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A Neuroimaging Approach to Evaluate Choices and Compare Performance of Tower Air Traffic Controllers During Missed Approaches

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Abstract. The aim of this research is to use functional Near-Infrared Spectroscopy to compare and contrast brain activation for professional versus novice Tower Air Traffic Controllers when performing their daily tasks, whilst accounting for missed approaches. With functional Near-Infrared Spectroscopy chosen due to its ability to continuously monitor brain activity for mobile participants in their workplace settings, increasing ecological validity, as well as being safe, inexpensive, and benefitting from low set-up times, resulting in excellent temporal resolution as well as superior spatial resolution over Electroencephalogram. If a significant difference in activation is observed between professional and novice ATCOs, the neuroimaging data can be used as a benchmark for future exploratory studies using the obtained neuroimaging data to serve as a reliable quantitative measure to track performance during Air Traffic Controller training, establishing a metric to distinguish novice from professional Air Traffic Controllers. Our hypothesis is that professional tower controllers will have a decrease in brain activation due to their experience. Contrastingly, novice tower controllers would have more extensive brain activation, given a lack of experience relying solely on training. Additionally, we expect to see a significant difference in sustained attention activation between professionals and novices. The tasks that the tower controllers will be expected to resolve will be a series of tower control duties that will be severely impacted by a range of factors that will intentionally make the successful performance of their duties strained.

Keywords: Human factors · Neuroscience · Neuroergonomics · Air traffic management · Neuroimaging · Brain-Computer interaction

1 Introduction

Human factors remains an integral part of Air Traffic Management (ATM) (Rodgers 2017; Leveson 2001). Despite technological advances in ATM systems and operations,

the human operators of these systems continue to be a crucial aspect in maintaining the safety and efficiency for successful task completion (Billings 2018; Rodgers 2017). Indeed, past ATM research has shown that the decision aiding systems currently at the disposal of Air Traffic Controllers (ATCOs) are at times disregarded or not used in the manner that they were designed, leading to misuse and disuse (Westin et al. 2015; Bekier et al. 2015). Hence, it is important that cognitive workload and performance remain at optimal levels to ensure a productive and safe working environment. Neuroergonomics, the amalgamation of neuroscience and human factors provides insight into these human factors by applying neuroscience to real-world working environments to address topics such as, but not limited to, individual differences in cognition, human error, operational safety, cognitive workload, and performance by utilising various neuroimaging devices and stimulation techniques (Arico et al. 2017; Parasuraman 2011; Fedota and Parasuraman 2010). Using neurophysiological measures as evaluators for optimal workload, and peak performance instead of previous subjective reports that do not consider the brain's current state (Curtin and Ayaz 2018). Allowing for greater accuracy and reliability in assessing human performance in naturalistic working environments, which will be especially pertinent into how new technologies and paradigms are developed in the future (Arico et al. 2017; Curtin and Ayaz 2018; Izzetoglu and Richards 2019; Derosière et al. 2013).

As air travel increases, current capacities will be exceeded within a decade (ICAO 2014). Based on projections such as these alongside airport expansion constraints, ATCOs are estimated not to be able to handle traffic that is 25% above present levels (FAA 2015). Leading to a degradation of performance by ATCOs and therefore, an increased chance of incidents occurring (Kirwan 2001). Furthermore, with human errors accounting for most operational errors that occur in the ATM environment, it is of utmost importance that these issues are minimised or in best case scenarios, eliminated entirely (Redding 1992). Being particularly crucial for Tower Controllers, considering Boeing found that 44% of all fatalities and 49% of fatal accidents globally, from 2008–2017, occurred during final approach and landing (Boeing Commercial Planes 2018). One of the tasks of Tower Controllers, that is infrequent, but can drastically affect performance and productivity, is a missed approach procedure leading to a go-around, where an aircraft rejects the chance to land during final approach and makes a subsequent attempt (Dai et al. 2019). Experience plays a key role in managing these complex situations, as it can help ease the demands associated with having to make quick and accurate decisions in a highly dynamic environment, by using a range of varied past experiences to help mediate new ones (Seamster et al. 1993; Liu and Wickens 1994). More specifically, tower controllers have the arduous responsibility in managing all of the movements made by aircrafts or vehicles within the vicinity of the airport, issuing taxi instructions, managing the clearances needed for take-off and landing, issuing Instrument Flight Rules (IFR), flight plan clearances, and transponder codes for Visual Flight Rules (VFR) aircraft. All whilst dealing with more traffic than ever before, that is only expected to increase (FAA 2015).

