Neuroergonomics of Cursor Control Devices in Spacecraft Cockpits for Spaceflight Participants

Troy R. Weekes, Kazuhiko Momose, and Thomas C. Eskridge

March 5, 2023

Abstract

The commercial space transportation industry is rapidly growing with increasing numbers of spaceflight participants (SFPs). These private individuals receive considerably less training than astronauts before embarking on space missions, which presents an urgent need to develop the cognitive ergonomics that simplify spacecraft cockpit design. Neuroergonomics is an emerging area within cognitive ergonomics, which Parasuraman described as “the study of brain and behavior at work”. This experimental study investigated the neuroergonomics of cursor control devices (CCDs) for spacecraft cockpits by applying electroencephalography (EEG) power indices as objective measures of concentration, relaxation, effort, fatigue, arousal, valence, and absorption during task performance. Data for this study were collected from a sample of twenty-seven participants who performed a Fitt’s cursor control task in PsyToolkit with a counterbalanced device sequence of four different CCDs, i.e., touchpad, touchscreen, joystick, and numpad. The devices were affixed to, and configured in the variable positioning Adaptive Spaceship Cockpit Simulator. The index of difficulty of the cursor control task was varied according to Fitt’s law across easy, medium, and difficult levels. The orientation of the simulator was varied between upright and head-down tilt (HDT) orientations. We administered a HDT treatment before the experimental trials in the HDT orientation to induce the physiological effects associated with increased intraocular pressure. A HDT recovery period was administered after the experimental trials in the HDT orientation. Participants completed a subjective questionnaire to capture perceived effort at the end of each experimental track. Using the Flow Choice Architecture, we processed EEG signals to compute the EEG power indices for a Multivariate Analysis of Variance. There were significant findings in concentration across CCDs during the two orientations. The HDT orientation demanded more concentration than the upright orientation across the devices. This result indicated that there was additional cognitive workload induced by manipulating the CCDs in the HDT orientation. There were significant differences in fatigue across the two orientations. The HDT orientation was associated with greater fatigue levels. The significant difference in fatigue across the two orientations was corroborated by a finding in the subjective questionnaire about the participants’ perceived effort using the devices during the HDT orientation. The touchpad device consistently outperformed the other CCDs. Task difficulty did not significantly impact any of the EEG indices. No significant interactions were observed in the EEG indices across the orientations, devices, and task difficulty levels. A striking result emerged during the HDT recovery period where most participants exhibited a sleepy-like EEG signature characterized by a consistently high relaxation index. Overall, these results indicated that computational neuroergonomics may produce objective insights about the human spaceflight experience related to orientation and control devices. We recommend that strategies to enhance spacecraft cockpit design include neuroergonomics of CCDs, control devices, and cockpit user interfaces, in general.

Keywords - neuroergonomics, spacecraft, cockpits

Troy R Weekes is a Research Associate at the L3Harris Institute for Assured Information at the Florida Institute of Technology. He conducts research into personalized choice architectures and human augmentation with artificial intelligence in high-performance knowledge work domains. He received a bachelor’s degree in Aeronautical Science, a master’s degree in Aviation Human Factors, and a Ph.D. in Human-Centered Design from the Florida Institute of Technology.

1 Introduction

Recent advances in commercial spaceflight have created the need for individuals of varying backgrounds and capabilities to safely perform control tasks in spacecraft cockpits. Spacecraft are unique vehicles that operate under variable gravitational conditions and orientations depending on the different phases of the spaceflight mission. The control tasks have motor and cognitive functions, which are affected by the physical and cognitive ergonomics of the spacecraft cockpit design.

Our research problem centers on understanding the effects of different cursor control devices (CCDs) on spaceflight participants (SFPs) performing control tasks in different spacecraft orientations. How might we design spacecraft cockpits with optimal CCDs based on neuroergonomics to have the highest positive impacts and least negative impacts on the task performance of SFPs?

Control tasks in vehicle settings have traditionally been evaluated using physical and cognitive ergonomics such as motor control, kinematics, memory, decision making, workload, attention, vigilance, drowsiness, and risk taking. The growing application of cognitive approaches demonstrate an increasing trend to directly measure the neural dynamics underlying human behavior and task performance. Our quantitative approach operationalized combined frequencies of neural oscillations to model the effects of work tasks, orientations, and technologies on the human brain.

Parasuraman (2003) introduced neuroergonomics as the study of the brain and behavior in naturalistic work contexts by examining brain signatures related to human task performance. Neuroergonomics merges neuroscience and ergonomics to explain the neural mechanisms underlying cognitive and motor functioning Parasuraman & Wilson (2008). Neuroergonomics is well-positioned as a method of scientific inquiry to provide a deeper understanding of human performance by exploring how the brain works during different tasks and situations.

