Neuroergonomics for aviation

Authors' notes

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Abstract

Neuroergonomics is the study of how the brain functions in real-world situations with the goal of developing technology to enhance human performance. Neuroergonomics constitutes a paradigm shift away from the standard reductionist approach to neuroscience. The neuroergonomic approach maintains that an understanding of neural processes underlying human behavior can best be understood by investigating the underlying interacting brain networks in the context of carrying out various real-world tasks under investigation, rather than under reduced isolated conditions that only occur in the laboratory. In this chapter we discuss why aerospace cerebral experimental sciences (ACES) is an ideal paradigm to implement this neuroergonomic approach. By using a combination of high resolution and lower resolution portable brain imaging techniques as well as non-invasive brain stimulation the goal of ACES is to determine brain processes underlying complex behavior during aviation and space operations such that neuroergonomic technology can be developed to improve human performance.

Keywords

Neuroergonomics, Brain Computer Interface, BCI, Aviation, Aerospace, EEG, EMG, fMRI, fNIRS,

Introduction

Aerospace cerebral experimental sciences ACES is the neuroergonomic investigation of how the brain works in natural complex real-world environments. Neuroergonomics is defined as the study of brain structure and function in relation to human cognition and behavior in real-world settings (Parasuraman and Rizzo, 2007). While the primary focus of ACES is related to the neuroergonomic investigation of processes underlying aviation and space operations the paradigm has far reaching implications relevant to all neuroscience and may constitute a shift in the way research is conducted and discoveries are made about global neural processing. The two primary goals of ACES are the following: 1. To determine the interactive neural processes underlying perception, motor control, cognition, and emotion occurring in the context of robust real-world situations. 2. To develop neuroergonomic based technology that can be implemented in real-world situations to improve human performance. It is maintained that this neuroergonomic approach to neuroscience will afford insight into underlying processes and provide a basis for developing technology that is not possible using standard reductionist methodology.

Challenges

The standard reductionist experimental method has been instrumental in discovering many aspects of how the brain caries out specific processes. The strength in this approach lies in its ability to manipulate independent variables to better control potential confounds. Most experimental research based on this approach break stimuli and tasks down into very basic elements to more easily understand the underlying neural processes and provide better control over confounds. It is assumed that more complex perceptual, motor, and cognitive processes, even in real-world situations, can be understood by combining these basic elements. This is an assumption yet to be verified and is perhaps not true.

While there are considerable advantages for the use of the standard reductionist approach with regard to experimental manipulation and control, there are also considerable disadvantages especially in the context of development of neuroergonomic technology. The tasks and stimuli used in standard experimental research are far removed from real-life experience. They are not ecologically valid. The only time a person is likely to experience the conditions presented in these experiments is in the laboratory. Additionally another disadvantage of the standard approach is that the experimental tasks are usually not engaging causing degradation of data due to fatigue. Even subjects with the best intentions and motivation have difficulty truly engaging in the typical experimental tasks employed. Differential engagement in experimental tasks can lead to differential activity related to arousal instead of the condition under investigation. As one subject remarked "Why are your experiments so boring it is like torture. All you are recording in your experiment is brain activity involved with being bored to death versus sleeping."

Wouldn't it be nice if we could investigate neural processes of complex engaging real-world tasks and have good experimental control? There are several advantages afforded by such a neuroergonomic paradigm. Experiments that are more engaging result in a greater degree of motivation in subjects. Therefore there is less degradation of data due to fatigue. Because the experiments are engaging and the subjects are motivated longer experiments can be conducted allowing for larger data collection. Additionally, the results can be directly applied to real-world conditions.

In stark contrast to the standard experimental approach, the neuroergonomic approach maintains that in order to investigate complex real world behavior it is necessary to understand the processes within the context of the underlying interacting brain networks rather than under reduced isolated conditions that only occur in the laboratory (Callan et al., 2012). Utilizing multiple brain imaging and stimulation methods (electroencephalography EEG, magnetoencephalography MEG, functional near infrared spectroscopy fNIRS, functional magnetic resonance imaging fMRI, transcranial magnetic stimulation TMS, transcranial direct current stimulation tDCS) the objective of ACES research is to determine the neural correlates of perceptual, motor, and cognitive processing as well as mental states (including alertness, fatigue, workload, and anxiety) that are difficult to quantify behaviorally. By understanding the underlying neural processes in the context of complex real-world tasks brain-computer-interfaces BCI can be used to control adaptive automation and give feedback to modulate brain activity and behavior to facilitate learning, situational awareness, and decision making to promote performance, safety efficiency, and wellbeing.

