ORIGINAL ARTICLE

The Effects of Microgravity on EEG Recordings: A Systematic Review

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ABSTRACT

To support extended human activity in space, it is essential to understand how microgravity affects cognitive and neurophysiological functions. Electroencephalography (EEG) is a non-invasive method of accurately monitoring neurological changes and has been widely used in aerospace research to study changes in human cognition under varying gravitational conditions.

This systematic review explores how EEG can be utilized to observe neural pattern changes in microgravity. Among the notable changes observed are the attenuation of the N200 and P300 event-related potentials (ERPs), as well as alterations to alpha power that persist even after returning to normal gravity conditions.

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INTRODUCTION

Space presents a novel environment in which reductions to gravitational forces create a state of free fall, often called *microgravity* [1]. Compared with the gravitational forces of terrestrial environments, such as Earth's 1G, the physics of microgravity and the sensation of weightlessness produce changes in human physiology. Therefore, a comprehensive understanding of how cognitive performance is affected by microgravity is critical to assess better the safety and potential consequences of humans performing tasks in space [2].

Electroencephalography (EEG) has been an established technology in aerospace research since the Gemini VII mission in 1965 [3,4]. It is often employed to monitor physiological neuronal alterations in zero-gravity environments and to investigate potential correlations between these changes and cognitive abilities [4]. According to recent research, when humans are in space, their brainwaves exhibit heightened alpha rhythms, indicating a relaxed wakefulness [5]. Conversely, studies conducted in space analogs, such as parabolic flights, have shown an increase in beta power, suggesting heightened levels of emotional stress [5].

According to a recent study by Becker and colleagues (2022), EEG technology is promising as a brain-computer interface (BCI) tool for spaceflight applications. By allowing for thought-based control of external systems, BCI devices have the potential to enhance astronaut performance and extend system control beyond traditional methods such as keyboards and touchscreens [6]. BCI devices could prove especially useful in hazardous situations for human extravehicular activity (EVA). Additionally, these devices could help researchers better understand the neural mechanisms underlying cognitive decrements in space, ultimately leading to the development of effective countermeasures to improve human safety and performance [5].

Technological advancements created for space exploration have found their way into other industries throughout history. NASA, for instance, has recorded over 2,000 spinoff products initially designed for space but are now utilized in various commercial applications [7,8]. The unique physical and cognitive challenges that astronauts face in microgravity are like those experienced by individuals with disabilities on Earth. Therefore, investigating how brainwaves can enhance astronaut performance may unlock new possibilities for restoring abilities in people with disabilities.

The potential advantages of neurotechnology that stem from microgravity studies are vast. However, much research still needs to be done to understand how the human brain reacts to this environment. Further investigation is required to reveal neural network rhythmicity in microgravity, enabling the development and application of these technologies in practical scenarios, whether in space or on Earth [3]. Our review highlights recent studies that utilize EEG to detect alterations in electrocortical activity space analogs, simulations, and microgravity environments.

LEARNING OBJECTIVES

Our goal is to investigate the effects of microgravity on human brainwaves during space travel. Through a thorough literature review, we analyzed the use of EEG in both actual and simulated spaceflight scenarios to identify disparities in EEG readings. Our research explores critical inquiries such as: *Can we observe any changes in human brainwave patterns during EEG recordings in microgravity? How do astronauts' brainwaves change when engaged in various activities in space? Are there any EEG phenomena that can* *be linked to cognitive tasks in microgravity environments?* Our findings can potentially guide future research and technological advancements that prioritize safety and health in space exploration.

METHODS

Since EEG has long been used in aerospace settings, we anticipated abundant information on the subject. We systematically reviewed the current literature using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [9].

Inclusion and exclusion criteria

Peer-reviewed journal articles published in English between January 2018 and October 2023 were eligible for review. Papers must deal specifically with the modulating effects of microgravity on human neural rhythmicity, documenting either measurable changes in the relative power of different frequency bands recorded with EEG or the possibility of retrieving such measurements to understand the cognitive performance of humans in space. Papers were excluded if they did not focus on EEG, did not focus on microgravity, were animal studies, or were otherwise too broad.