This paper seeks to provide evidence of the cognitive factors at play during human spaceflight by investigating the neuroergonomics of the CCDs that are commonly used in spacecraft cockpits. We computed seven power indices from electroencephalography (EEG) data to gain objective insights into the neurocognitive and neuroaffective states of SFPs performing a Fitts (1954) law cursor control task with different CCDs in a spacecraft cockpit simulator environment. We hypothesized that certain CCDs have better neuroergonomics for SFPs. Further, we predict that spacecraft orientation has a significant impact on the neuroergonomics of CCDs for SFPs.

In the following Section 2, we summarize the characteristics of SFPs, and hone in on the cursor control tasks that are performed in spacecraft cockpits. We synthesize the literature on computational neuroscience to derive neural correlates in the form of EEG indices. In Section 3, we outline the experiment that was conducted to measure the EEG indices and test hypotheses related to the neuroergonomics of the four CCDs with participants in two different orientations. We present the results in Section 4 followed by a discussion of the challenges and limitations faced in the computational neuroergonomics approach in Section 5. Section 6 concludes this paper by emphasizing the value of computational neuroergonomics in the human-centered design of spacecraft cockpits for SFPs.

2 Related Work

This paper focuses on SFPs, who are not crew but space tourists and consumers of commercial space transportation FAA (2006). The spacecraft cockpit presents a potentially challenging work environment considering the individual differences among SFPs. The controls of the cockpit user interfaces (UIs) are peripheral devices that transfer human inputs into spacecraft operations. We hypothesized that orientation and device would affect the way SFPs perform cursor control tasks, as observed in neural signals.

Computational neuroergonomics analyzes time-based and frequency-based EEG features of brain activity to determine the effects of performing a task in a given situation and context. In the transportation sector, computational methods with EEG data have been used to evaluate human task performance in operational environments such as driving, flight, air traffic control, and road and rail transportation. We utilized signal processing to mathematically transform time-series EEG data into frequency-based neurocognitive and neuroaffective states, which were used to evaluate the neuroergonomics of each CCD.

We combined the power spectral density (PSD) features from five frequency bands into multivariate functions. Table 1 shows the neural correlates mapped to the neurocognitive and neuroaffective states and events found in the computational neuroscience literature.

Table 1: Experiments highlighting EEG indices and their neural correlates

EEG Index	Neural Correlates	References
Concentration	Higher frontal beta power Lower global theta power Higher global beta/theta ratio Lower frontal theta/alpha ratio	Grammer et al. (2021)
Relaxation	Higher global alpha power Lower beta power Higher theta power Lower global delta power	Freeman et al. (1999) Prinzel et al. (2000) Berka et al. (2007) Teplan et al. (2014)
Effort	Higher beta/alpha ratios	Keller (2007) Berka et al. (2007)
Fatigue	Higher fronto-central delta power Higher fronto-central theta power Lower global relative beta power	Boksem et al. (2005) De Gennaro et al. (2007) Cheng & Hsu (2011)
Arousal	Higher frontal alpha power Lower parietal delta power	Ota et al. (1996) Reuderink et al. (2013)
Valence	Asymmetry in frontal alpha power Lower frontal theta power	Tomarken et al. (1990) Alves et al. (2008) Reuderink et al. (2013)
Absorption	Lower theta power Lower central beta power Lower central gamma	Nacke (2009) DeLosAngeles et al. (2016)

3 Method

3.1 Research Questions

Our research objectives were to measure the effects of two important factors of ergonomics, i.e., work tools and environment. Due to the environmental dependency of orientation on cursor control device use, we anticipated that the HDT orientation would negatively affect neural states. We aimed to differentiate the neuroergonomics of different CCDs using a randomized controlled trial experiment. The following research questions (RQ) were defined according to the objectives of the study:

- RQ1: What are the effects of orientation on the EEG indices?
- RQ2: What are the effects of CCD on the EEG indices?

3.2 Experiment Design

The experiment was based on a three-way (2 x 4 x 3), repeated measures design with three independent variables: (i) two seating orientations - upright and HDT, (ii) four CCDs - touchpad, touchscreen, joystick, and numpad, and (iii) three levels of task difficulty - easy, medium, and difficult. The dependent variables included EEG indices derived from the neural correlates identified in Table 1 - concentration, relaxation, effort, fatigue, arousal, valence, and absorption.