The aim of this research is to use a quantitative neuroimaging approach, specifically employing functional Near-Infrared Spectroscopy (fNIRS) to compare and contrast sustained attention and decision-making related brain activation for professionally-trained

and unprofessionally-trained Tower ATCOs, when executing complex non-nominal events such as handling multiple arrivals, whilst accounting for missed approaches. fNIRS has been utilized here for its ability to continuously monitor brain activity for mobile participants in their workplace settings, increasing ecological validity. Moreover, fNIRS is safe, inexpensive, and benefits from low set-up times, resulting in excellent temporal resolution as well as superior spatial resolution over Electroencephalogram (EEG) allowing for more accuracy in identifying the brain regions associated with specific tasks (McKendrick et al. 2015). fNIRS is able to measure the differences in brain activation by focusing near-infrared light on the scalp, in order to measure changes in blood oxygenation as neurons that are more associated with specific tasks require more energy, or oxygenated haemoglobin (Izzetoglu, et al. 2004). fNIRS measures the cerebral hemodynamic response or the conversion of oxy-haemoglobin to deoxy-haemoglobin using specific wavelengths of light from the absorption spectrum regions of 650 to 950 nm, as the absorption spectra of oxy-haemoglobin and deoxy-haemoglobin are distinct in this region, allowing for the determination of concentration change between the two via scattered light diffusion measurement (Jobsis, 1977; Ferrari et al. 2004).

If a significant difference in activation is observed between professional and novice ATCOs, the neuroimaging data can be used as a benchmark for a future exploratory utilising neuroimaging to assist in neurostimulation via transcranial Direct Current Stimulation (tDCS). Enabling ATCOs to be better equipped to manage the rigors of their duties using neuroimaged-guided neurostimulation. This method could potentially mitigate cognitive deficiencies, or momentary lapses in judgement that ATCOs could potentially face due to stress and fatigue (Ayaz et al. 2012). Indeed, previous studies have suggested tDCS on specific brain regions can augment the performance of tasks associated with that region. (Fregni et al. 2005; Dockery et al. 2009; Coffman et al. 2014; Nelson et al. 2012; Parasuraman and McKinley 2014; Coffman et al. 2012; Falcone et al. 2012; Nelson et al. 2014; Clark et al. 2012). The proposed experimental paradigm would be to identify the executive decision-making brain regions that are most activated when operators are under high cognitive loads using the hemodynamic response obtained through fNIRS selected over other neuroimaging device due to an optimal level of both spatial resolution and portability (Parasuraman 2011). Though attentional networks are interconnected with various regions of the brain, the frontal regions have traditionally been most associated with tasks involving sustained attention or vigilance (Parasuraman et al. 1998). Past studies conducted using other neuroimaging devices with superior spatial resolution compared to fNIRS, ranging from Positron Emission Topography (PET) to functional Magnetic Resonance Imaging (fMRI) have implicated the lateral portions of the frontal lobe, for vigilance-related tasks; with particular activation of the right lateral frontal cortex (Parasuraman 2011; Berman and Weinberger 1990; Cohen et al. 1992; Coull et al. 1998; Lewin et al. 1996; Pardo et al. 1991). Moreover, it was discovered that patients who suffered from right frontal lesions, had increased reaction times and missed more targets in the Continuous Performance Test (CPT), even when their performance was contrasted with patients who had left and bilateral frontal lesions (Rueckert and Grafman 1996).

