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An era of brain-computer interface: BCI migration into space

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ABSTRACT: Brain-computer interface's (BCI) potential applications increased tremendously over the past decade. The rising of this new technology is providing promising solutions in the field of aerospace and space exploration. As astronauts face diverse challenges in long-duration spaceflight, BCI can help astronauts deal with complicated tasks with a minimal mental workload. It may provide intelligent communication systems, maximize safety and security, facilitate space discovery missions, and enhance astronauts' overall health and wellbeing. In new ventures such as SpaceX, Starlink, and Neuralink, pioneers adopt futuristic strategies that use BCI as their main anchor. Such efforts are valuable in neuroscience as they will reveal information that will allow neuroscientists to deeper understand the brain's mechanisms.

Keywords: Brain Computer Interface (BCI); neuroscience; neurotechnology; space science; NASA; SpaceX; Starlink; Neuralink

1.0 INTRODUCTION

The field of neuroscience refers to the multidisciplinary sciences that analyze the nervous system to understand the biological basis for behavior (Arzi et al., 2014). This term was introduced in the mid-1960s as a signifying factor to the beginning of an era in which each of these disciplines would work together cooperatively, sharing a common language, familiar concepts, and shared goals to understand the structure and the function of the normal and the abnormal brain (Squire et al., 2012). Today, neuroscience spans a wide range of research ranging from the molecular biology of nerve cells (the genes encoding proteins needed for nervous system function) to the biological basis of normal and disordered behavior, emotions, and cognition (Chatterjee, 2018). Neuroscience is currently one of the most rapidly growing science areas (Mathangasinghe & Samaranayake, 2019; Oktar, 2006). The neuroscience antibodies and assays market is poised to grow by USD 1.36 billion during 2020-2024, progressing at a CAGR of over 8% during the forecast period (Maida, 2020).

One of the major organs in the body most affected by these technologies is the brain. The brain is the most complex organ in the human body. It comprises the cerebrum, brain cells, and cerebellum. Three protective layers of tissues surrounding it called the meninges and bathed in a liquid called cerebrospinal fluid. This fluid protects the brain from injury and provides nourishment to the surrounding tissues. The brain cells consist of three components, the medulla, the point, and the midbrain. These three structures contain motor and sensory nerves that receive information from the skin and muscles from the head and the unique sense organs of hearing, balance, and taste. The cerebellum is divided into symmetrical right and left hemispheres. The core of the cerebellum is made up of white matter, and the exterior is covered by a grey matter known as the cortex. The cerebrum accounts for over 85% of the brain weight (Chatterjee et al., 2020a). It has a highly convoluted surface, with ridges and valleys called gyri and sulci, respectively.

The application of neuroscience technology has revolutionized the National Aeronautics and Space Administration (NASA) and SpaceX. Space exploration technologies (SpaceX) was founded in 2002 with the primary mission to become a space-faring civilization and multi-climate species by building a self-sustaining city on Mars (Hochleitner et al., 2020). SpaceX's Falcon 1 became the first privately developed liquid-fuel launch vehicle to orbit the Earth, NASA awarded SpaceX with contracts to carry cargo and crew to the International Space Station (ISS). NASA Space operations mission directorate is tasked with providing space exploration services in the United States and the entire globe (May, 2020).

In recognition of various significant achievements in neuroscience, the decade of the 1990s was declared the 'decade of the brain' (Stahnisch, 2016). NASA then agreed that an essential and significant contribution could be made to the national research effort through a shuttle/Spacelab mission (Neurolab) dedicated to researching the nervous system and behavior (Homick et al., 1998). This was a significant step in furthering the agenda of neuroscience and how it can be exploited to the benefit of solving day-to-day technological challenges (Oktar, 2006). Numerous technological changes have occurred since then to strengthen this field of science further. Sending humans to space is always tricky as the foremost fear is that humans may face paranoia, anxiety, fear, and other complicated negative feelings due to the uncertainty of the situation. BCI and Neuralink can counteract these feelings by infusing positive and intelligent AI-based feelings so the astronauts will go and win the situation with grace.