3.3 Participants

Twenty-seven (27) healthy volunteers (15 males, 10 females, 1 non-binary, 1 preferred not to say; $M =$ 22.5 years, $SD = 5.2$) wearing shirtsleeves conducted the experiment. Inclusion criteria applied during recruitment were: (i) height between 5 feet and 6 feet 3 inches, (ii) weight under 280 pounds, (iii) no eyesight conditions related to intraocular pressure (IOP), (iv) not using medications which might cause drowsiness, (v) no blood circulation problems, and (vi) not pregnant. The research study was reviewed and approved by the IRB at Florida Institute of Technology (IRB Number: 22-114).

3.4 Experiment Setting

3.4.1 Adaptive Spaceship Cockpit Simulator (ASCS)

The experiment was conducted in the ASCS Doule (2018), which was adopted for the wider research plan centered on participants in various seated orientations while wearing spacesuits and normal sleeve clothing. The ASCS was configured in the upright (0°) and HDT (34°) orientations.

3.4.2 PsyToolkit Cursor Control Task

A PsyToolkit cursor control task was customized for use with the three devices connected via USB to a Raspberry Pi touchscreen display. The display presented randomized target squares of varying sizes and distances from four randomly sequenced starting locations in PsyToolkit Stoet (2017). The task was based on Fitts (1954) law, and trials involved controlling the cursor with the CCD to click on the starting square followed by the center of the target square quickly and accurately.

3.4.3 Cursor Control Devices (CCDs)

The participants used the following four devices to complete the cursor control task:

1. Touchpad - Apple Magic Trackpad
2. Touchscreen - Raspberry Pi Touchscreen
3. Joystick - Logitech Freedom 2.4 Cordless Joystick
4. Numpad - Jelly Comb 2.4G Number Pad

The CCDs were affixed to the control device platform of the ASCS by Velcro tapes that facilitated easy adjustment and removal of the devices throughout the experiment. The order of the devices was counterbalanced to mitigate practice effects across the participants.

3.4.4 Muse EEG Headband

Prior studies using the Muse EEG headband have found the device to be non-invasive and efficacious for scientific research Cannard et al. (2021). The study participants wore a Muse EEG headband (Model Muse MU-02-BK-EN) that measured their neural oscillations. EEG signals were sampled at 256 Hz and transported via Bluetooth to a local database on a Windows desktop computer using a Bluetooth Low Energy Device (BLED) dongle. Figure 1 depicts the active sensors of the headband that were located at AF7, AF8, TP9, and TP10 with a reference sensor at FPz and two bridged grounds based on the 10–10 International sensor placement convention Krigolson et al. (2017).

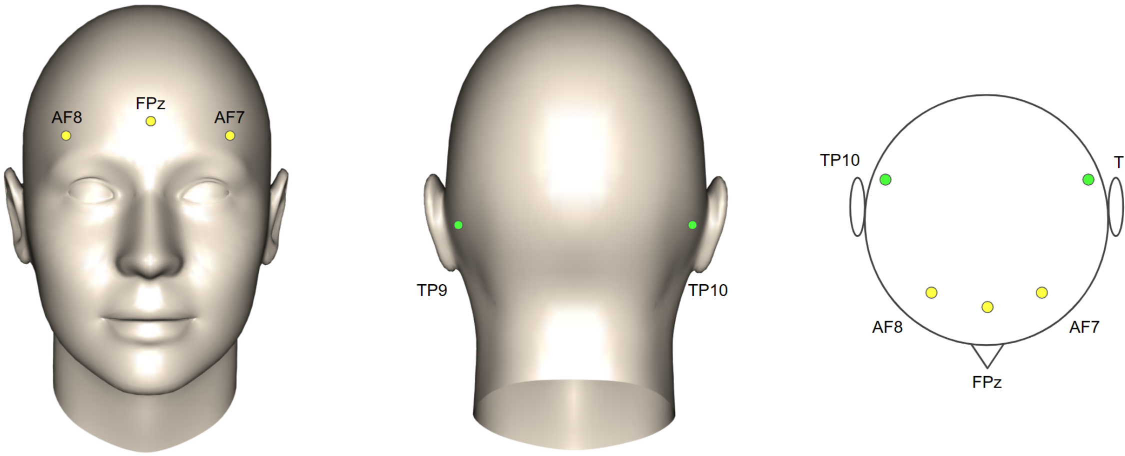

Figure 1: EEG sensors in frontopolar (FP), anterior frontal (AF), and temporoparietal (TP) regions.

3.4.5 Flow Choice Architecture (FCA)

EEG signals from the Muse headband were processed by the Flow Choice Architecture (FCA) Weekes (2021). FCA was configured with the experimental procedure for each participant to guide the experimental sessions. The FCA data pipeline in Figure 2 utilized a bandpass filter between 1 Hz to 75 Hz to smooth the raw signals followed by the removal of noise and artifacts, i.e., eye blinks, jaw clenches, head movements, and power line noise. The filtered data were segmented into 2-second epochs and converted by a Fast Fourier Transform (FFT) into the PSD features of 5 frequency bands, i.e., delta (1–4 Hz), theta (5–8 Hz), alpha (9–12 Hz), beta (13–30 Hz) and gamma (31–50 Hz). The results from the multivariate functions of the PSD features were scaled using min-max normalization to produce EEG indices with values between 0 and 1. The normalized features were segmented based on timestamped task events imported from PsyToolkit's output file, and averaged over the segments to measure the neuroergonomics of the devices during specific task trials.

