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Evaluating the Potential of Using EEG to Monitor Cognitive Workload in Simulated Suborbital Flight

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Abstract

Mental workload can be assessed using electrophysiological measures of brain activity, such as electroencephalography (EEG). EEG signals reveal cortical electrical activity. This cortical activity was recorded using specialized headsets. The focus of this research was to study cognitive performance (CP) in four pilots during simulated suborbital flights under nominal day and night profiles and under contingency day and night profiles. A 14-channel EMOTIV EEG headset measured the participants' brain activity while they flew simulated flights in a Suborbital Spaceflight Simulator (SSFS). Several sessions of EEG data were recorded from each subject, and feature extraction was applied. Data revealed that real-time pilot CP can be decoded from the EEG signals. If these data can be transmitted to mission control under operational conditions, they may be used to monitor pilot safety and performance.

Keywords: alpha band, beta band, brain, cognitive performance, delta band, electroencephalography, pilot, suborbital flight, theta band

Introduction

The human factor is a key element that determines safety when flying suborbital spacecraft, such as SpaceShipTwo, which is operated by Virgin Galactic. The automated control systems that are integrated into the complex system that is a suborbital spacecraft may function reliably within the parameters predicted by the developers of those systems, but in unpredictable circumstances, it may be the pilot who saves the day. In such unpredictable circumstances, cognitive workload may be a critical element in determining the outcome of a contingency. An example of just such an unpredictable event was highlighted in the break-up of SpaceShipTwo on October 31, 2014, when the vehicle was conducting its fourth test flight. In this flight, co-pilot

Michael Alsbury unlocked the vehicle's re-entry feathering system prematurely. The result of this error was the breaking apart of the vehicle and Alsbury's death. The National Transportation Safety Board (NTSB, 2015) stated pilot error was to blame. In a less serious, but equally unpredictable incident, in July 2021, the pilots of SpaceShipTwo were faced with a split-second decision that led to the vehicle deviating from its flight path because the pilots had failed to adjust a trajectory error. This incident was another example of the potential utility of being able to monitor and predict pilot performance.

A pilot's cognitive state is a significant factor which may impact their performance while flying a suborbital spacecraft, especially when reacting to a contingency. In such an event, a pilot's reflexes, decision-making, and control of the spacecraft may be influenced by their cognitive state. Research has been published on the cognitive state of pilot's flying aircraft (Dehais et al. 2019; Di Stasi et al., 2015; Sauvet et al., 2014; Sterman et al., 1988), but no research has characterized a suborbital pilot's cognitive state during a simulated spaceflight.

One reason for the lack of research in suborbital flights is that, until very recently, with the crewed flights of Blue Origin's New Shepard and Virgin Galactic's SpaceShipTwo in 2021, 2022 and 2023, there have been very few suborbital flights. In fact, before the crewed flights of Virgin Galactic's SpaceShipOne in 2004 and the aforementioned SpaceShipTwo and New Shepard flights, there had only been five crewed suborbital flights (four American and one Russian: the first two flights of Project Mercury, two X-15 flights and the Soyuz 18a, which was an aborted orbital launch that flew a suborbital trajectory). While some studies (Han et al., 2002; Marušič et al., 2014; Niedermeyer & Lopes da Silva, 2005) have investigated the role of EEG in changing gravity and microgravity, none of these studies investigated how EEG signals might be used to monitor pilot performance in suborbital flights.

Flying a suborbital spacecraft, especially during the pull-up phase (see Figure 1), is a stressful and cognitively demanding task that comprises a myriad of sub-tasks that must be executed in quick succession (Holleman, 1964). The climb to suborbital space, re-entry and landing phases exerts high cognitive demands on the pilot (Holleman, 1964). Thus, understanding the impact of in-flight procedures on pilot cognitive performance (CP) at various flight phases, and detecting the onset of CP decline may improve safety of suborbital operations (Causse et al., 2019; Wilson, 2002). By detecting onset of CP decline (Krishnan et al., 2014), it may be possible to avoid landing off course and prevent loss of mission and/or loss of crew.

CP, or mental workload, describes the degree of mental resources utilized by a person when performing a task (Basar et al., 1997; Klimesch, 1999). Traditional CP assessment techniques include subjective measures, performance measures and physiological measures. Subjective and performance measures are normally taken following task completion and are considered static measures. This makes this group of measures somewhat limited. Subjective measures may also be affected by bias (Schomer & Lopes da Silva, 2011). The utility of physiological measures such as EEG is that measuring brain activity may provide a valuable insight into CP (Zhu et al., 2021). Furthermore, wearing an EEG headset does not interfere with task performance, which means such a system may be useful in measuring CP (Raghavachari et al., 2006).