Search strategy.

Three major databases were searched: PubMed, Science Direct, and Springer Link. Six keywords were used: *eeg microgravity, electroencephalography microgravity, brainwaves microgravity, astronaut eeg, cosmonaut eeg,* and *astronaut brainwave* (Table 1).

Keywords	PubMed	Springer Link	Science Direct	Total records
Brainwaves microgravity	0	0	2	2
Astronaut brainwaves	0	4	5	9
Cosmonaut eeg	3	16	9	28
Electroencephalography microgravity	3	13	13	29
EEG microgravity	3	41	36	80
Astronaut EEG	4	64	89	157
Total records	13	138	154	305

Table 1. Search results by keyword.

RESULTS

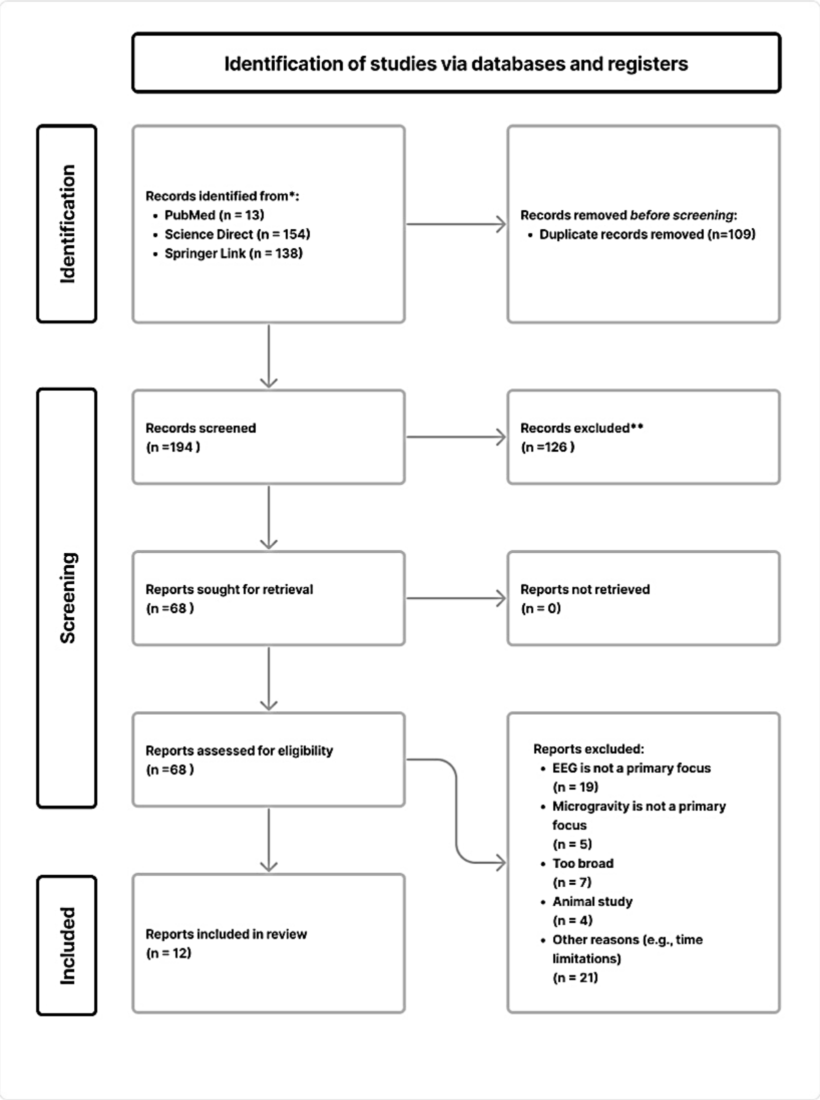

Figure 1. PRISMA flow diagram.