BCI may also revisualize the field as the human brain can be linked with super AI-based robots, and experts can be utilized as beta testers. They can visualize and experience life in space without actually going into it and at zero risk of wasting any human lives in the process. BCI can also be proved an essential tool in space communication as astronauts send information and pictures back to Earth using the Deep Space Network (DSN), a collection of big radio antennas. The antennas also receive details about where the astronauts are and how they are doing. If the BCI is appropriately implemented, the brain signals feelings and experiences transcribed directly into meaningful information. Similar phenomena can also be utilized in group discussions and exchanging information between the astronauts in outer space. This article explores these technologies in detail and highlights how NASA and SpaceX have applied these technologies in their operations.

2.0 Brain-Computer Interface: Revolution of Artificial Intelligence in Neuroscience

Artificial intelligence refers to the field of science that aims to provide machines with the capacity to perform functions such as logic, reasoning, planning, learning, and perception, resulting in both operational and social results.

Communication between people and artificial systems and machines is an application that is still in its early stages. Scientists have for a long time speculated on the possibility of a direct interface between the brain and a machine with the initial ideas being put forward from the 1970s, which saw initial experiments being carried out, basically analyzing the brain's electrical activity generated in response to changes in gaze direction (De Negueruela et al., 2011). The basic understanding of how the brain works have significantly improved since then, leading to prototypes that use this principle to develop robots' direct control and movement (Rodgers & Xiong, 1997). Figure 1 shows the architecture of the BCI cycle stating from signal accusation end with output and feedback.

One of these new fields of application is the use of Brain-computer interface (BCI) in the space environment, where astronauts are subject to extreme conditions and therefore could greatly benefit from direct mental teleoperation of external semi-automatic manipulators of robotic agents. This allows for mental commands to be sent without any output delays, as experienced from manual control in microgravity conditions (De Negueruela et al., 2011).