There are several neuro-imaging techniques available to investigate brain function. These include functional magnetic resonance imaging (fMRI), EEG, and functional near-infrared spectroscopy (fNIRS). fMRI is effective in localizing neural activity, but its disadvantage is that participants must lie still. This disadvantage does not apply to fNIRS, but this system, while convenient for long-term monitoring, has poor temporal resolution in contrast with EEG. EEG can capture brain activity when a person is completing complex tasks. Furthermore, an EEG system can capture dynamically changing brain activity and can detect CP changes. Until recently, EEG systems have been bulky, but recent developments in reducing the size of such brain-computer interfaces means participants can comfortably wear such a system while completing tasks such as flying a suborbital spacecraft in a simulator or in actual spacecraft. This is also possible because the latest developments in EEG systems include wireless monitoring systems. One such system is the EMOTIV EPOC EEG headset used in this study.

EEG is a complex signal comprising several frequencies that oscillate simultaneously. Lower frequencies show greater power than higher frequencies and power decreases as frequency increases (Nunez et al., 2016). Most brain activity occurs at frequencies below 100 Hz. The spectrum of frequencies of brain activity is divided into bands which are, in increasing order of frequency, as follows: delta (< 3.5 Hz), theta (4 – 7 Hz), alpha (8 – 13 Hz), beta (14 – 30 Hz), and gamma (>35 Hz). Across this spectrum, alpha activity has more power than beta activity and beta activity more power than gamma activity. Each frequency band reveals specific neural phenomena. For example, beta activity reveals alertness and the regulation of processing states while theta band activity correlates with attention and information processing. Theta band frequencies become more pronounced with greater task difficulty (Buzsáki & Lopes da Silva, 2012; Klimesch et al., 2005) and cognitive processing demands, which is why this was one of the bands, along with the beta and alpha bands, of interest for characterizing performance of the participants in this study.

This pilot study tested the feasibility of measuring a suborbital pilot’s workload in a simulator with a portable commercial off-the-shelf 14-electrode EEG system. The experimental scenario consisted of flying a suborbital spacecraft in a simulator at low and high cognitive load conditions. The first objective was to determine if it was possible to extract EEG features that discriminated between the two flying conditions. The second objective was to determine if it was possible to infer the participant's CP. The third objective was to determine if the EMOTIV EEG system was suitable for pilots to wear while flying in a simulator.

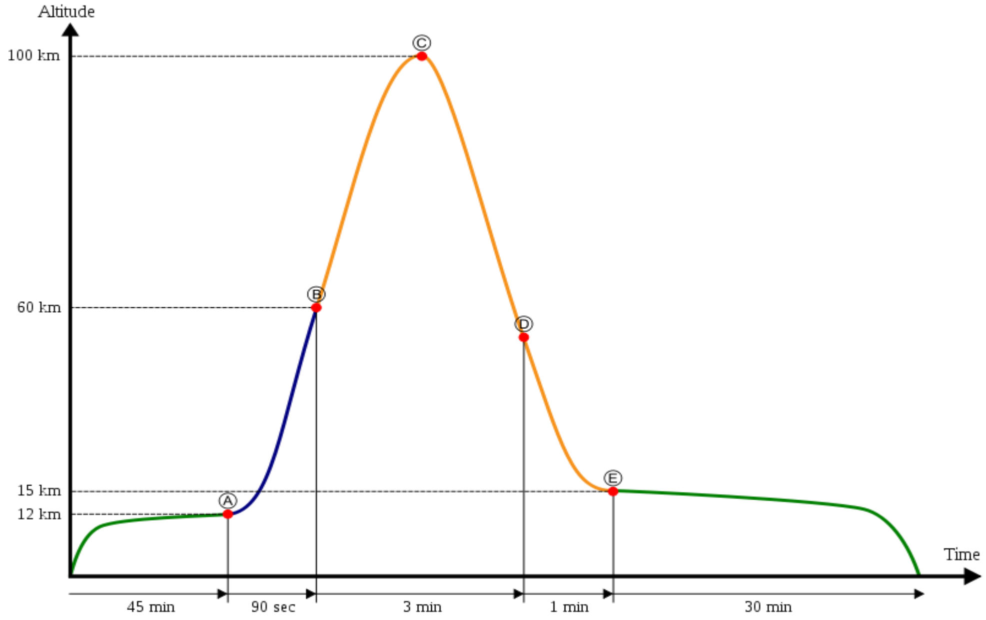
Methodology

Four participants (three male, one female) were recruited from Embry-Riddle Aeronautical University's (ERAU) College of Aviation. The ERAU Institutional Review Board (IRB) approved the methods used to test participants in this study. Each participant gave written informed consent to be involved in the study. The mean age of the participants was 20.4 years (SD ± 1.3 years). By comparison, none of the SpaceShipTwo pilots flying in 2023 are less than 40 years of age.