Suggesting that the longer vigilance is sustained, the more crucial the right frontal region becomes (Rueckert and Grafman 1996).

Additionally, any significant differences observed between professional and novice ATCOs, can be used for another potential study in which the neuroimaging data could serve as a reliable quantitative measure to track performance during training, thus establishing a metric to distinguish novice ATCOs from experts.

In this study, our hypothesis is that experienced tower controllers will implement more varied and innovative problem-solving strategies to resolve these situations which will be reflected by an decrease in associated brain region activation as their years of experience augments their ability to resolve conflicts faster. Contrastingly, novice tower controllers will not be at the liberty to use more varied problem solving skills and must rely solely on their training, resulting in more extensive brain activation (Liu and Wickens 1994; Milton et al. 2007). The tasks that the tower controllers will be expected to resolve will be a series of tower control duties that will be severely impacted by a range of factors that will intentionally make the successful performance of their duties strained, such as runway capacity limitations, high density of ground movement, and most cognitively taxing, re-routing missed approach flights (Fig. 1).

Fig. 1. Summary of rationale and experimental procedure

2 Materials and Methods

2.1 Ethics Statement

All participants provided informed consent to take part in this study, which was approved by the Nanyang Technological University Institutional Review Board

Participants. A total of six participants (all male) from the Air Traffic Management Research Institute (ATMRI) volunteered to participate in the study. Two of the participants were classified as novice ATCOs given that they had no professional training for tower ATCO duties. Another two were classified as professional ATCOs given that they had previous professional training in tower ATCO duties. The remaining 2 participants served as pseudo-pilots in the scenarios. The pseudo-pilots communicated to the ATCOs if an incoming flight would be a missed approach.

ATCO Vigilance Task. The vigilance task used in this experiment was a simulated tower ATCO task in which, participants had to actively manage 15 arrivals into Changi Airport, with 5 of those 15 scheduled flights being classified as a missed approach requiring the aircraft to execute a go-around procedure and attempt to land again at a future point. Artificially increasing the workload, whilst calling for participants to stay particularly vigilant in order to avoid potential collisions with other aircraft moving in and around the aerodrome. Moreover, the simulation included heavy rain and reduced visibility to mimic the real-world environments in which a missed approach would be most likely. 20 flights were chosen to mimic the average workload a tower controller will experience at Changi Airport based on data taken from 4:01 pm on the 15th of December 2019, to 4:01 pm 16th of December. The vigilance task took approximately 1 h for completion. Before the vigilance task commenced, the novice ATCOs partook in a preliminary practice run of the simulation for approximately 10 min in order to familiarise themselves with the functionality of the simulation, this familiarisation step was not required for the professional ATCOs considering the ample experience they possessed. This practice run was not as cognitively taxing as the actual vigilance task, but still required careful attention and allowed the student ATCOs to get familiar with the commands needed to relay to the pseudo-pilot. The simulation was administered in the ATMRI's state-of-the-art aerodrome simulator that offers the ability to provide the most naturalistic environment for aerodrome control duties and operations given its ability to simulate the working environments of the Changi Airport Control Tower Cabin including a 360-degree view of the aerodrome (Figs. 2 and 3). The simulator runs on specialised ATM simulation software such as the NLR Air Traffic Control Research Simulator (NARSIM) and AirTOP, two of the simulation tools used for airfield performance assessment and for airport resource utilisation optimisation.

fNIRS System and Procedure

The entirety of the experiment was conducted utilising a continuous-wave fNIRS device first described by Chance et al. (1998), further developed at Drexel University (Philadelphia, PA), manufactured and supplied by fNIR Devices LLC (Potomac, MD). The purpose of the fNIRS device is to continuously monitor the prefrontal cortex or the executive decision-making brain regions, whilst participants complete the vigilance task.