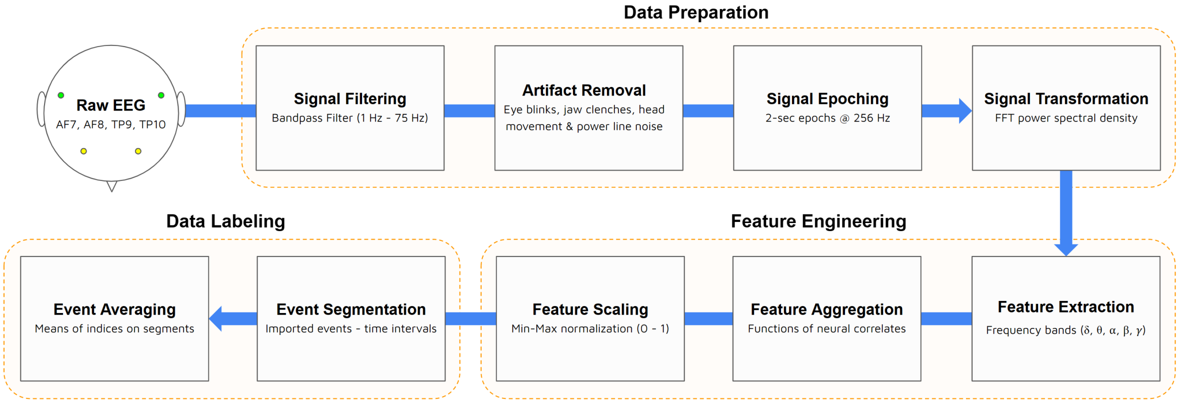

Figure 2: FCA data pipeline transforms raw EEG signals into labelled averages of normalized features.

3.5 Procedure

The experiment procedure comprised the following six sessions: (i) briefing, (ii) familiarization, (iii) first orientation condition, (iv) second orientation condition, (v) post hoc questionnaire, and (vi) debriefing. Before the experiment, an FCA account was created to store the participant's data. During the briefing, the participants were provided an overview of the experiment using a brief presentation, which outlined the study objectives, experiment flow, and safety instructions. After the briefing, participants completed the informed consent form. The participants embarked on the ASCS, engaged the seat-belts, and donned the Muse headband with assistance from the researchers. During the familiarization session, the participants practiced the cursor control task for approximately 30 minutes using the four CCDs. The participants were then assigned to one of two counterbalanced tracks, i.e. Track A (upright then HDT) or Track B (HDT then upright) as depicted in Figure 3.

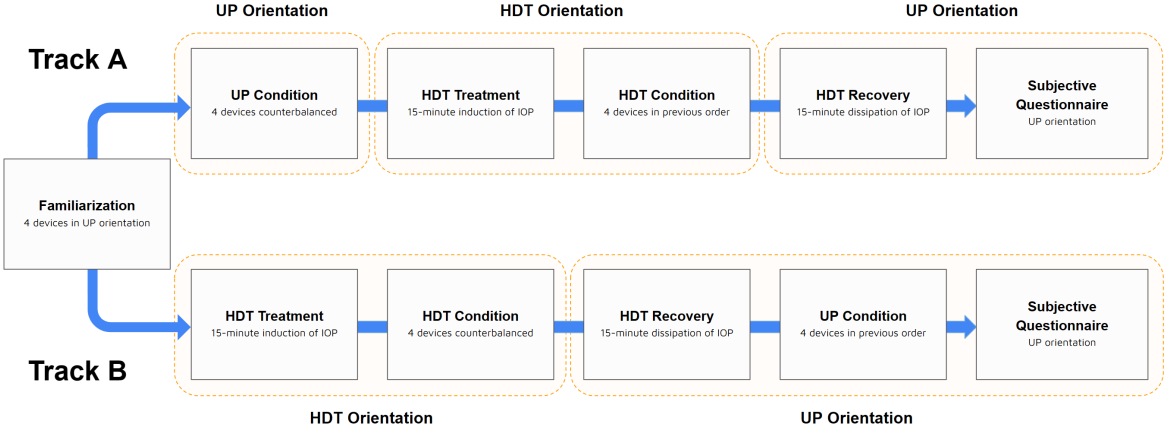

Figure 3: Experimental sessions highlighting Tracks A and B, excluding briefing and debriefing.