Each participant had normal uncorrected 20/20 vision and no history of vision problems. Each participant held a private pilot's license, had accumulated an average pilot-in-command time of 102 hours (±18.1 hrs), and had been trained to fly the SpaceShipTwo suborbital profile (see Figure 1) which lasts approximately 11 minutes from airdrop to landing. The number of flight hours accumulated by the participants in this study was much less than the number of flight hours accumulated by SpaceShipTwo pilots. By comparison, each pilot flying SpaceShipTwo in 2023 has more than 4,000 hours flight experience in more than 30 vehicles.

Figure 1

SpaceShipTwo Flight Profile



Note. A: Pull-up/Boost. B: Coast. C: Apogee. D: Re-entry. E: Glide

From “Virgin Galactic Suborbital Research – The Suborbital Space Lab for Your Next Mission” [Brochure], by Virgin Galactic, n.d. (https://assets.ctfassets.net/mdbdgwuz60cu/61MJ4hgU3qSkRMkCZHsfHy/ab872b854acf6fcaafd73ecb979cc30d/Research_Brochure_Final.pdf)

The training for this study required each participant to fly twenty nominal SpaceShipTwo suborbital profiles. This number of flights provided enough experience flying a suborbital profile for each participant to consistently perform a nominal landing under nominal flight conditions. Simulated suborbital flights following the SpaceShipTwo flight profile (shown in Figure 1) were flown in the ERAU SSFS (see Figure 2).

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Figure 2

Suborbital Spaceflight Simulator

Note. Suborbital Spaceflight Simulator [Photograph] by E. Seedhouse, n.d. Copyright n.d.by Erik Seedhouse.

The SSFS is based on a twin seat cockpit of a Cessna 172 equipped with four-point single release harnesses. The cockpit has an ultra-high-definition glass cockpit with a center stick, rudder-pedal assembly, and a multiscreen display. These screens were used to help the participant navigate the simulated spaceship along a suborbital trajectory. Externally mounted to the SSFS were three primary flight screens that displayed the flight profile. The SSFS can be categorized as a low fidelity simulator and was of a lower fidelity than the simulator used by SpaceShipTwo pilots. The SSFS is a fixed-base motion simulator, which means it does not move while being operated, whereas the actual SpaceShipTwo simulator used by Virgin Galactic is a high-fidelity full-flight simulator, which means it moves while being operated. No G-loads or vibrations are simulated in either the SSFS or the Virgin Galactic simulator. The sensation of G-load and/or vibration is helpful to a pilot in actual flight because G-load can affect maneuvering of the vehicle and provide tactile feedback to the pilot that may help them decide which control inputs to make.

The software used was X-Plane v.10 Flight Simulation. The following parameters were selected for each simulated suborbital flight: 12,587 kg initial total mass; 1,020.1 kg for crew; 7,030.7 kg for fuel; and 4,535.9 kg for structural mass. These parameters, which were published on the Virgin Galactic website (www.virgingalactic.com), are identical to the parameters that apply to the SpaceShipTwo spacecraft.

Simulated suborbital flights were conducted from Eielson Air Force Base (EAFB), 26 miles southeast of Fairbanks, Alaska. Each participant flew eight flights as follows: two nominal flights day followed by two nominal flights night followed by two contingency flights day followed by two contingency flights night. The reason for the different types of flights was to increase task difficulty, i.e., flying a contingency flight at night was considered more demanding than flying a nominal flight during the day. The reason for flying the flights in order of increasing complexity was to provide participants with experience to prepare them for the most challenging contingency flight. This meant it was not possible to separate task difficulty from sequential effects on the EEG signals or to evaluate learning from previous experience. Each flight was flown manually and there was no autopilot. The average interval between flights was 4 days (SD ±2.1 days). Each flight followed the standard SpaceShipTwo flight profile from air drop to landing. Each contingency flight was characterized by the failure of the heads-up display (HUD) and loss of power 10 seconds following rocket ignition.

The key tasks in each flight type were partly dependent on the difficulty of the flight but included checking the following: 1. airspeed and altitude; 2. acceleration; 3. angle of attack, pitch, roll and yaw; 4. control surface deflections; 5. yaw-rate-to-roll; 6. subsonic and transonic trim changes; and 7. extension of landing gear.

