

A BCI-based system could improve communication between astronauts during extra-vehicular activities. Communication—command generation—can be difficult when a space suit is worn, and previous research has focused on this issue. For example, researchers at NASA's Ames Research Center have developed a system based on sub-vocal speech recognition aimed at improving interfaces in EVA operations [18]. BCIs could be used for the same purpose and might in theory provide an interface with a very high number of functionalities. The system could be integrated in the space suit and could in addition be used as health monitoring system. Furthermore, feedback signals provided by different sensing systems could be integrated in the interface improving the performance and versatility of BCIs.

3.2.2 Scenario 2: intra-vehicular activities (IVA)

Spaceships, such as the International Space Station, have limited space available and the astronauts often find their movements constrained. BCIs could be an efficient interface to have full control of robotic systems and semiautomatic devices of the spaceship through a single wearable interface. BCIs could therefore be an essential element in the field of space domotics.[1] BCIs could integrate the use of different existing interfaces that currently cannot be used simultaneously as they rely on limited physical capabilities. Robotic control might be executed without the use of haptic interfaces that often require synchronising arm movements and therefore representing a limiting factor due to the limitation of our natural body skills.

3.2.3 Scenario 3: exploration

As third possible application, BCIs could find use during exploration missions. Astronauts' brain activity could be monitored to control rovers, scouts and probes. In this visionary application, astronauts are asked to perform in loco analyses as during the Moon Apollo missions. Augmentation could also allow them to have full control of additional robotic arms and robotic devices, thus enhancing performance and time efficiency. Astronauts could always be synchronised to robots' navigation system and be able to send high-level commands to have full control of robotic operations. In addition, astronauts' BCIs could also share one single computer platform to synergistically coordinate the guidance of different artificial systems and astronauts own operations. The use of BCIs could therefore be advantageous to reduce the number of interfaces.

3.2.4 Scenario 4: safety

In the case of an extensive use and validation of BCIs in the space environment, leading to a consolidated technology, BCIs could ultimately be integrated on space safety systems, as they could be considered for monitoring brain activity and detecting emergency situations that could promptly be analysed. Possible uses could be during launch, landing, EVA, IVA and exploration. For example, BCIs could be employed to control thrust modules embedded on the space suit during EVA. The Manned Manoeuvring Unit (MMU) [19] and the Simplified Aid for EVA Rescue (SAFER) [20] are examples of thrust modules that could be controlled by a BCI. Commands could directly be read from the astronaut's brain activity, thus bringing the advantage of bypassing the need of any manual interface as joysticks, buttons and any other physical means that, due to the cumbersome space suit, inherently make safety tasks difficult to be accomplished. A BCI could also enable astronauts to perform manual operations while controlling their thrust units, as their arms are not used to guide such a system. This solution could also be considered as an alternative solution to standard interfaces to be employed as redundant system or when the astronauts' arms cannot manoeuvre the unit.

The aforementioned possible far-future applications could materialise only after numerous tests and following a development programme that considers current technological limitations and takes into account near-future possible improvements. A first step is to improve performance and solve issues of current BCIs. In particular, it is fundamental to increase the number of commands that can be transduced by current BCIs. Although BCIs are envisaged to be used only for high-level control input, there is the need to have an interface capable of reading more than few commands. In addition, it is necessary to have a wearable system that does not need any tuning, and which is practical to be used (current systems based on EEG, for example, need conductive gel at the interface scalp-electrode which is generally distributed by assistants through syringes). Further research is needed to track bias effects and generally to improve signal-processing techniques. These and others issues will be discussed in the next section.

4 Challenges for implementation

Human anatomy and physiology are the result of the evolution through time to adapt to life on Earth. Space is a completely different environment, and the human body undergoes important changes when in space, noticeable even during short journeys [21].

The sum of all the physiological responses that are elicited upon prolonged exposure to space environment will surely lead out of the scope of this article, and good general reviews are provided elsewhere [21, 22]. Instead, we will focus on the effects related to the exposure to

[1] Domotics: Use and control of robotic and semi-automatic devices in domestic applications.

microgravity, such as the adaptation to new strategies for spatial orientation, cosmic particle radiation, as well as the effects of plasticity changes of the CNS and in particular the brain, including space-related psychological stressors. We can rightfully assume that the onset and the persistence of these psycho-physiological stressors and their evoked physiological responses will most probably influence the operation of the BCI, presumably in an unacceptable way. This assumption is based on results reported by electroencephalographical recordings during parabolic flights and in space [23].