Track A participants conducted 40 trials using each device in the upright orientation. The device sequence was counterbalanced. During the device switches, participants were given rest periods for approximately 1 minute. Following completion of the trials in the upright condition, the ASCS was configured into the HDT orientation where participants experienced a 15-minute HDT treatment to simulate the effects of increased IOP. After the HDT treatment, the participants conducted 40 trials using each device in the upright orientation. The order of the devices was repeated from the upright condition. Following completion, the ASCS was reconfigured in the upright orientation where participants experienced a 15-minute HDT recovery treatment to dissipate the effects of increased IOP.

In contrast, Track B participants started with the 15-minute HDT treatment. After the HDT treatment, the participants conducted 40 trials using each device in the HDT orientation. Following completion of the trials in the HDT orientation, the ASCS was reconfigured in the upright orientation where participants experienced the 15-minute HDT recovery treatment. After the HDT recovery treatment, the participants conducted 40 trials using each device in the upright orientation.

At the end of Track A or Track B, participants sat in the upright orientation and completed a subjective questionnaire using the Raspberry Pi touchscreen display. Following the questionnaire, the participants were allowed to disembark from the ASCS and engage in an open debriefing session.

3.6 Data Analysis

We conducted a three-way repeated measures MANOVA with post hoc pairwise comparisons and the alpha level at 0.05. Six participants were excluded from the analysis due to incomplete data. We carried out a preliminary comparison of the responses from the subjective questionnaire with the results from the statistical analysis.

4 Results

The results from the randomized controlled trial experiment shown in Figure 4 and Figure 5 were obtained from the three-way MANOVA on EEG data from participants who performed trials of cursor control tasks repeatedly across conditions with different orientations and devices.

4.1 Effects of Orientation on the EEG indices

Orientation had significant effects on concentration, $F(1{,}19) = 7.06$, $p < .01$, $\eta_p^2 = 0.02$ and fatigue, $F(1{,}19) = 4.31$, $p < .05$, $\eta_p^2 = 0.01$. The HDT condition resulted in more concentration and fatigue. There were no significant interactions between orientation and other independent variables.

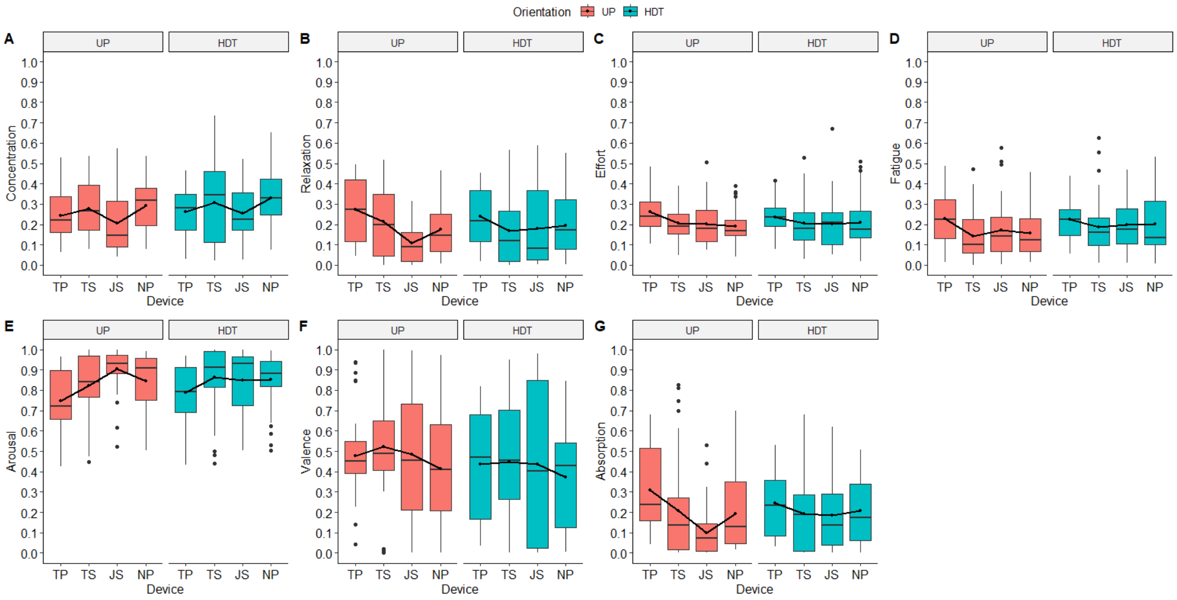

Figure 4: Box plots of EEG indices: (A) concentration, (B) relaxation, (C) effort, (D) fatigue, (E) arousal, (F) valence, and (G) absorption, grouped across two orientations (UP - orange, HDT - turquoise) then split into four devices (n = 21). The differences of means between subgroups with the same orientation are depicted by the solid lines across devices.