The limitations of the study included the small number of participants, the restricted number of flights performed by the participants and the fidelity of the SSFS not matching the fidelity of Virgin Galactic's simulator.

Each task was performed manually by the participants. Performance of tasks was checked visually by the principal investigator who observed each flight by standing next to the SSFS. For contingency flights there remained one option and that was landing at an alternate runway. The contingency flight was selected because it was determined to be the easiest contingency to perform by the participants who had limited experience flying a suborbital spacecraft. Participants were not briefed on the location of the alternate runway prior to the flight. The consequence of not reaching the runway was crashing.

A wireless brain signal acquisition system manufactured by EMOTIV (see Figure 3) was used to assess EEG/CP. The system used gold-plated contact sensors fixed to flexible plastic arms of a wireless headset which featured 14 sensors aligned with the 10-10 International System as follows: left and right anterior-frontal (AF3, AF4); anterior temporal (F7, F8); frontal (F3, F4); frontal-central (FC5, FC6); posterior temporal (T7, T8); parietal (P7, P8); and occipital (O1, O2). The device used a 14-channel, high-resolution (2048 samples per second down-sampled internally to 128 samples/s) signal acquisition wireless headset. Each participant placed the EMOTIV headset on their head under the guidance of the principal investigator. Felt pads covering the electrodes were moistened with saline solution to increase conductivity between the electrodes and the participant's scalp.

Figure 3

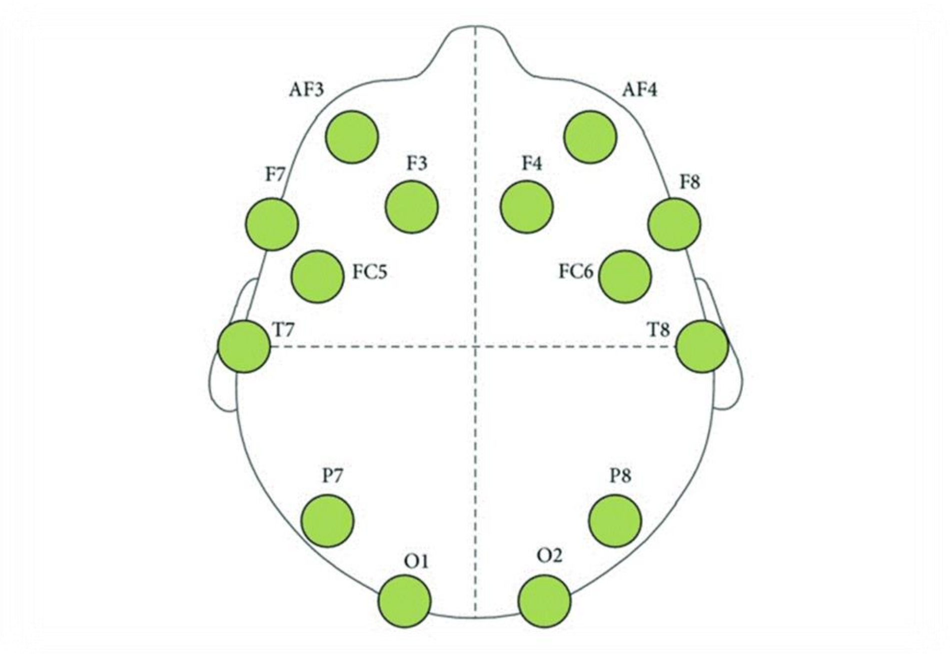
EMOTIV EPOC EEG Headset

Note. From *EPOC Headset*, by EMOTIV, 2018 (https://www.emotiv.com/independent-studies/validation-of-emotiv-epoc-for-extracting-erp-correlates-of-emotional-face-processing/). Copyright 2018 by EMOTIV.

The recording positions are shown in Figure 4. These positions are based on the International 10-20 System that allows for standardized EEG electrode placement across each brain region as follows: F (frontal), T (temporal), P (parietal), and O (occipital). This system (Jasper, 1958) also ensures inter-electrode spacing is equidistant and ensures electrode placements are proportional to skull size and shape. Prior to each test, the participant was told to relax with closed eyes for 60 seconds to simulate a relaxed (baseline) state, a procedure that was in accordance with the instructions provided by EMOTIV (https://www.emotiv.com/epoc-x/) and served to record baseline EEG activity (Teplan, 2002). Following the “relaxed period” the participant was deemed to be in an active state in which he/she was able to conduct flight maneuvers.