Search results.
A total of 305 records were identified during our initial search of the three databases mentioned above. The results of each search were compiled in CSV format and analyzed using a Python script to identify duplicates. A total of 109 duplicate records were removed before the screening. The remaining 194 records were manually screened for relevancy by examining article titles and abstracts, resulting in a trimmed CSV file containing 68 relevant articles. This CSV file was then parsed by a Python script that used the pyautogui library and the Zotero Chrome extension, allowing for the automatic downloading and categorization of all

Source	Sample Size	Tasks	EEG Apparatus	# Electrodes	Effects on EEG	Effects on cognition
(Yule et al., 2023)	59	Manage four unique medical events in a fully immersive spacecraft simulator.	Muse	4	No significant changes were observed.	No significant changes were observed.
(Cebolla et al., 2022)	5	Match positions of a virtual spaceship and ISS (docking) using a joystick	Multi-electrode electroencephalogram mapping module (M.E.E.M.M)	58	Amplitude of a P300 component in the in the parietal lobe of astronauts decreased during, and recovered after, exposure to microgravity. Good dockings in microgravity showed earlier voltage distributions over the scalp compared to bad dockings.	Positive or negative valence information is processed differently in weightlessness compared to Earth.
(Chu et al., 2022)	20	Multi-Task Attribute Battery (MATB) task Complete three sub-task: system monitoring, tracking, and resource management.	Ant Neuro EGGO device	64	EEG accuracy peaked at 26 channels. Increases of β1and β2 power in the occipital region coincided with task difficulty.	Task performance significantly decreased and subjective scale score increased with the increase of mental workload.
(Lipshits & Levik, 2023)	Not mentioned	Reconstruct angles and turns of a virtual tunnel from memory using a trackball.	Not mentioned	Not mentioned	EEG activity in response to visual stimuli changes in microgravity.	Microgravity affects the perception of time, the recognition of symmetry, image processing, and orientation in 3D space.
(Klein et al., 2019)	17	Participants performed mental arithmetic tasks in 1G and 0G conditions during a parabolic flight.	EEG actiCAP (Brain Products)	32	Event-related potential amplitudes decreased during microgravity (0G), irrespective of hemodynamic changes.	Decreased reaction time relative to task complexity. Fewer cognitive resources may be needed to perform task well in space.
(Takács et al., 2021)	5	Lines and Clock tasks were used to assess visuospatial memory for rotation and position.	EEG Cap	58	Both P3a and P3b amplitudes were lower in in-flight and post-flight states compared to pre-flight state.	Reaction time increased and accuracy significantly decreased in both the in-flight and post-flight states when compared to the results in the pre-flight state.
(Wollseiffen et al., 2019)	a) 11 b) 17	Arithmetic equation task, Auditory Oddball task, press key when certain tone is played.	EEG actiCAP	a) 64 b) 32	N200 ERP amplitude was lower for 0G environment in both experiments.	Reaction time decreased but accuracy also decreased slightly in in-flight environment vs pre-flight environment for the arithmetic task. The reaction time for the auditory task remained about equal.
(Farjoud Kouhanjani et al., 2023)	17–28	Memory tasks, change body positions, surveys.	Not mentioned	Not mentioned	The authors describe prior work by Schneider et al. (2008) detailing reductions in Beta-2 EEG activity (18–35 Hz) in the right superior frontal gyrus in weightlessness. This could be related to the emotional experience of weightlessness.	Emotional processing of the experience of weightlessness may be responsible for the changes observed on EEG recordings.