4.2 Effects of Device on the EEG Indices

Device significantly affected the EEG indices as follows: concentration, $F(3{,}17) = 8.03$, $p < .01$, $\eta_p^2 = .02$; relaxation, $F(3{,}17) = 10.09$, $p < .001$, $\eta_p^2 = .08$; effort, $F(3{,}17) = 6.48$, $p < .005$, $\eta_p^2 = .005$; fatigue, $F(3{,}17) = 6.46$, $p < .001$, $\eta_p^2 = .05$; arousal, $F(3{,}17) = 13.00$, $p < .001$, $\eta_p^2 = .10$; and absorption, $F(3{,}17) = 10.96$, $p < .001$, $\eta_p^2 = .08$.

Pairwise comparisons revealed that the numpad required significantly more concentration ($p < .0001$) than the joystick. The touchpad was significantly more relaxing to use than the joystick ($p < .0001$), numpad ($p < .05$), and touchscreen ($p < .01$). However, the touchpad required significantly more effort than the joystick ($p < .01$), numpad ($p < .01$), and touchscreen ($p < .01$). The touchpad also generated significantly more fatigue than the joystick ($p < .0001$), numpad ($p < .05$), and touchscreen ($p < .01$). The fatigue effect was corroborated by the increased effort using the touchpad. The touchpad generated significantly less arousal than the joystick ($p < .0001$), numpad ($p < .0001$), and touchscreen ($p < .0001$). The touchpad promoted significantly more absorption than the joystick ($p < .0001$), numpad ($p < .01$), and touchscreen ($p < .01$). Surprisingly, there were no significant effects on valence across the devices in spite of the consistently lower means in the HDT orientation. There were no significant interactions between device and other independent variables.

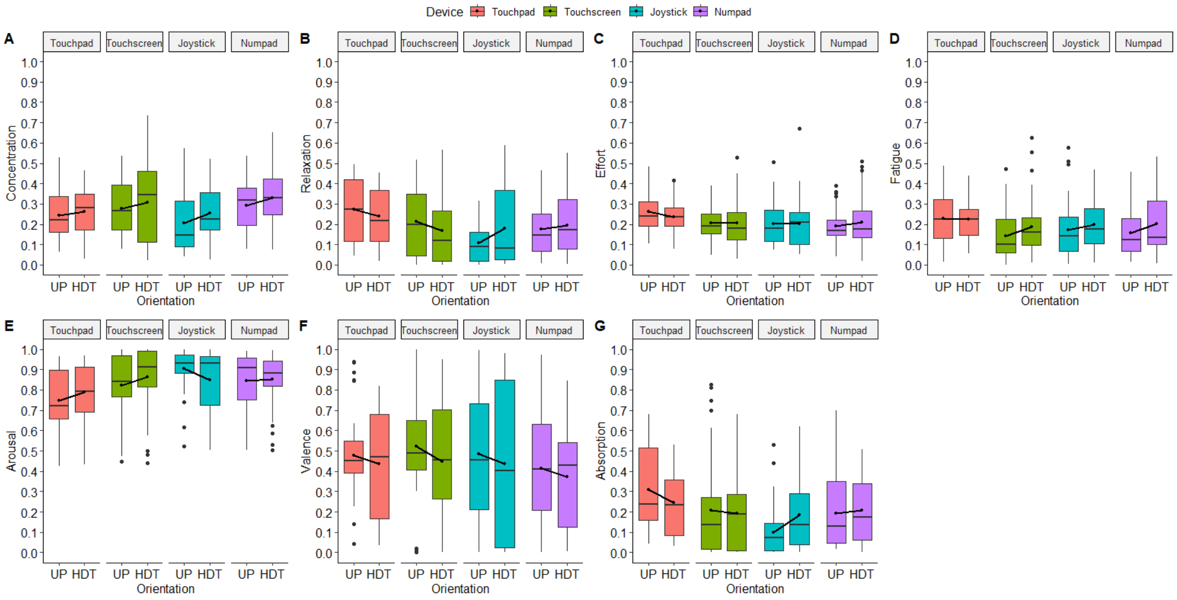

Figure 5: Box plots of EEG indices: (A) concentration, (B) relaxation, (C) effort, (D) fatigue, (E) arousal, (F) valence, and (G) absorption, grouped across four devices (touchpad - orange, touchscreen - green, joystick - turquoise, numpad - purple) then split into two orientations (n = 21). The differences of means between subgroups with the same device are depicted by the solid lines across orientations.