Figure 4

Placement of EEG Electrodes



Note. From *EEG Electrode Placement*, by EMOTIV, 2018 (https://www.emotiv.com/independent-studies/validation-of-emotiv-epoc-for-extracting-erp-correlates-of-emotional-face-processing/). Copyright 2018 by EMOTIV.

The flight profile comprised 7 segments for the nominal day and night flights (1. Pre-launch, 2. Ignition, 3. Climb-Out, 4: Microgravity, 5. Re-Entry, 6. Pull-Up, 7. Landing) and 5 segments for contingency day and night flights (1. Pre-Launch, 2. Ignition, 3. Engine-Out/Loss of HUD, 4. Recovery, 5. Landing). Each participant was briefed on the type of flight prior to the flight. Three EEG bands (beta: 13 – 20 Hz, theta: 4 – 7 Hz, and alpha: 8 – 12 Hz) were sampled. Beta band has been linked to visual attention (Wróbel, 2000), alpha band has been linked to mental workload (Puma et al., 2018) and cognitive fatigue (Borghini et al., 2012), and theta band has been linked to mental fatigue and mental workload (Gevins et al., 1995).

EEG Analysis and Artifact Removal

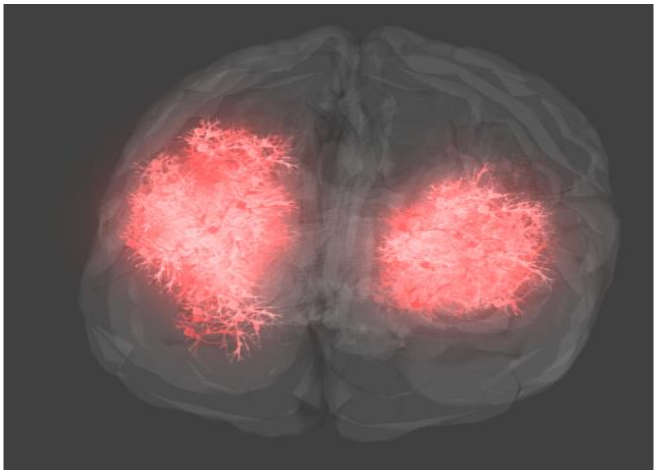
The sampling rate was 256 Hz. EEG analysis was performed using EEGLaB and Matlab. EEGLab is an interactive Matlab toolbox used to process continuous and event-related EEG. The software incorporates independent component analysis (ICA) and artifact rejection: brain signals contain artifacts that make it difficult to analyze signals when artifact activity amplitude is greater than the signals created by actual neural sources. Such artifacts are commonly caused by muscle contractions and eye movements. Removing these artifacts ensured only “clean” neural sources were analyzed.

Results

The average time for nominal day flights was 696±93.2 seconds. This time was measured from rocket ignition to landing. The average altitude attained during these flights was 109337±123.7 meters. For reference, the altitude attained by the actual SpaceShipTwo vehicle that flew in May 2023, was 87,200 meters. The average time for nominal night flights was 725±63 seconds. The average altitude attained during these flights was 104557±145 meters. The average time for contingency day flights was 414.8±38.1 seconds. The average altitude attained during these flights was 94980±565 meters. The average time for contingency night flights was 715.5±115.03 seconds. The average altitude attained during these flights was 96271.5±52.03 meters. During the flights, it was possible to visually observe changes in EEG activity as depicted in Figure 5, which provided a visual indication of changes between nominal and contingency flights.

Figure 5

EEG Activity During a Nominal Day Flight



Note. This image shows the cortical map of one participant flying a nominal night flight. The colored areas represent topography of the areas of the brain involved during task performance. As performance improves, this topography changes. Although these topographical changes were not measured in this study, changes in the cortical map could provide an estimation of workload.

Each participant that flew the nominal day and nominal night flights and contingency day flights was able to execute a landing at either EAFB or an alternate. Only two participants who flew the contingency night flight task executed successful landings at EAFB. For each nominal day and night flight phases, the mean percent total power for theta, alpha and beta bands was calculated for 7 phases of flight: pre-climb, ignition, climb-out, microgravity, re-entry, pull-up, landing. For each contingency day and night flight phases, the mean percent total power for theta, alpha and beta bands was calculated for 5 phases of flight: pre-climb, ignition, engine-out/Loss of HUD, recovery, landing. The results of these data are represented in Figure 6.