(Pusil et al., 2023)	5	Virtual scenarios where a ship is piloted towards the ISS or a ship is controlled from the ISS. Match the positions between spaceship and ISS.	a) multi-electrode electroencephalogram mapping module (M.E.E.M.M), b) ANT system	a) 58 b) 64 channel	Reduction of alpha band power in the frontoparietal regions during microgravity conditions that persisted for at least 20 days post-flight.	Task performance and error control impacted.
(Zhang et al., 2023)	9	Go/Nogo tasks.	BrainAmp	62, 18	Frontal theta phases changed occipital gamma amplitudes during tasks demanding high inhibitory control.	Inhibitory control reduced.
(Weber et al., 2019)	16	Participants Isolated for 30 days inside the NASA HERA module at Johnson Space Center. Cognitive tests included the Memory matrix, Speed match game, and Chalkboard challenge.	ActiCap	16	Alpha activity in the prefrontal cortex was not significantly impacted by 30 days of isolation.	Cognitive ability was not reduced by 30 days of isolation.
(Ilyin, 2018)	12	Participants lived and worked at the Vostok Station in Antarctica for over one year in 1968.	No detail provided	No detail provided	Alpha and beta activity fluctuated throughout the experiment.	In first 1-2 months, cognitive performance increased, likely due to adaptation to new conditions. Later, behavioral problems were observed, such as mood swings and argumentative tendencies. These patterns mirrored those observed in cosmonauts in space at similar time intervals.

Table 2. Selected papers from our review [2,4,10-19].

record PDFs. These PDFs were then manually reviewed, and records were excluded from the final review if they did not focus sufficiently on EEG, did not discuss microgravity, did not study adult human populations, or were otherwise too broad. A total of 12 records were included in our final review (Figure 1 and Table 2).

Significant papers

Pusil et al. (2023) describe a reduction of alpha power in the frontoparietal regions in microgravity, noting how this effect persists for at least 20 days upon return to Earth [4]. The lingering changes under normal gravity conditions suggest that weightlessness is not the only reason why alpha power is attenuated and that cosmic radiation may also contribute to the effects observed. They describe how radiation can increase β-amyloid deposits in the cerebral cortex, corresponding to reduced alpha power in the frontoparietal region. Similar neural patterns are commonly observed in patients with Alzheimer’s disease [4].

Cebolla et al. (2022) document changes to event-related potentials (ERPs) of astronauts, specifically a P300 component in the parietal lobe, noting how the amplitude of the P300 decreased during exposure to microgravity and recovered upon return to normal gravity conditions [11]. Observations were made on

Earth and in space as astronauts completed a task simulating the docking of a spacecraft with the International Space Station (ISS) to assess astronaut decision-making processes. The latency of the P300 was reduced for “good dockings” compared to “bad dockings,” indicating perceptual changes to positive or negative information in microgravity.