Human operations in aviation and space constitute an ideal paradigm to implement this neuroergonomic approach. Unlike many human activities that involve running, jumping, throwing, etc… in which there is considerable movement of the body, piloting an aircraft/spacecraft involves control of multiple degrees of freedom with relatively little movement of the hands and feet. This is critical when using high-resolution brain imaging techniques such as MEG and fMRI that are highly susceptible to movement artifacts with some body motions not being possible during scanning at all. It is important to be able to use these high-resolution brain-imaging techniques under simulated real-world situations in order to determine the relevant underlying brain processes involved with the task at hand. This information can serve to guide and constrain analysis of brain processes made with more mobile brain recording devices such as EEG and fNIRS. Flight simulation programs allow for control and output of hundreds of parameters in real-time that can be used for experimental manipulation and analysis. This level of control allows one to design experiments with the ability to address potential task relevant and extraneous variables. The addition of motion-platform based flight simulation and force feedback controls adds an additional level of similarity with real-world conditions such that brain-computer-interface machine learning procedures can be developed that may transfer successfully into operation in real aircraft. Because of the diversity of tasks involved in aviation and space operations diverse topics can be investigated ranging from motor control, attention, learning, alertness, fatigue, workload, decision making, situational awareness, anxiety, etc… This diversity will allow for better understanding of how the brain works in real-word situations and will provide for a large number of potential neuroergonomic applications to be developed. One final reason why aerospace is an ideal paradigm for to investigate brain processes under real-world conditions is that Aviation/Aerospace is one of the biggest industries in the world with the consequences of failure being quite severe. With technological advancement in aircraft/spacecraft it is necessary for the application of neuroergonomic technology to improve the synthesis of human and machine to enhance performance and safety.

It is important for neuroergonomic approaches to utilize constraints based on neuroscience instead of purely applying an engineering based solution. In engineering, a data-driven hypothesis-free approach is often employed to make task related predictive models based on the brain recordings (e.g. EEG, fNIRS data). However, without utilizing proper constraints based on neuroscience there is a greater chance of contamination by artifacts instead of true brain processes. This could inherently reduce the ability of the BCI to generalize to novel situations. Without utilizing constraints from neuroscience research crucial features may not be integrated into the analysis to make successful predictions that will generalize from the laboratory to real-world situations.

Electro-encephalography

Several experiments have been conducted using EEG in simulated and real aviation and space operations (Sem-Jacobsen et al., 1959; Maulsby, 1966; Sterman and Mann, 1995; Wilson, 2002; Coffey et al., 2010; Borghini et al., 2012; Marusic et al., 2014; Dehais et al, 2017). One area of extensive research has been to determine neural correlates that assess and predict mental workload. An extensive review of the literature related to workload in aircraft pilots is given in Borghini et al., (2012). Their review indicated that high mental workload is generally characterized by an increase in EEG power in the theta band (4-8Hz) and a decrease in alpha-band power (8-15Hz) and that a transition between high mental workload and mental fatigue is characterized by increased EEG power in theta as well as delta (<4Hz) and alpha bands (Borghini et al., 2012). More extensive research using aviation and space related tasks with high-resolution brain imaging (fMRI and MEG) is necessary to better determine the brain regions and underlying neural processes involved with mental workload and transition to mental fatigue. Research into the relationship between attention, working memory, and affective states such as arousal and drive will bring considerable insight into an understanding and functional specification of mental workload that goes beyond simple 'capacity' definitions.

In order for EEG to be effectively utilized in aviation and space operations it must be highly portable, easy to wear, comfortable, wireless, and use dry sensors (Coffey et al., 2010; Callan et al., 2015). It has been demonstrated that dry-wireless

EEG can be utilized in motion platform simulated and real in-flight aviation related situations despite the considerable inherent vibration and noise. Utilizing artifact cleaning (Automatic Subspace Reconstruction; Mullen et al., 2013) and removal (Independent Component Analysis; Delorme and Makeig, 2008) techniques it was possible to train a classifier to detect the presence or absence of an audio stimulus with around 79.2% predictive performance even in an open cockpit biplane in-flight with considerable vibration, wind, acoustic noise, and physiological artifacts (Callan et al., 2015). Additionally, the ability to detect the occurrence of pilot-induced oscillations with 79% accuracy in-flight with dry-wireless EEG has also been successful (Scholl, et al., 2016).