Figure 6

EEG Activity for Theta, Alpha and Beta Bands:Nominal Day vs. Nominal Night Flights

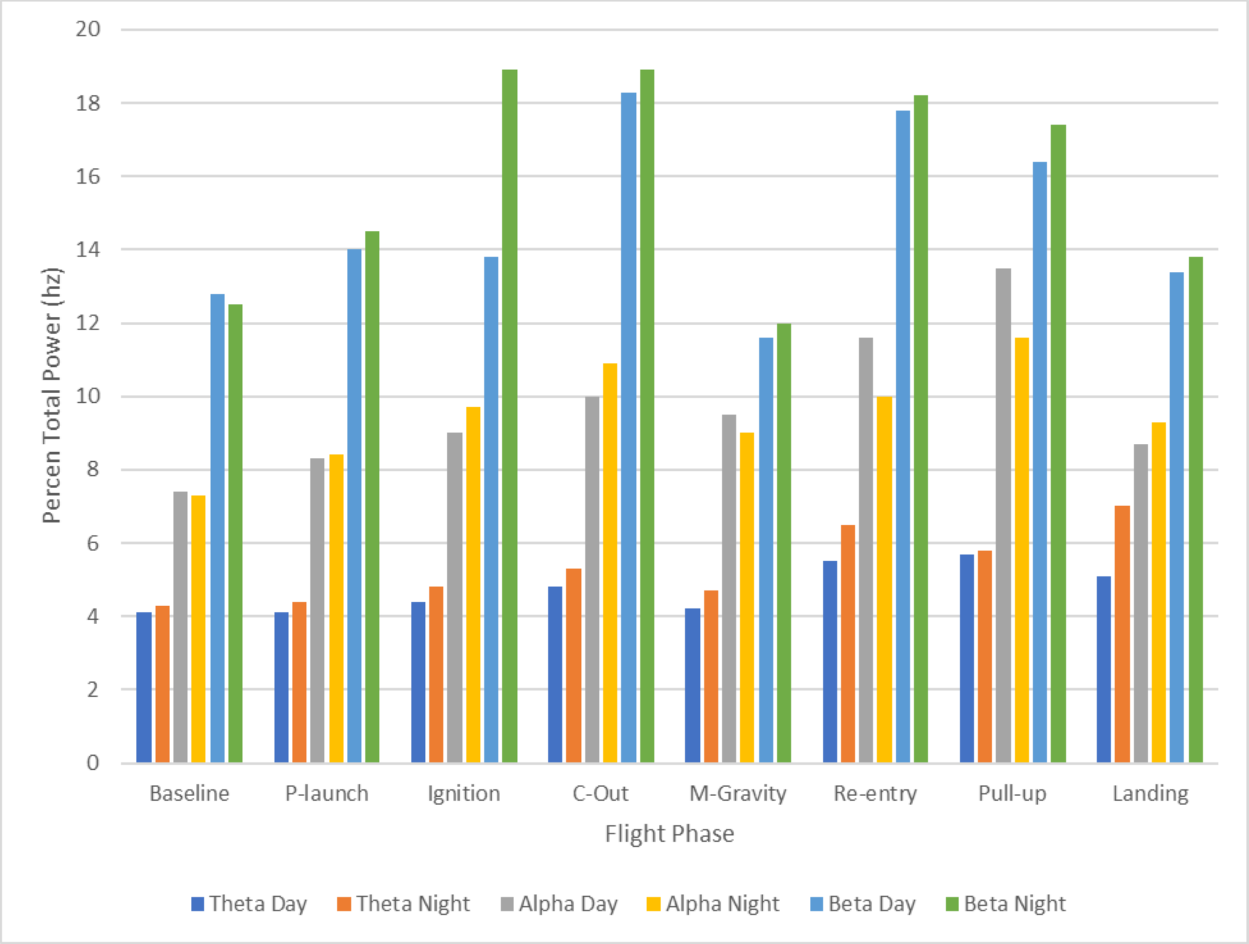
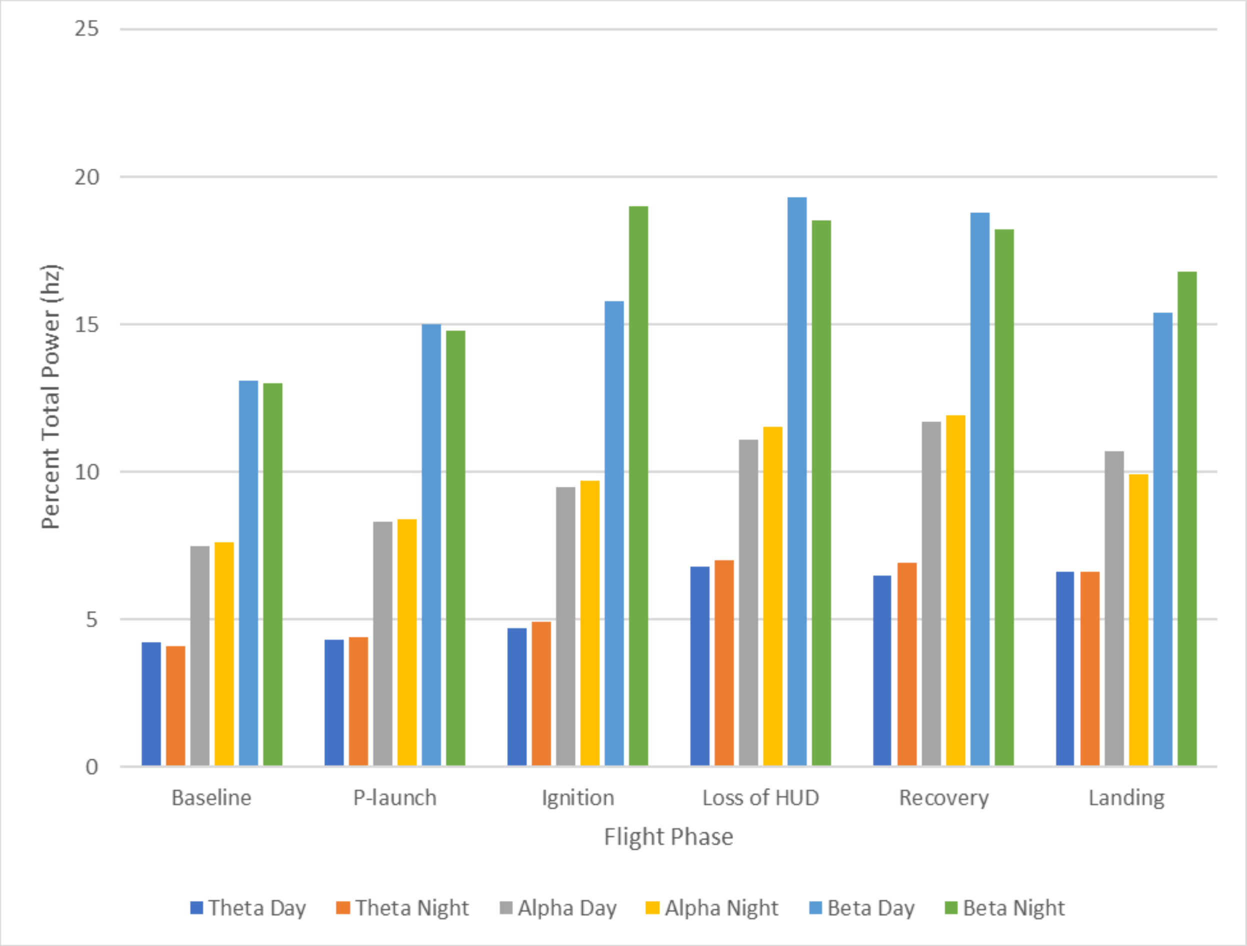