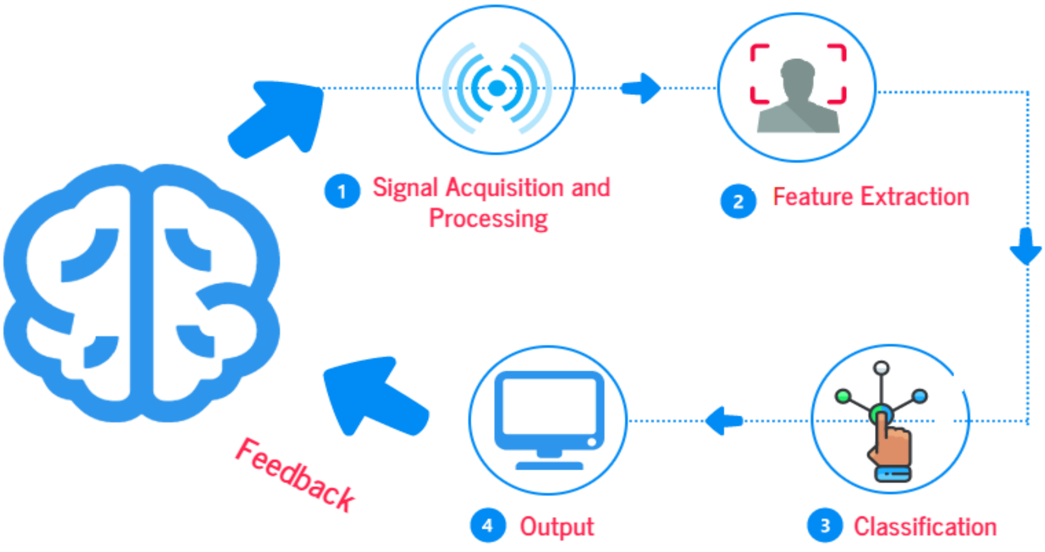

Figure 1: The architecture of BCI cycle

The Brain-computer interface is a powerful communication tool between users and its systems (Abdulkader et al., 2015). It does not require any external device or muscle intervention to command and complete an interaction (Demertzi et al., 2016). The signals used in BCI technology are mainly the P300 waves. It evoked potentials related to activation patterns induced by mental task strategies and slow cortical potentials recorded from the scalp, cortical neuron activity. Implanted electrodes generally record these. The neuromagnetic signals are recorded through the Magnetoencelography (MEG), bold responses are recorded through functional Magnetic Resonance Imaging (fMRI) (Chatterjee et al., 2018), and activity-related localized brain oxygenation level (Chatterjee et al., 2020b) are recorded through Near-Infrared Systems (NIRS) (Poli et al., 2013). Most of these approaches concentrate on building BCI spellers.

Over the years, there has been some interest in understanding BCI technology possibilities in space exploration. BCI robotic devices, surface rovers, and semi-automatic manipulators are the most relevant fields of application. Several researchers in both NASA and the European Space Agency have considered the potential advantages and limitations of BCI in space. This application's benefits include sending commands with minimum delays and high accuracy, astronauts collaborating in the control of machines, gaining machine control in conditions of restricted mobility, and hands-free direct control of cabin instrumentation and equipment. However, the application of this technology also comes with certain disadvantages. These are also some factors that can limit the efficacy of this application in the space environment. These factors include sensory and motor adaptation, microgravity, psychological stress, poor sleep, vestibular disturbances, and a slow rate of information transfer (Van Ombergen et al., 2017).

Many research and development institutions have solved such difficulties and provided efficient solutions in this regard. For instance, Rappaport et al. (2020) have presented neuroplasticity as a foundation for human enhancements in sensory and motor adaptation in space. Similarly, Colucci et al. (2020) suggested that Irisin can prevent the impairment of osteoblast differentiation induced by microgravity in vitro during space flight. Meanwhile, Lan et al. (2021) proposed a mechanism to reduce jugular vein flow in microgravity during spaceflight, Crucian et al. (2020) presented a solution to employ improvements in BCI induced Stress, Latent Herpesvirus Reactivation (LHR), poor sleep, and Immune System Dysregulation (ISD) during space flights. Khossravi & Hargens (2021) provided a solution using BCI for visual problems and vestibular disturbances during prolonged space missions. The circadian phase-shifting in space flight has been a massive issue for astronauts. It was found if there is a way to pre-calculate the phase resetting values, the paranoia can be avoided. In this regard, Tekieh et al. (2020) proposed improved physiologically based arousal dynamics to incorporate the effects of the light spectrum on circadian phase resetting, subjective sleepiness, and melatonin suppression and achieved a significant milestone. Lastly, Katyal & Singla (2020) proposed a novel paradigm to enhance the information transfer rate in space based on steady-state visually evoked potential & P300 and BCI.

A typical BCI system has a simple architecture. The first step involves the acquisition of brain signals to be monitored, the nature of which will determine the instrumentation to be used. Once acquired, the signs are conditioned and converted to digital format for further processing. To ensure that the information strictly comes from the brain signals, they may be filtered to remove unwanted artifacts, e.g., large-amplitude ocular movements signals). According to previous models, the extraction of the relevant features and their classification will indicate its action. Underlying all these processes is a well-crafted application-dependent protocol that specifies the choice of mental tasks to be performed and the stimulus parameters (i.e., the information presented to the user at every moment) (De Negueruela et al., 2011).

Methods to monitor brain activity can be broadly classified as invasive and non-invasive. Most non-invasive BCI systems use electroencephalogram (EEG) signals. This involves the electrical brain activity recorded directly from the scalp's surface, the primary 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 small brain areas' activity. It is characterized by noisy measurements and small amplitudes in the range of a few micro-volts (De Negueruela et al., 2011).

Besides electrical signals, neural activity produces different signals that can still be used in BCI, such as magnetic and metabolic. The magnetic activity can be recorded with MEG, while metabolic activity can be (as shown in changes in blood flow and blood oxygenation level) monitored with fMRI, Positron Emission Tomography (PET), and optical imaging (Chatterjee et al., 2019). However, these alternative techniques require very sophisticated devices that can only be operated in special facilities, making their use impractical for prototyping and practical implementation (da Silva-Sauer et al., 2016).