Near Infra-red spectroscopy

Another approach for ACES is to consider the use of functional near infrared spectroscopy (fNIRS). fNIRS is a non-invasive and easy-to-use optical brain imaging device that is suitable to monitor cortical activity under highly ecological settings. Since the work of Takeuchi (2000), this technique has gained momentum to measure pilots' cognitive performance in flight simulator (Çakır, et al., 2016; Gateau et al, 2015; Ayaz et al., 2012) or actual flight conditions (Dehais et al., 2016; Kikukawa et al., 2008; Kobayashi et al., 2002). It can provide objective measurements to assess pilot's training (Choe et al, 2016) or system design (Andeol et al, 2017), but as for EEG, most of the efforts are put into the investigation of the neural correlates of mental workload. Several studies pointed out that changes in oxygenated hemoglobin concentration in the prefrontal cortex are relevant markers of mental workload variation (Çakır et al., 2016 ; Gateau et al, 2015; Ayaz et al., 2012). Interestingly enough, the spatial resolution of fNIRS allows the measure of specific brain area such as the dorsolateral prefrontal cortex in which disengagement predicts drop in performance (Durantin et al., 2015; Durantin et al., 2014; Harrivel et al., 2013). Eventually, the implementation of fNIRS-based BCI in ecological settings remain challenging but the design of adapted filtering techniques (Durantin et al, 2015) allow to discriminate different level of working memory loads with up to 75% accuracy in a motion flight simulator. However, one perspective for ACES is the combination of EEG and fNIRS to offer a unique insight on the neurovascular coupling (Mandrick et al, 2016) to better understand and predict pilot's performance.

Brain Computer Interface and neuro-adaptive technology

Interfaces and automation (artificial intelligence) will continue to grow in augmenting human information processing and communication both amongst individuals and between individuals and machines. For seamless efficient interaction it is necessary to develop intelligent interfaces that optimally deliver relevant information and control automation based on environmental demands and decoded brain/mental states of the user. Neuroadaptive automation based on integrating decoded operator neural states (using BCI technology) in relation to situation assessment is used to enhance overall system performance, safety, and efficiency. The ability to utilize BCI technology practically in neuroergonomic applications requires that it does not interfere with the normal operation of the task at hand, does not increase workload, and improves overall system performance /efficiency in some manner. Active BCIs, (often demanding some type of mental imagery) require extensive concentration and increase workload without performance benefits in task operation carried out by normal means (Coffey et al., 2010; Zander et al., 2011). For these reasons it is maintained that passive BCI that utilizes spontaneous neural activity related to the task at hand is more appropriate for neuroergonomic applications for aviation and space operations (see Coffey et al., 2010).

One example of neuroadaptive automation that can improve human performance using spontaneous brain activity on a piloting task is given in Callan et al., (2016b). The objective of this research was to design neuroadaptive automation that can decode motor intention in response to an unexpected perturbation in flight attitude while ignoring ongoing motor activity related to piloting the airplane. The goal was not to take control away from the pilot but rather to facilitate the response speed of the pilot through the use of automation. The BCI was trained on a simple task and was found to be able to generalize to more complex tasks with the ability to differentiate between motor intention to an unexpected perturbation from that used during normal maneuvering. The neuroadaptive automation was able to enhance the response speed (to superhuman levels in some cases) to recover from the perturbation without additional workload utilizing only brain activity naturally occurring during the perceptual motor piloting task (Callan et al., 2016b). Although this experiment was conducted off-line it demonstrates the feasibility of utilizing spontaneous brain activity naturally occurring during a task for neuroergonomic applications.

One of the primary components of neuroergonomic research is to determine brain structures and functions underlying perceptual, motor, and cognitive processes that occur during real-world type situations. There have been several experiments carried out using high-resolution brain imaging concerning aviation tasks to learn about underlying neural processes involved with the task and/or skill under investigation (Callan et al., 2012; Callan et al., 2013; Causse et al, 2013; Ahamed, et al., 2014, Adamson et al., 2014). Insight into the neural processes underlying transcranial direct current stimulation tDCS (shown to enhance human abilities in a neuroergonomic context; Parasuraman and Mckinley, 2014) to modulation of resting state brain activity was investigated using simultaneous fMRI and tDCS on an aviation related visual search task (Callan et al., 2016a). It was found that the degree of functional connectivity from the site of stimulation in the precuneus to the substantia nigra predicts future enhancement in visual performance induced by tDCS (Callan et al., 2016a). The substantia nigra is part of the dopaminergic system and is involved with value dependent learning. This study gives insight to the possible neural mechanisms by which tDCS enhances human performance.