How would these changes affect the operation of a BCI? It is clear that one cannot expect that a BCI system developed and tested on Earth—even more under laboratory conditions—will function with the same performance in space environments. It can only be speculated to which extent space stressors will have impact on the functioning of the BCI [24]. In the worst case, it could stop working or would require algorithms of online adaptation and learning [25] to dynamically adjust its parameters to the psycho-physiological modifications induced in the brain and the CNS.

4.1 Environment effects

4.1.1 The space environment

Without the protection of the Earth's atmosphere, spacecraft and those inside them are exposed to the hostile space environment. Understanding this environment helps us to understand the challenges that any system—and in particular BCIs—will encounter when space bound.

One of these environmental effects is electric charging. Charged particles in the space plasma could have enough energy to attach themselves to the surface of the spacecraft and build up a charge that will in time cause a discharge. This can cause several problems, like degradation of solar panels, sensors, and onboard electronics. Charging may also occur due to solar energy [26].

Another effect is the extreme thermal cycling to which the spacecraft will be subject, with a temperature difference between day and night of up to 300°C.

Cosmic radiation also affects spacecraft and is especially harmful for humans, while it could cause degradation of onboard equipment.

But possibly the most obvious environment effect of space is the absence of gravity. Human physiology undergoes many changes that are simply an adaptation to the space environment. Since these adaptations can create severe problems after returning to Earth, proper countermeasure strategies, e.g., physical exercises to prevent muscular atrophy and bone loss, should be implemented onboard the spacecraft.

4.1.2 Human physiology in space

Even on a short journey into space, the cardiovascular system changes the way it operates. On Earth, gravity pulls the various body fluids down towards the feet. In the absence of gravity, these fluids redistribute upwards towards the chest and the head. The body perceives it as an increase in fluid volume in its upper part, and multiple physiological changes in the kidneys, in the cardiovascular system and in the red blood system take place.

The muscles of astronauts undergo deep changes as they adapt to the absence of the natural gravitational pull. The bone formation and calcium metabolism also change in microgravity [27].

Our brain and overall nervous system work together providing us with the direction, guidance, and impulses necessary to move about and function day to day. The absence of gravity affects the way the sensory and balance centres within our brains perceive the outer environment and the position and the orientation of the body within it.

All these changes, further explained in the next section, make necessary a validation of BCIs as conceived in the 1 g environment of the Earth.

4.1.3 Effects of microgravity on the brain

In the absence of gravity, the brain must re-adapt internal models of the laws of dynamic. Gravity dictates the laws of motion of our body and limbs, as well as of the objects in the external world with which we interact. Even for the simplest movements, the central nervous system must quickly perform complex considerations starting from internal models to generate coordinated motor actions in response to incoming sensory information [28]. In absence of gravity, the brain has to re-adapt these models to the new environment.

In a microgravity environment, the brain must change the strategies it uses for spatial orientation. On Earth, contact forces of support opposing the acceleration of gravity indicate the "down" direction. The otolith organs, hosted in the vestibular labyrinth of the inner ear provide information about head orientation with respect to the gravito-inertial acceleration [29]. Removal of gravity leads to enhanced sensitivity to acceleration because of fluid motion in the otolith organs. As a result, during motion, conflicts with the visual perception can cause motion sickness and the adaptation may take a few days.

All these changes in what the brain receives and how it processes the information might lead to modifications that can reflect on the functioning of a BCI. The signals and patterns a BCI is based upon can be disrupted, reduced, enhanced or changed by the different environment and its consequences. Therefore, we cannot exclude that a BCI developed and tested on Earth could stop working in space or need a new tuning of the parameters of the algorithm to adapt to the psycho-physiological modifications of the CNS.

Although the restricted duration of parabolic flights makes it difficult to investigate the functioning of the brain in microgravity conditions, previous studies [23] have allowed evaluating which factors affect the brain in these conditions. In addition, the Spacelab-1 mission and Gemini flights contributed with data related to the changes of EEG in space, but due to the difficulty in obtaining artefact-free and reliable data the database of EEG in microgravity conditions remains poor and in need of further research [23].