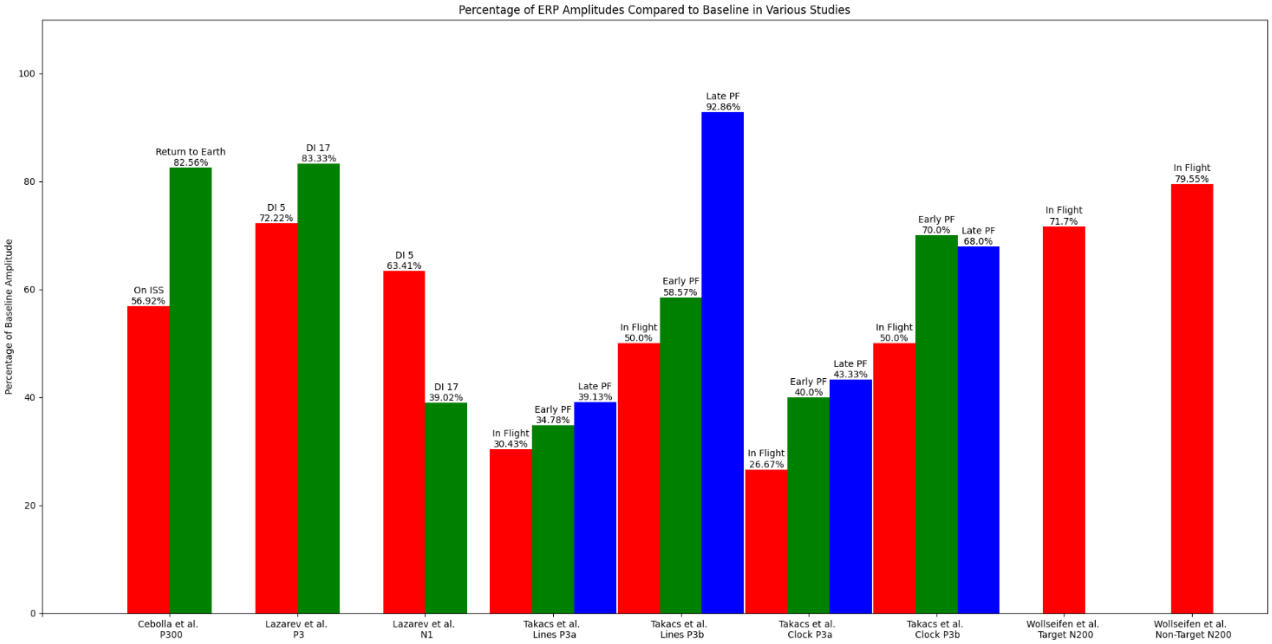

Figure 2. A comparison of various event-related potential (ERP) amplitudes as percentages of their corresponding baseline amplitudes. Details of the studies included in this graphic are explained below. DI = Dry Immersion, PF = post flight, flight = parabolic flight (DI and parabolic flight are both microgravity analogs). DI 5 = 5 days in dry immersion, DI 17 = 17 days in dry immersion [10,12,13,14.

Klein et al. (2019) provide insights into the relationships between cerebral blood flow and electrocortical activity in microgravity. Participants performed mental arithmetic tasks in 1G and 0G conditions during a parabolic flight [13]. A generalized reduction of ERP amplitudes was observed in microgravity across all brain regions despite increased cerebral blood flow. Additionally, reaction times decreased relative to task complexity [13]. The authors speculate that these counterintuitive effects indicate that fewer cognitive resources are needed to perform tasks well in space.

Lazarev et al. (2021) had ten male participants, with no neurological disorder and not on any medication during the experiment and during the baseline tests. The process used here is the dry immersion which means, the participants were placed in a tub filled with water (temperature was maintained at 33°C) but there was a free-floating waterproof material between the water and the participant. The patients were free floating in the tub in the supine position for 21 days (about 3 weeks). The experiment had three sessions in total [20]. During the first session, participants were seated relaxed and, in the second and third session, they were floating in the dry immersion tub. Each session was about three hours. During EEG recording, participants were supposed to close their eyes and relax. It was a tracking task in which the mouse pointed at a red dot on a black screen on a computer, and they must chase the yellow target that appears on the computer every one sec of time. If they chase the target correctly on time, the target changes to green. EEG was recorded with the help of 64 electrodes (electrode cap). The ground electrode was placed near the Fz electrode, and the reference electrode was placed near the vertex area. Impedance was kept below 20KΩ, band pass filtered (0.15-400Hz) and was digitized at 1000Hz. EEG was analyzed within EEGLAB, and ERPs were analyzed within EEGLAB and ERPLAB software. During the Off-Line processing, the sampling rate was changed to 250Hz. EEG was re-referred to averaged reference and filtered above 30Hz. EEG was visually examined for the irregular artifacts were proposed to independent component analysis and at last, artifact components were removed based on visual examination.

Takács et al. (2021) looks at the correlation between visuospatial performance and microgravity. Like Klein et al. (2019), participants performed the same tasks before and during a parabolic, weightlessness-inducing flight [14]. However, this study also measured the participants' performance on the tasks after the flight as well. The tasks performed were the "Lines" task, where participants were shown a line and then later shown another line and asked if it was rotated in the same orientation as the original, as well as the "Clock" task, where participants were shown a number and then later shown a position of a dot and asked if that position corresponded to the same clock location as the number shown before; with these, researchers were able to evaluate both visual memory as well as imaginative visualization performance. The researchers found a significant mean increase in reaction time (about 8%) for both tasks when comparing the base pre-flight results with the microgravity in-flight results. Similarly, task accuracy showed a mean decrease (about 3% for "Lines", and 9% for "Clock"). Interestingly, mean reaction times were higher and mean accuracies were lower when participants were tested soon after the parabolic flight finished, though these scores reached baseline when the participants were finally tested a while after the flight, indicating potential lingering effects from microgravity. Researchers also noted a decrease in P3a and P3b amplitudes during the tasks performed in the in-flight and early post-flight stages when compared to the pre-flight baseline.