Conclusion

This chapter gave a brief description of the neuroergonomic approach of aerospace cerebral experimental sciences. Because of the limited space a focus was given to our own research. There are considerable contributions to this field of neuroergonomics that is moving closer to the goal of establishing a paradigm shift in the way neuroscience research is conducted such that an understanding of the how the brain functions in natural settings will lead to development of technology to improve human performance, efficiency, safety, and wellbeing.

References:

Adamson M, Taylor JL, Heraldez D, Khorasani A, Noda A, Hernandez B, Yesavage JA (2014): Higher landing accuracy in expert pilots is associated with lower activity in the caudate nucleus. *PLoS ONE 9(11)*: e112607. doi:10.1371/journal.pone.0112607

Ahamed, T., Kawanabe, M., Ishii, S., Callan, D. (2014). Structural differences in gray matter between glider pilots and non-pilots. A voxel based morphometry study. *Frontiers in Neurology 5(248),* 1-5.

Andéol, G., Suied, C., Scannella, S., & Dehais, F. (2017). The Spatial Release of Cognitive Load in Cocktail Party Is Determined by the Relative Levels of the Talkers. *Journal of the Association for Research in Otolaryngology*. doi: 10.1007/s10162-016-0611-7.

Ayaz, H., Shewokis, P. A., Bunce, S., Izzetoglu, K., Willems, B., & Onaral, B. (2012). Optical brain monitoring for operator training and mental workload assessment. *Neuroimage*, *59*(1), 36-47.

Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., Babiloni, F. (2012). Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue, and drowsiness. *Neuroscience and Biobehavioral Reviews. 44*, 58-75. DOI: 10.1016/j.neubiorev.2012.10.003.

Çakır, M. P., Vural, M., Koç, S. Ö., & Toktaş, A. (2016, July). Real-Time Monitoring of Cognitive Workload of Airline Pilots in a Flight Simulator with fNIR Optical Brain Imaging Technology. In *International Conference on Augmented Cognition* (pp. 147-158). Springer International Publishing.

Callan, D., Durantin, G., Terzibas, C. (2015). Classification of single-trial auditory events using dry-wireless EEG during real and motion simulated flight. *Frontiers in Systems Neuroscience 9(11)*, 1-12. doi: 10.3389/fnsys.2015.00011.

Callan, D., Falcone, B., Wada, A., Parasuraman, R. (2016a). Simultaneous tDCS-fMRI identifies resting state networks correlated with visual search enhancement. *Frontiers in Human Neuroscience 10(72)*, 1-12. Doi: 10.3389/fnhum.2016.00072.

Callan, D., Gamez, M., Cassel, D., Terzibas, C., Callan, A., Kawato, M., Sato, M. (2012). Dynamic visuomotor transformation involved with remote flying of a plane utilizes the 'Mirror Neuron' system. *PLoS ONE 7(4)*, 1-14.

Callan, D., Terzibas, C., Cassel, D., Callan, A., Kawato, M., Sato, M. (2013). Differential activation of brain regions involved with error-feedback and imitation based motor simulation when observing self and an expert's actions in pilots and non-pilots on a complex glider landing task. *NeuroImage 72*, 55-68.

Callan, D., Terzibas, C., Cassel, D., Sato, M., Parasuraman, R. (2016b). The brain is faster than the hand in split-second intentions to respond to an impending hazard: A simulation of neuroadpative automation to speed recovery to perturbation in flight attitude. *Frontiers in Human Neuroscience 10(187)*, 1-21. Doi: 10.3389/fnhum.2016.00187.

Causse, M., Péran, P., Dehais, F., Caravasso, C. F., Zeffiro, T., Sabatini, U., & Pastor, J. (2013). Affective decision making under uncertainty during a plausible aviation task: An fMRI study. *NeuroImage*, *71*, 19-29.

Choe, J., Coffman, B. A., Bergstedt, D. T., Ziegler, M. D., & Phillips, M. E. (2016). Transcranial direct current stimulation modulates neuronal activity and learning in pilot training. *Frontiers in human neuroscience*, *10*.

Coffey, E., Brouwer, A., Wilschut, E., Erp, J. (2010). Brain-machine interfaces in space: Using spontaneous rather than intentionally generated brain signals. *Acta Astronautica 67*, 1-11.