Figure 7

EEG Activity for Theta, Alpha and Beta Bands:Contingency Day vs. Contingency Night Flights



Assessment of EEG characteristics for nominal flights day versus nominal flights night was evaluated by comparison of mean total power for theta, alpha and beta bands for each flight phase. These results were analyzed statistically by analysis of variance and differences were regarded as significant at $p \leq 0.05$. Analysis of the results showed that differences were associated with each band compared with the baseline values: theta band: $p \leq 0.709$, alpha band: $p \leq 0.82$, beta band: $p \leq 0.119$.

Assessment of EEG characteristics for contingency flights day versus contingency flights night was evaluated by comparison of mean total power for theta, alpha and beta bands for each flight phase. These results were analyzed statistically by analysis of variance and differences were regarded as significant at $p \leq 0.05$. Analysis of the results showed that differences were associated with each band compared with the baseline values: theta band: $p \leq 0.81$, alpha band: $p \leq 0.74$, beta band: $p \leq 0.21$.

Flight complexity modulated the EEG power spectrum: the more demanding contingency day and contingency night flights were associated with higher EEG power bands and the less demanding flights such as the nominal day and nominal night flights were associated with lower EEG power over the same frequency bands. Specific attention was paid to the theta band because this generally increases under high workload (Borghini et al., 2013; Dehais et al., 2017; Feltman et al., 2020). In this study the theta band revealed significant increases in activity during the flight phases that were associated with increased cognitive demands during the sub-phases of climb-out, re-entry, pull-up and landing. The alpha band was less sensitive to the cognitive demands of the four flight categories.