During the flights of the space, a complex neural activity resides in the human brain that includes dendritic and synaptic dynamics, axonal propagation, firing response, and corticocortical, or corticothalamic pathways that can be modeled through Evoked response potentials (ERPs) and other transients' impulse responses by exploiting the physiology-based neural field theory. The characteristics of such ERPs can be discovered during the corticothalamic system's stability zone, and wavelet spectra can be analyzed as well. This can be helpful to provide a unified treatment of predicted ERPs for both standard and abnormal states within the brain's stability zone (Zobaer et al., 2018). Technically, an astronaut may interrelate with K-complexes, spindles, evoked response potentials (ERPs), and spontaneous electroencephalography (EEG) using neural field theory (NFT). They compared the impulse response function with transient waveforms in sleep studies and explained a wide variety of transient waveforms that have only been phenomenologically classified to date. This enables non-invasive fitting to be used to infer underlying physiological parameters.

Invasive BCI systems measure the activity of single neurons from microelectrodes directly implanted into the brain. This approach's primary limitation is that it requires a surgical operation, although it can provide less noisy signals than EEG signals and higher spatial resolution. In some cases, the scar tissue might form from surgical procedures, impacting the electrical signal's strength, requiring repeated surgical corrections to maintain the signal strength. However, this limitation can be corrected using partially invasive BCI (semi-invasive), which reduces the risk of surgery infection and scar tissue formation since they are implanted inside the skull but on top of the brain surface. The signal strength and recognition are weaker than in invasive BCI and are still susceptible to noise. This control option is suggested to be more powerful and stable compared to the use of non-invasive BCI (De Negueruela et al., 2011).

3.0 BCI Applications in Space

Based on the unique advantages inherent to BCI, specific space applications can benefit from BCI technologies. The interest in BCI use in space was explored in December 2007, when the European Space Agency ESA conducted a parabolic flight campaign to examine the potential of BCIs. Later, in 2009, Millan et al. investigated the feasibility of using BMIs for space applications by conducting microgravity tests. Two subjects' brain signals were logged with non-invasive electroencephalography EEG before and during the parabolic flights. The two subjects had prior experience with BCI. The experiment results illustrate that an experienced BCI user can attain steady performance in all gravity conditions examined. This validates the feasibility of operating non-invasive BCIs in space (Millàn et al., 2009). Furthermore, Blankertz et al. (2006), and Parikh & George (2020) support that BCI can be utilized without prior training of subjects as well there will be no significant difference in adopting the mechanism. Figure 2 presents the application of BCI in Space.

In August 2013, researchers at the University of Washington had used a non-invasive BCI/BBI interface combining electroencephalography EEG and transcranial magnetic stimulation TMS in a set of experiments using a visuomotor task. The method was illustrated by transferring information between two test subjects cooperating to achieve specific computer game goals. The first test subject was able to view the game via a computer screen but was not provided with any control device. The EEG detected motor imagery, and then the information was recorded and transmitted over the internet to the motor cortex region of a second subject located a mile away. The second test subject was provided with a control input without viewing the game on the screen. The desired motor response was then cultivated via TMS. The two computers communicated using the standard hypertext transfer protocol (HTTP). The results provided evidence for direct information transmission from one human brain to another using the currently available non-invasive interface (Armstrong & Ma, 2013).

A BCI-based technology can advance communication between astronauts, space stations, and mission controls since the current spacesuit design hinders communication and command generation. According to NASA, "The headsets, sometimes referred to as the "snoopy caps," on the suits in use today can become sweaty and uncomfortable inside the helmet, and the microphone does not always track well with the astronaut's movements.". NASA is currently developing a new audio system that will include multiple microphones inside the upper torso to detect the astronaut's voice when they speak (Mahoney, 2019). Incorporating a BCI system for communication can be a lifesaver for astronauts in case of emergency. It can also reduce time-lapse communication when traveling further into space. NASA's efforts to upgrade audio systems and microphones may not overcome current communication challenges in space.