4.1.4 Effects of radiation

In interplanetary space missions, in absence of a protective atmospheric layer and outside the Earth's shielding magnetic field (prolonged), exposure to the elevated doses of electromagnetic (X and γ-rays) and ionising radiation of deep space impose great challenges on both technology and the human crew [30]. Constituting one of the most serious hazards of spaceflight [31], its accumulative character may result in temporary or permanent alterations, degradation and catastrophic effects in semiconductor electronics and biological material, showing the occurrence of potential late physiological damage starting from single cell lesions and mutations to genetic alterations [32].

The two dominant components that are typically characterising interplanetary radiation are Galactic Cosmic Rays (GCR) and Solar Cosmic Radiation (SCR) [32, 33]. GCR are highly energetic fluxes of ionised particles originating from outside the solar system. Due to collisions with interstellar medium, the composition and energy spectra of GCRs unpredictably alter during their passage through space and secondary particles form. By its ionic nature, this particle flux also depends on the location in space and its interaction with the solar wind and eventually existing magnetic fields. SCR is composed of UV-radiation and Solar Particle Radiation (SPR). The latter comprises constantly flowing solar wind particles and so-called Solar Particles Events (SPE) [32, 34], which are randomly released from the solar surface to space (solar flares). In the presence of magnetic fields of planets or other celestial bodies, trapped charged, highly energetic particles make up a third important component of space radiation to be considered.

Although conventional EEG recordings, which are already considered as a valuable tool for electrophysiological monitoring in space [35], indicate that the electronic circuits and microprocessors of EEG-acquisition devices and the stability of data links appear to work inside the protective hulls of spacecraft and space stations, it is not verified whether the output quality of the raw signals will suffice to be used as input data for classification and feature extraction for hardware control. In any case, as already under controlled laboratory conditions on Earth, the EEG signals used for BCIs are weak and noisy, space radiation in combination with microgravity add more complexity and non-linearity requiring autonomous systems with embedded intelligence to cope with these intangible uncertainties.

A possible technological avenue to follow is the implementation of routines and control architectures based on Artificial Intelligence (AI), in particular Artificial Neural Networks (ANN) and Fuzzy logic as an efficient way to anticipatory and proactive software behaviour for on-line adaptation of the parameters [36].

Due to the general accumulative effects of any kind of radiation, even at considerably lower doses, with prolonged times of unprotected exposure the risk of non-recoverable long-term impairments rises exponentially. Among others, mainly neurological disorders such as e.g. loss of concentration, fluctuations in mood, tiredness or headaches are the first symptoms. Imbalances like those are of direct relevance for BCI operation.

Undisturbed visual feedback is crucial for the operating of BCIs, thus interactions of cosmic particle radiation with the visual system, as they were first experienced during the Apollo-11 mission in 1969 to the Moon [31, 37, 38], should be critically considered and investigated. The causes of this phenomenon, known as "light flash", are energetic cosmic ray particles (heavy ions, also termed HZE particles) that penetrate the eye globe and impinge on the retina [38] producing visual sensations that are moving across the visual field [37]. Light flashes are generally described as mainly faint white or colourless spots or flashes of light with a variety of types and shapes [37]. In the Apollo missions, on the average, after some 15–20 min of dark adaptation, about one light flash per 3 min was perceived [38]. Similar results were obtained in systematic studies outside the Earth's magnetosphere, in Low-Earth Orbit (LEO) and also in ground-based experiments with heavy ions accelerators, however, with different patterns flash types [37].

The cortical activity following visual stimulation gives much weight to the assumption that the operation of a BCI probably could be disturbed by the occurrence of light flashes [24]. It cannot be excluded that this kind of unpredictable external stimulation might interfere with the operation of the BCI, posing even higher performance requirements on the algorithms of filtering, discrimination and interpretation of the EEG patterns. However, evidence is needed whether the occurrence of light flashes is distractive for astronauts such as it could hinder them from safe BCI operations during scotopic (low lightning) and night conditions.

4.1.5 Effects of neuroplasticity

The nervous system is not a static, but a functionally and structurally highly dynamic system. When confronted with sudden changes of behavioural or environmental settings, the CNS—and first of all the brain—dynamically adapts on the neuronal level to these new conditions, a strategy which is commonly termed brain, cortical, or neural plasticity. One can also look on the concept of brain plasticity as a process of continual structural reorganisation of neurons in response to altering external and internal stimuli offering the capability of self-assignment of neural circuits [39] and functional remapping of specific cortical areas assigning them other roles [39, 40], as the result of repeated learning and experience gained. To do so, as triggering factors, frequent environmental stimulation of appropriate duration each need to be present, and for successful learning, subjects should have a certain consistency and motivation. Plasticity can also occur on the synaptic level, denominated as synaptic plasticity, and reflected in the abilities of the synapses to change their efficiency of information transfer (the synaptic strength or "weight", respectively). Basically, synaptic plasticity results from the interaction of various biochemical and neuromolecular mechanisms and presents an important factor in higher brain functions such as learning and memory [41].