5 Discussion

Different orientations and CCDs impact the control task performance of participants in the ASCS. Orientation plays a critical role in determining the neuroergonomics of different devices. During the HDT recovery period, most participants exhibited a sleepy-like EEG signature characterized by a consistently high relaxation index. This finding is notable considering the impacts of drowsiness and vigilance decrement that are likely to degrade task performance. The cursor control task in this experiment was primarily an attention and motor response type of task. Future work in neuroergonomics for SFPs should include a battery of cognitive tasks to measure different aspects of cognition that are relevant to spaceflight missions, such as memory and decision making with risk and uncertainty.

The selection of control devices for spacecraft cockpits influences the neuroergonomics experienced by SFPs. Devices with poor neuroergonomics should be avoided to mitigate their negative impacts on task performance. The touchpad consistently outperformed the touchscreen, joystick, and numpad. The neuroergonomics of the touchpad may be due to the following factors: (i) good balance between challenge and skill, (ii) forgiving, and direct gestural touch input for cursor control, (iii) small, scaled, and well mapped cursor control envelope, and (iv) high accuracy in large and fine cursor control inputs.

The EEG indices were efficacious in revealing differences among the orientations and devices. However, valence exhibited noticeably large variances in the HDT orientation for the devices but did not yield any statistically significant results. In contrast, effort exhibited relatively small variances across all orientations and devices, and yielded statistically significant results with a small effect size.

Five participants agreed (0 - strongly agreed, 5 - somewhat agreed, n = 27) that there was an effect of the HDT orientation on their cognition. Eleven participants agreed (2 - strongly agreed, 9 - somewhat agreed, n = 27) that there was an effect of the HDT orientation on their breathing. The perceived impacts of the HDT orientation on cognition and breathing need to be investigated in future work in spite of the objective EEG indices, which already indicate potential adverse impacts on SFPs.

Overall, the results of this study suggest that computational neuroergonomics may produce objective insights about the human spaceflight experience. In this case, EEG-based neuroergonomics enabled the researchers to observe the near-real time operational state of humans during situated task performance. This is especially significant when considering the complex control tasks that SFPs may be required to perform during spaceflight missions. We recommend that strategies to enhance spacecraft cockpit design include neuroergonomics of devices and cockpit UIs, in general.

5.1 Limitations

In this computationally intensive type of investigation, the acquisition and analysis of EEG data were problematic steps due to several potential sources of error. A primary source of error was variable signal quality, which is caused by participant movements and electrical noise.

The EEG indices measured across the participants were relatively consistent given the prevalence of individual differences in EEG datasets. However, the Bluetooth connection malfunctioned occasionally, which resulted in data being lost or not recorded for 6 of the 27 experiment sessions. The reduced dataset limited our ability to fully explore the range of individual differences among the SFPs.

The Muse EEG headband limited the data collection to four sensors. In spite of the sensors being well positioned to examine asymmetrical brain regions, the sparse spatial coverage of EEG signals restricted analyses from exploring neural correlates related to other brain regions.

The participants' subjective responses about the effects of the HDT orientation on cognition and breathing may be influenced by recall bias depending on the orientation track. Future work should analyze the impacts of orientation track on the dataset, and utilize photoplethysmography sensors in subsequent studies to collect objective measures of breathing rates, heart rate variability, and galvanic skin response. Further data collection is required to further examine whether or not task difficulty and other factors such as clothing affect the neuroergonomics of CCDs.

6 Conclusion

With increasing focus placed on space tourism and human spaceflight with SFPs, it is becoming more important to ensure the human-centered design of spacecraft cockpit UIs for mission success. This study applied computational neuroergonomics to human-system integration with the goal of enabling SFPs to safely and productively operate control devices on their spaceflight missions. The results provide meaningful interpretations of the participants' neurocognitive and neuroaffective states. The touchpad device exhibited the most favorable neuroergonomics and HDT orientation negatively impacted the neuroergonomics of the SFPs. We leveraged EEG-based computational neuroergonomics to inform the design of spacecraft cockpits.

Acknowledgment

This study was funded by the Federal Aviation Administration (FAA) Center of Excellence (COE) for Commercial Space Transportation (CST) via FAA Cooperative Agreement 15-C-CST-FIT-016. The authors thank the FAA COE CST for funding. The opinions expressed are those of the authors and do not necessarily reflect the views of the FAA.

References

Alves, N. T., Fukusima, S. S. & Aznar-Casanova, J. A. (2008), 'Models of brain asymmetry in emotional processing', *Psychology & Neuroscience* **1**, 63–66.