Wollseiffen et al. (2019) tested neurocognitive performance by having participants perform an arithmetic equation task, like Klein et al. (2019), as well as an oddball auditory task in both pre-parabolic-flight as well as in-parabolic-flight conditions [15]. In contrast to the findings of Takács et al. (2021), researchers found no significant changes in the average reaction time for the oddball task in both gravity conditions, though the average reaction time for the arithmetic task decreased while the participants were in the microgravity in-flight condition. Nonetheless, error rate did increase for the arithmetic task while in microgravity, and researchers found the participants experienced P300 and N200 ERPs of lower amplitude while performing both tasks in the microgravity condition when compared to the pre-flight baseline.

DISCUSSION

Implications

Our research has revealed a need for greater consensus regarding the impact of microgravity on cognitive tasks and accompanying EEG data. For instance, Takács et al.'s (2021) study uncovered a significant increase in reaction time and a decrease in event-related potentials (ERPs) when participants engaged in visuospatial tasks [14]. Conversely, Wollseiffen et al. (2019) noted that reaction time decreased during a mixed mental processing task that involved solving arithmetic equations while reacting to an auditory tone [15]. However, this study also found that ERP amplitudes decreased in microgravity environments. Interestingly, decreased reaction time and reductions in ERP amplitude seem to occur even when cerebral blood flow increases [13]. Nonetheless, several studies have concurred that a decrease in ERP amplitudes is a notable effect of microgravity. Therefore, we recommend the following tasks and markers to monitor when assessing neurophysiological changes in microgravity.

ERP Marker	Key Electrodes	Suggested Tasks
N200	Cz	Oddball task
P300	Pz, Cz	Mental arithmetic
P3	Pz	Visuospatial imagination task

Table 3. Suggested ERPs and Tasks.

Limitations

Although the papers we reviewed appear to follow established practices for collecting EEG data in terrestrial contexts, substantial variations in methodology are used to conduct EEG research in microgravity. Notable differences exist among EEG device types, numbers of electrodes, units of measurement, data normalization techniques, sample sizes, and participant tasks. While standard methods may exist in communities of practice, the papers in our review describe no such system that can guide EEG research in the unique context of microgravity.

Future research

The absence of standardized methods for conducting EEG research in microgravity limits the repeatability of studies describing human cognitive phenomena in space. Methods that broadly describe cognitive changes occurring in space may overlook cognitive decrements that require nuance and precision to detect. Psychological risk assessment for spaceflight has historically faced similar challenges of imprecision and inconsistency [21]. Future work could center around establishing consensus standards that address how

EEG data should be collected and reported during spaceflight to improve data integrity and minimize risks posed by imprecise methodologies.

Klein (2019, p. 1061) describes how electrical activity decreases across the entire brain in microgravity, irrespective of increases in cerebral blood flow. More work is needed to elucidate the counterintuitive relationship between intracranial pressure and neuronal activity in microgravity [13]. Additionally, the implications of long-duration spaceflight on human cognition and behavior remain unclear [2].

Emerging BCI technologies that rely on classifying EEG patterns show promise as robot control mechanisms in low-gravity context [23]. However, it is still being determined how systems reliant on machine-learning models trained with data collected in terrestrial environments will perform in microgravity, where EEG patterns are measurably altered. Clarifying how fluctuations in neural activity impact the automated interpretation of EEG signals is a significant factor in the safe and reliable deployment of these devices in spaceflight contexts.

CONCLUSION

Through our analysis of multiple studies, it is evident that microgravity has a significant impact on electrocortical and cognitive activity. With the increasing commercialization of space travel, it is now more important than ever to deepen our understanding of human cognition in microgravity. By developing a standardized set of methods for gathering EEG data and conducting cognitive tasks in space, researchers can consistently evaluate the effects of microgravity on human cognition. This has the potential to lead to groundbreaking tools and technologies that can support human activity in space.

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