Space travel has noticeable effects on astronaut's overall health. An astronaut's body changes on a cellular level; Therefore, it is vital to monitor the health and determine human body performances through the various launch sequences, spaceflight, and landing (Chancellor et al., 2014). The central challenging aspect of spaceflight is microgravity. An astronaut experiences weightlessness and redistribution of body fluids as well as the loss of muscle mass. Numerous instant consequences include disorientation, lack of eye-head coordination, illusions, nausea, and motion sickness. However, with the nervous system's rapid adaptability to microgravity, astronauts usually can overcome gravitational stimulation loss in the first week.

Astronauts face additional challenges when returning to Earth as they temporarily lose the memory of orientation and movement in gravity, leading to multiple side effects similar to those during the launching phase (Blaber et al., 2010). In addition to microgravity, exposure to radiation and space hazards in long-duration space missions create significant health concerns for astronauts. A BCI application enables continuous monitoring of the astronauts' health, measuring astronauts' performance, and providing telemedicine. Astronauts use bulky and invasive medical devices, including electrocardiographs, blood pressure cuffs, fingertip oxygen saturation monitors, and ankle-bracelet activity sensors. Using these devices is troublesome and time-consuming. Recent advances in biosensing diagnostic instrumentation include portable and wearable biosensors (Roda et al., 2018).

BCI technology can also monitor and provide characterizations of astronauts' mental states. BCI can send warning feedback and controlling commands related to alertness, arousal, mental fatigue, and cognition, thus improving performance and preventing erroneous operations and commands. The current measure used to monitor astronauts' cognitive state is self-report, which is considered insufficient and even dangerous (De Negueruela et al., 2011).

Astronauts' capabilities in the limited workspace while their bodies are constrained in a bulky spacesuit could be further enhanced using BCI. The use of BCI suggests a new approach for astronaut operations' organization through the cerebral activity's ability to perform various uncorrelated activities simultaneously. This could be fully exploited by a machine that interprets commands directly from an astronaut's brain—enabling astronauts to improve efficiency multi-task. Because these missions are very costly, efficiency should be a priority for every accomplished mission (Wolpaw et al., 2000).