Dehais, F., Hasan, A., &Gateau, T. (2016) Assessing working memory load in real flight condition with wireless fNIRS. Presented at the *Neuroergonomics'16*, Paris (2016).

Durantin, G., Gagnon, J. F., Tremblay, S., & Dehais, F. (2014). Using near infrared spectroscopy and heart rate variability to detect mental overload. *Behavioural Brain Research*, *259*, 16-23.

Durantin, G., Dehais, F., & Delorme, A. (2015). Characterization of mind wandering using fNIRS. *Frontiers in Systems Neuroscience*, *9*.

Durantin, G., Scannella, S., Gateau, T., Delorme, A., & Dehais, F. (2015). Processing Functional Near Infrared Spectroscopy Signal with a Kalman Filter to Assess Working Memory during Simulated Flight. *Frontiers in Human Neuroscience*, *9*.

Dehais, F., Roy, Durantin, Gateau, Callan (2017) EEG-engagement index and auditory alarm misperception: an inattentional deafness study in actual flight condition. *AHFE Conference*, Procedia Manufacturing, Elsevier

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods 134*, 9-21.

Gateau, T., Durantin, G., Lancelot, F., Scannella, S., Dehais, F. (2015). Real-time state estimation in a flight simulator using fNIRS. *PLoS One 10(3)*: e0121279. Doi: 10.1371/journal.pone.0121279.

Harrivel, A. R., Weissman, D. H., Noll, D. C., & Peltier, S. J. (2013). Monitoring attentional state with fNIRS. *Frontiers in Human Neuroscience*, *7*, 861.

Kobayashi, A., Tong, A., & Kikukawa, A. (2002). Pilot cerebral oxygen status during air-to-air combat maneuvering. *Aviation, Space, and Environmental Medicine*, *73*(9), 919-924.

Mandrick, K., Chua, Z., Causse, M., Perrey, S., & Dehais, F. (2016). Why a Comprehensive Understanding of Mental Workload through the Measurement of Neurovascular Coupling Is a Key Issue for Neuroergonomics?. *Frontiers in Human Neuroscience*, *10*.

Marusic, U., Meeusen, R., Pisot, R., Kavcic, V. (2014). The brain in micro- and hypergravity : The effects of changing gravity on the brain electrocortical activity. *European Journal of Sport Science, 14(8)*, 813-822.

Maulsby, R. (1966). Electroencephalogram during orbital flight. Aerospace Medicine October, 1022-1026.

Mullen, T., Kothe, C., Chi, YM., Ojeda, A., Kerth, T., Makeig, S., Cauwenberghs, G., Jung, TP. (2013). Real-time modeling and 3D visualization of source dynamics and connectivity using wearable EEG. EMBC, 25th Annual International Conference of the IEEE, 2184-2187.

Parasuraman, R., McKinley, R. (2014). Using noninvasive brain stimulation to accelerate learning and enhance human performance. *Human Factors 56(5)*, 816-824.

Parasuraman, R., Rizzo,M., 2008. *Neuroergonomics: The Brain at Work*. Oxford University Press, New York, NY.

Scholl, C., Chi, Y., Elconin, M., Gray, W., Chevillet, M., and Pohlmeyer, E. (2016). Classification of pilot-induced oscillations during in-flight piloting exerceises using dry EEG sensor recordings. *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Orlando, FL, 2016, pp. 4467-4470. doi: 10.1109/EMBC.2016.7591719

Sem-Jacobsen, C., Nilseng, O., Patten, C., Eriksen, O. (1959). Electroencephalographic recording in simulated combat flight in a jet fighter plane. *Electroencephalography and Cinical Neurophysiology 11*, 154-155.

Sterman, M. Mann, C. (1995). Concepts and applications of EEG analysis in aviation performance evaluation. *Biological Psychology 40*, 115-130.

Takeuchi, Y. (2000). Change in blood volume in the brain during a simulated aircraft landing task. *Journal of Occupational Health*, *42*(2), 60-65.

Wilson, G. (2002). An analysis of mental workload in pilots during flight using multiple psychophysiological measures. *The international Journal of Aviation Psychology 12(1)*, 3-18.

Zander, T., Kothe, C. (2011). Toward passive brain-computer interfaces: applying brain-computer interface technology to human-machine systems in general. *Journal of Neural Engineering 8(2)*. doi: 10.1088/1741-2560/2/025005.