In spaceflight, and during some period of recovery thereafter, most of all, the deprivation of gravity with its consequent effects on the astronaut's body, manifesting in a variety of neurological changes [42], plays a crucial role. Especially the control of body and limb movements, such as eye-hand coordination and postural balance, the loss of spatial orientation, symptoms of motion sickness, or the regulation of circadian and sleep rhythm, just to mention a few, are significant problems astronauts have to overcome. The fact that astronauts after a short time of acclimatisation in space can nevertheless perform their tasks demonstrates the enormous compensatory abilities of the nervous system.

The ability of learning and neural plasticity are also essential features involved in the control of a BCI. The most important elementary learning processes resulting from plasticity, as detailed in [24, 41], are habituation (the attenuation of a response due to prolonged or strong stimuli), sensitisation (the increase of the strength of the response), and associative learning where subjects learn to associate the occurrence of different inputs with each other, eliciting a certain behavioural response. An example of the latter was already demonstrated in the experiments of Ivan Pavlov about 100 years ago in which he conditioned dogs in such a way that they started salivating at the ringing of a bell, independent of the simultaneous presentation of food.

During the utilisation of a BCI in space as well as on Earth, neuroplasticity as a response to the particular environmental conditions the operator has to cope with must be considered in the conceptual system design [24]. Above all, habituation and sensitisation, as they are directly associated with changes in the synaptic strength [41], affect the amplitudes of the brain's responses, which, according to the authors' laboratory experiences, go along with fatigue, i.e. the gradual loss of attention and concentration, that will be reflected in variations of the EEG signal strength.

In the EEG signal, which is typically characterised by a poor signal-to-noise ratio anyway, either significant parts of the activity pattern might therewith become undetectably weak beyond the resolution of the acquisition hardware whereas others, irrelevant parts of the spectrum, could be reinforced in an unacceptable extend disguising thus the desired features and impeding straightforward data analysis and correlation.

In space, and in contrast to meticulously controlled laboratory conditions, manifold stimuli, difficult to predict, are continuously bombarding the nervous system. Neurons excited by a certain combination of concurrent stimuli can start associating one with the other sensory input. This might be leading to either wanted or unwanted learning effects, a process referred to as associative learning. In practical applications of BCIs, undesired and even wrong associations of different inputs constitute a considerable error potential in the recognition of the operator's intent [25] that needs to be accounted for in the underlying algorithms for translation, discrimination, and classification.

4.2 Technical challenges

To meet the demands of real-world applications, BCI technology has to be developed to a point in which it can address a series of challenges, in principle common to both space and rehabilitation applications, and that can be generalised in several categories [43]:

4.2.1 Throughput (information transfer rate)

Even the best average information transfer rates for experienced subjects and well-tuned BCI systems are relatively low, in the vicinity of 24 b/min (roughly three characters per minute) [15]. This is too slow for natural interactive communication so, in order to effectively use BCIs as an alternative to conventional interfaces, it is necessary to research ways of optimising selection techniques and incorporating prediction mechanisms to speed up communication.

4.2.2 High error rate

A significant complicating factor in the slow information transfer rate of BCI users is the high probability of errors.

Brain signals are highly variable, and this problem is exacerbated in severely disabled users by fatigue, medications and medical conditions such as seizures or spasms. Reporting one's own errors is also extremely difficult, particularly if the subject has little or no communication channel outside of the BCI system itself. Devising methods of quickly resolving or preventing errors is critical to successful BCI interaction. A way of preventing the execution of erroneous commands is to detect directly the users' EEG potentials generated in response to errors made by the BCI [44].

4.2.3 Autonomy

Ideally, a communication system should be completely controlled by its user. Unfortunately, BCI systems require extensive assistance from caretakers who need to apply electrodes or signal-receiving devices before a user can communicate. In addition, the set-up and initiating procedures should be made easy for usage by everyone even in difficult conditions, like in zero gravity. Furthermore, most BCI systems are system initiated, meaning that the user cannot switch them on and off independently. The user may be able to perform a selection to turn the BCI system off, but turning it on again is an issue. It is possible to use hybrid systems, combinations of different BCI techniques, and other biometric interfaces to solve this problem [43].