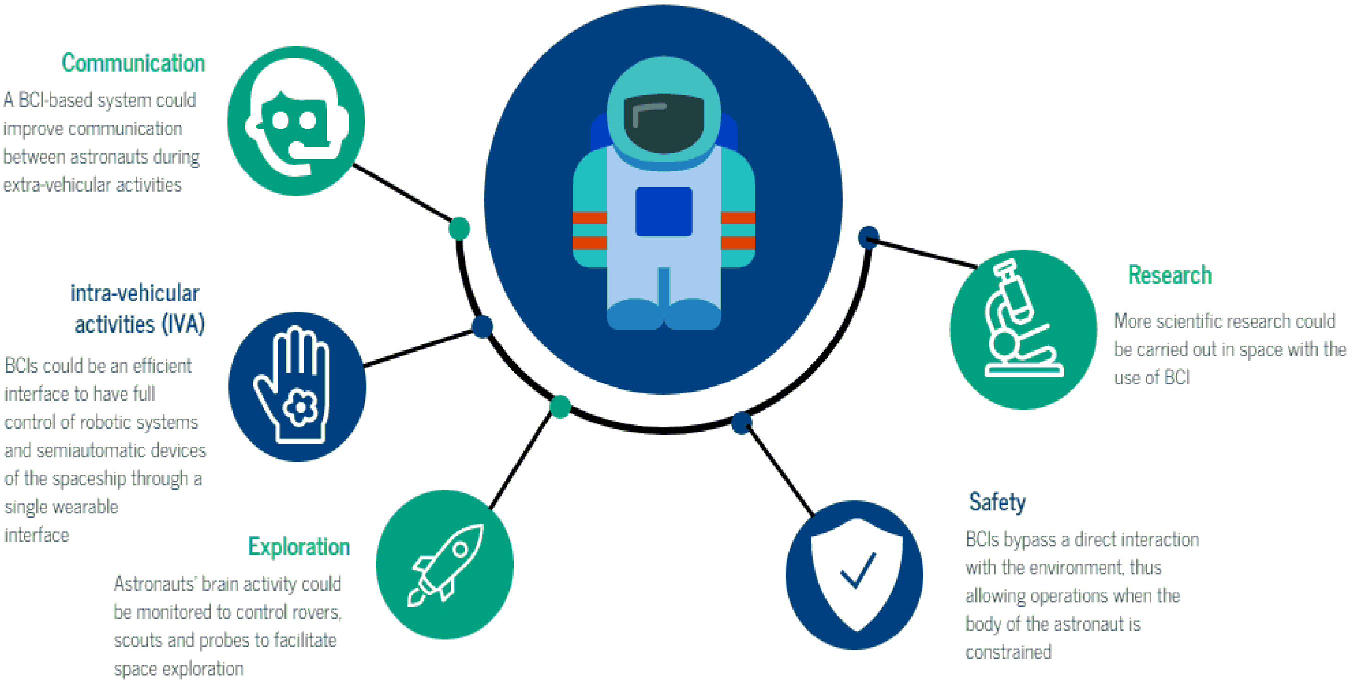

Figure 2: Applications of BCI in Space.

Another possible application of BCI is in the field of space exploration. Controlling rovers, probes, and scouts with astronauts' brain activity can be performed. Complete control of robotic devices through augmentation would enhance the mission performance and efficiency (Rossini et al., 2009).

4.0 SpaceX, Starlink, and Neuralink: The Futures Triangle of Neuroscience

Space exploration technologies (SpaceX) was founded in 2002 by Elon Musk with the primary mission to become a space-faring civilization and multi-climate species by building a self-sustaining city on Mars (Hochleitner et al., 2020). In December 2015, SpaceX reached a breakthrough when Falcon 9 made a triumphant return to Earth, marking the world's first orbital-class reusable rocket and an essential step towards lower-cost space travel. During the same year, SpaceX utilized building rockets and spacecraft to construct Starlink, a pioneer satellite internet constellation featuring low latency, broadband internet system that will offer speeds close to 300 Mbps. In 2016, SpaceX president Gwynne Shotwell explained Starlink's long-term vision by stating, "If you send a million people to Mars, you better provide some way for them to communicate." Starlink has included a hint in its terms and conditions of service that is an eye-opener: "For services provided on Mars, or in transit to Mars via Starship or other colonization spacecraft, the parties recognize Mars as a free planet and that no Earth-based government has authority or sovereignty over Martian activities" (Crist, 2021).

In 2016, Elon Musk introduced Neuralink, developing implantable ultra-high bandwidth brain-machine interfaces to connect the human brain to a computer. The company's initial goal is to allow patients with spinal cord injuries to control prosthetic limbs with their minds by linking their brains to the devices. It also aims to treat neurological disorders such as Alzheimer's, Parkinson's, Autism, and Multiple Sclerosis. Neuralink's plan for the next few years involves increasing people's memory and brain performance. Neuralink can also warn the user about an upcoming heart attack or stroke based on the measured temperature, pressure, and movement data. Neuralink's technology would enable people to save and retrieve memories and download this information into a robot or another person. Musk also hopes to give people supervision using infrared, ultraviolet, and X-ray using digital camera data (Musk, 2019).

5.0 CONCLUSIONS

Space exploration has enabled scientists to be in a position to study space beyond the confines of planet Earth. The evolution of neuroscience has significantly impacted the development of new technologies that have made this work more accessible. Through these technologies, such use of artificial intelligence in designing the Brain-Computer Interface (BCI), the study of the astronauts' health has been enabled. The monitoring of their brain function has been made possible. It is no doubt that the efficiency of space missions has been dramatically improved through these technologies.

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