Berka, C., Levendowski, D. J., Lumicao, M. N., Yau, A., Davis, G., Zivkovic, V. T., Olmstead, R. E., Tremoulet, P. D. & Craven, P. L. (2007), 'Eeg correlates of task engagement and mental workload in vigilance, learning, and memory tasks', *Aviation, space, and environmental medicine* **78**(5).

Boksem, M. A., Meijman, T. F. & Lorist, M. M. (2005), 'Effects of mental fatigue on attention: an erp study', *Cognitive brain research* **25**(1), 107–116.

Cannard, C., Wahbeh, H. & Delorme, A. (2021), Validating the wearable muse headset for eeg spectral analysis and frontal alpha asymmetry, *in* '2021 IEEE International Conference on Bioinformatics and Biomedicine (BIBM)', IEEE, pp. 3603–3610.

Cheng, S.-Y. & Hsu, H.-T. (2011), *Mental fatigue measurement using EEG*, IntechOpen.

De Gennaro, L., Marzano, C., Veniero, D., Moroni, F., Fratello, F., Curcio, G., Ferrara, M., Ferlazzo, F., Novelli, L., Pellicciari, M. C. et al. (2007), 'Neurophysiological correlates of sleepiness: a combined tms and eeg study', *Neuroimage* **36**(4), 1277–1287.

DeLosAngeles, D., Williams, G., Burston, J., Fitzgibbon, S. P., Lewis, T. W., Grummett, T. S., Clark, C. R., Pope, K. J. & Willoughby, J. O. (2016), 'Electroencephalographic correlates of states of concentrative meditation', *International Journal of Psychophysiology* **110**, 27–39.

Doule, O. (2018), Adaptive Spaceship Cockpit Architecture, PhD thesis, Florida Tech.

FAA, F. A. A. (2006), 'Human space flight requirements for crew and space flight participants: Final rule', *Online at http://edocket.access.gpo.gov/2006/pdf/E6-21193.pdf* .

Fitts, P. M. (1954), 'The information capacity of the human motor system in controlling the amplitude of movement.', *Journal of experimental psychology* **47**(6), 381.

Freeman, F. G., Mikulka, P. J., Prinzel, L. J. & Scerbo, M. W. (1999), 'Evaluation of an adaptive automation system using three eeg indices with a visual tracking task', *Biological psychology* **50**(1), 61–76.

Grammer, J. K., Xu, K. & Lenartowicz, A. (2021), 'Effects of context on the neural correlates of attention in a college classroom', *npj Science of Learning* **6**(1), 1–4.

Keller, B. M. (2007), Cognitive avionics toolset for operator state classifacation based on physiological signals, *in* '2007 IEEE/AIAA 26th Digital Avionics Systems Conference', IEEE, pp. 6–A.

Krigolson, O. E., Williams, C. C., Norton, A., Hassall, C. D. & Colino, F. L. (2017), 'Choosing muse: Validation of a low-cost, portable eeg system for erp research', *Frontiers in neuroscience* **11**, 109.

Nacke, L. (2009), Affective ludology: Scientific measurement of user experience in interactive entertainment, PhD thesis, Blekinge Institute of Technology.

Ota, T., Toyoshima, R. & Yamauchi, T. (1996), 'Measurements by biphasic changes of the alpha band amplitude as indicators of arousal level', *International journal of psychophysiology* **24**(1-2), 25–37.

Parasuraman, R. (2003), 'Neuroergonomics: Research and practice', *Theoretical issues in ergonomics science* **4**(1-2), 5–20.

Parasuraman, R. & Wilson, G. F. (2008), 'Putting the brain to work: Neuroergonomics past, present, and future', *Human factors* **50**(3), 468–474.

Prinzel, L. J., Freeman, F. G., Scerbo, M. W., Mikulka, P. J. & Pope, A. T. (2000), 'A closed-loop system for examining psychophysiological measures for adaptive task allocation', *The International journal of aviation psychology* **10**(4), 393–410.

Reuderink, B., Mühl, C. & Poel, M. (2013), 'Valence, arousal and dominance in the eeg during game play', *International journal of autonomous and adaptive communications systems* **6**(1), 45–62.

Stoet, G. (2017), 'Psytoolkit: A novel web-based method for running online questionnaires and reaction-time experiments', *Teaching of Psychology* **44**(1), 24–31.

Teplan, M., Krakovská, A. & Špajdel, M. (2014), 'Spectral eeg features of a short psycho-physiological relaxation', *Measurement Science Review* **14**(4), 237–242.

Tomarken, A. J., Davidson, R. J. & Henriques, J. B. (1990), 'Resting frontal brain asymmetry predicts affective responses to films.', *Journal of personality and social psychology* **59**(4), 791.

Weekes, T. R. (2021), Flow Choice Architecture: Cognitive Augmentation of Knowledge Workers, PhD thesis, Florida Tech.