4.2.4 Cognitive load

Most BCI systems are tested in quiet and controlled laboratory environments, allowing users to be fully concentrated on the task at hand with minimal distractions. BCI users in the real world will have to deal with much more complex situations, including the cognitive load of the task being performed, emotional responses, interactions with other people, and possibly even safety considerations. Careful study of the effects of cognitive load on the efficacy of BCI controls is necessary in order to determine whether BCI's could be used for rather "quiet" in-home everyday living situations up to challenging living situations of spaceships or space stations.

5 Preferred concepts

Matching the requirements of the scenarios and potential applications presented in Sect. 3 with current technology developments, one can realise that there is still much to do for a practical implementation of BCIs into space. This section presents a preliminary list of requirements, ranging from practical aspects to more technical aspects inherent to the implementation and operation of the BCI. These requirements allow us to trace a roadmap for the development of BCI technology for space applications [2].

- Non-invasiveness—because of their reduced risk and short time frame for qualification in space environment. In addition, there is a more favourable public perception of non-invasive BCIs than invasive ones.
- High reliability—since there is hardly any possibility of repair once in space.
- High efficiency—to justify its benefits over other alternatives.
- High sensitivity—as above.
- Ease of use by the astronaut—especially taking into account the difficulty of operating in a micro-gravity environment.
- Sufficient comfort for the astronaut—since functioning in space is tiring and astronauts have to perform demanding tasks; the BCI should not be perceived as a disturbing or distracting burden.
- Electromagnetic compatibility with electronic equipment of the spacecraft cabin—to avoid interferences guaranteeing functionality and safety.
- Low weight and volume of the driving and reading equipment—both for a financially affordable access to space and ease of use.
- Robustness both in the interface with the body and in the response of the system under various environmental and movement conditions.

The need of respecting at least all these characteristics limits the types of BCI potentially useful. In particular, it tends to exclude, in principle, PET, fMRI- and MEG-based interfaces for the following reasons:

- These systems require bulky and heavy equipment, being definitely not practical for astronauts, especially in consideration of the activities that they have to perform.
- Additionally, PET requires the administration of radioactive marker substances into the astronauts' bodies.
- On the contrary, EEG-based interfaces seem to represent the most suitable candidates for short-term applications.

6 The way forward

From a programmatic perspective, we see the introduction of BCIs into the space field as a careful yet promising process. A first step would be flying experiments in microgravity conditions on parabolic flights to assess the effects of the environment over the operation of the BCI.

Once the system is properly functioning in the 0-g environment we could assess the feasibility of the novel technology for space applications without presenting any hazard to the safety conditions of a crewed space station. Experiments should be simple and reliable, aimed at validating hypotheses formulated during ground tests while showing potential applications in space. The control of artificial limbs and space devices is not recommended for the first experiments as it would be too risky. As first experiment, the use of BCIs to control the keyboard and mouse of a laptop could be proposed. This experiment only needs very simple hardware and, although ambitious, it is already feasible from a technological point of view. It could also present a first interesting space application—astronauts currently have in fact some issues to control laptop trackballs in space. Another initial micro-gravity experiment, based on a virtual reality environment and representing operations to be performed by a robotic system, could be aimed at substituting standard interfaces for the control of semi-automatic devices with a BCI.

In addition to BCIs, we believe that the concurrent use of additional and auxiliary human–machine interfaces could bring considerable benefits when advanced human–machine interfaces will be introduced first. They could in fact increase the speed and efficiency of some operations despite current BCI drawbacks. As an example of non-invasive human–machine interfaces to be used as auxiliary systems for a BCI, electromyographical signals detected from arm muscles of an astronaut may permit the control of a robotic arm. Electrical activity recorded in proximity of muscles could be elaborated and used as the control input for the robotic mechanism. Such an action may be performed, in an early stage, in parallel to those controlled by the brain interface. Therefore, the two interfaces could work at the same time to enable easier and efficient implementation of multiple tasks.

We believe that this combination of BCIs and other human–machine interfaces could ease the introduction of BCIs into space. However, in the long term we envisage that BCIs will be robust enough to be independent.

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