Fig. 2. ATMRI Tower Simulator

Fig. 3. Participant conducting the ATCO Vigilance task in the ATMRI's Tower Simulator. Heavy rain and reduced visibility are introduced into the simulation to provide a more naturalistic setting for multiple missed approaches.

The device consists of three main components: a headpiece (sensor pad) which is responsible for holding the light sources and detectors, establishing placement for the

16 opcodes: a control box to manage the hardware: and a computer which receives and stores the continuous fNIRS data for further data analysis (Fig. 4).

Fig. 4. fNIR sensor with 4 light sources and 10 detectors (left, top) and 16 optode (channel) measurement locations registered on sensor (left, middle) and juxtaposed on brain surface image

The fNIRS sensor provides 10 Hz sampling rate, and a 2.5 cm source-detector separation offering approximately 1.25 cm–1.5 cm penetration depth. The light emitting diodes (LEDs) were activated one light source at a time with the four surrounding photodetectors being sampled. The headpiece containing the sensor is positioned over the forehead providing a total of 16 active optodes or channels, that monitor the dorsal and inferior cortical areas located underneath the forehead (Ayaz et al. 2012; Baunce et al. 2006; Izzetoglu 2005). The difference in light absorption between oxygenated haemoglobin and deoxygenated haemoglobin (HbO_2 and HbR) and is measured by fNIRS by their respective wavelengths as dependent measures versus time by using a modified Beer-Lambert law (Jobsis 1977; Cope and Delpy 1988).

(Bottom right) fNIR Device model 2000s (bottom, left). Brain surface image is from University of Washington, Digital Anatomist Project.

3 Results

Preliminary results from an independent samples t-test indicated that when comparing the oxygenation values underneath channel 14 between the professional ATCO and the novice ATCOs for the first 3 missed approaches, there was a significant difference in oxygenation values for professional ATCOs ($M = 7.58$, $SD = 2.14$) vs novice ATCOs ($M = 0.17$, $SD = 3.61$); $t(16) = 5.10$, $p = .0002$ (Fig. 5). These results suggest when comparing the brain activation between pro ATCOs vs novice ATCOs, there exists a significant difference in activation from the right dorsolateral prefrontal cortex, which has been associated with sustained attention or more precisely, vigilance (Sanchez et al. 2016).

Fig. 5. Comparison of average OXY values between professional and expert ATCOs.

4 Conclusion and Discussion

This study has provided insightful understanding of how fNIRS can be incorporated into realistic, high-fidelity environments to quantitatively measure the performance of operators in their workplaces. Although significant differences existed between the professional vs novice ATCOs in terms of their vigilance activation as reflected in channel 14 representing the right dlPFC, the left dlPFC, which is more associated with spatial working memory was not activated at the same levels. We hypothesise that this could be attributed to the fact that both pro and novice ATCOs seldomly had to take into account where the aircraft was located on the simulation, since they had access to a radar display monitor that showed the aircraft's positioning as it entered their purview. Future studies could specifically inform ATCOs to attenuate to both the simulation screen and their radar display to reflect this spatial working memory task in the left dlPFC. Moreover, fNIRS studies typically include a behavioural component in which the quantitative fNIRS data can be compared to. However, in our study, this was not included due to increased complexity to the experimental protocol. To account for this, All participants had to adhere to the ICAO standard of 5 nautical mile separation; equivalent to approximately one minute and a half of separation between arrivals, thus establishes an uniform behavioural baseline across all participants. Though only 4 ATCO were used for our study, half were professionally trained ATCOs, which negated the need to acquire more

participants. Future studies would utilize more ATCOs in order to see if any other differences could emerge from a larger sample size, as well as seeing if our results could be replicated. Furthermore, there were times in which participants would become bored due to the waiting period between arriving flights and would move their heads around, increasing the amount of motion artefacts and reducing the amount of usable data. To circumvent this in the future, we would implement a more robust experimental protocol that would have participants not moving around too much, in order to have more usable data to analyse.

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