Discussion

This pilot study evaluated the feasibility of measuring a suborbital pilot’s workload in a simulator with a portable commercial off-the-shelf 14-electrode EEG system. The first objective was to determine if it was possible to extract EEG features that discriminated between the two flying conditions, the second objective was to determine if it was possible to infer the participant’s CP from the EEG data, and the third objective was to determine if the EMOTIV EEG system was suitable for pilots to wear while flying in a simulator.

Cognitive workload was measured during performance tasks requiring low cognitive workload (nominal flight conditions) against tasks requiring high cognitive workload (contingency flights involving engine-out/loss of HUD). Suborbital pilots face several tasks for which cognitive skills are important. Such skills include the memorization and recall of procedures for the entire flight and occasionally pilots poor recall of such procedures can lead to pilot error, which was the case in the SpaceShipTwo accident in October 2014 in which one pilot was killed, and in the case of the May 2021 flight which resulted in the pilots deviating from the flight path.

Loss of HUD and loss of engine power represent unpredictable flight events that require the execution of tasks that impose high cognitive demands which in turn require changes in cognitive processing. One indicator of an increase in cognitive effort during a task can be seen in changes of the EEG power spectrum in the theta band. In this study, an increase in cognitive effort as measured by changes in the theta band was observed in the contingency flight tasks. On assessment of these data, the theta band could be used to discriminate certain types of cognitive activity associated with demanding flight phases. This finding aligns with similar data when performing other tasks, such as driving a car (Borghini et al., 2014).

Flight procedures during the nominal day flights were associated with lower EEG power than flight procedures during the nominal night flights. Also, executing day and night flight procedures in response to loss of HUD and loss of engine power was associated with higher EEG power than flight procedures conducted during nominal day and nominal night flights.

So, could EEG signals be used to monitor CP in suborbital pilots? Technically, this is possible since neurophysiological data could be streamed. This data could be represented by cortical maps and/or the evolution of EEG rhythms from flight phase to flight phase. In this study, a good EEG tracing was obtained, and the wearability of the device was reported by participants as being comfortable. Interpretation of pilot’s EEG patterns when flying would require training, but this would be feasible. One problem may be the operational constraints imposed by the flight itself, since in the dynamic flight environment associated with suborbital flight, G-state transitions during release, boost, coast, and re-entry phases could generate variable pressure to the EEG electrodes which might generate motion artifacts which would render an uninterpretable EEG signal for analysis.

Another consideration is to measure the effect on learning because the theta power band is affected by learning (Taya et al., 2016) and to also consider other cognitive constructs of interest such as mental fatigue, workload, and anticipation of visual events. Such measures could also be aligned with the measurement of personalized learning progress in the training of a suborbital pilot and whether this progress could be tracked using a neurometric such as theta band power.

A subsequent study could also focus on additional neurometrics that could provide objective measures of a pilot's cognitive state and see to what degree these measures align with the theta band data, for example. Such a measure could include the EEG Engagement Index (Dehais et al., 2017) and the NASA Task Loading Questionnaire (TLX). It could also utilize the Cognitive Stability Index (Borghini et al., 2017) which can quantify learning progress using neurophysiological metrics such as the theta band.

A subsequent study could also consider simulator fidelity, since neurophysiological results may be difficult to interpret between studies that use different kinds of simulators. One suggested simulation platform could be virtual reality (VR) since this provides a consistent field of research and is cost-effective compared with more traditional simulators.

Conclusion

This study revealed that at different phases of simulated suborbital flight, pilots showed changes in EEG characteristics and that increases in cognitive demands were revealed most noticeably in the theta band. For the participants, flying the contingency flights were the most difficult types of flight. One element that was not measured in this study was the effect of learning and how learning/training corresponds with changes in the theta band. This should be considered when developing a potential neurometric for monitoring pilot performance.

The EEG system used in this study is non-disruptive, is comfortable to wear, and provides cognitive workload accuracy with good resolution. It is believed the methods presented in this paper may be a step towards developing a cognitive monitoring procedure and neurometric that helps track the neurophysiological workload of suborbital pilots and possibly for pilots in training.

Research on the application of neurophysiology and spaceflight is incomplete and few studies have identified candidate neurometrics of pilot cognitive performance. Following this pilot study, it is suggested that more research be conducted into the utilization of the theta, alpha and beat bands as a neurometric and evaluate the accuracy of this against other objective measures suggested in the discussion.

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Conflict of Interest and Ethical Approval

The author certifies that he has no affiliations with or involvement in any organization or entity with any financial interest in the subject matter or materials discussed in this manuscript. This study was approved by the Institutional Research Board of Embry-Riddle Aeronautical University.

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