Multimodal Analysis using Neuroimaging and Eye Movements to Assess Cognitive Workload: a Case Study of ATCT Local Controllers

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Works cited:
Lesiuk, T. (2008). The effect of preferred music listening on stress levels of air traffic controllers. Arts in Psychotherapy 35, 1-10.
Finkelman, JM. (1994). A large database study of the factors associated with work-induced fatigue. Human Factors 36, 232-43.
Ahlstrom, U., Friedman-Berg, F. J. (2006). Using eye movement activity as a correlate of cognitive workload. Int. J. Ind. Ergon, 36(7), 623-636.
Vogt, J., Hagemann, T., Kastner, M. (2006). The impact of workload on heart rate and blood pressure in en-route and tower air traffic control. J. Psychophysiology 20, 297–314.
Di Nocera F, Fabrizi R, Terenzi M, Ferlazzo F. (2006). Procedural errors in air traffic control: effects of traffic density, expertise, and automation. Aviation Space Environ Med 77, 693-643
Edwards T. (2013) Human performance in air traffic control. Dissertation, University of Nottingham.
Izzetoglu, K., Richards, D. (2019). Human Performance Assessment: Evaluation of Wearable Sensors for Monitoring Brain Activity. In M. Vidulich & P. Tsang (Eds.), Improving Aviation Performance through Applying Engineering Psychology: Advances in Aviation Psychology (1st ed., pp. 163–180). Boca Raton, FL: CRC Press.
Kostenko, A., Rauffet, P., Chauvin, C., Coppin, G. (2016). A dynamic closed-looped and multidimensional model for Mental Workload evaluation. IFAC - Papers On Line 49(19), 549–554.

Introduction & Background

Video Introduction

- In addition to the already established high levels of workplace-related stress (Lesiuk, 2008; Finkelman, 1994), the environment where Air Traffic Controllers (ATC) carry out their tasks is expected to become more complex (e.g. higher demand, the introduction of new technologies and procedures)
- This increasing complexity can impose higher cognitive demands on ATCs (Vogt et al, 2006; Ahlstrom & Friedman-Berg, 2006), subjecting them to a higher risk of human error (Di Nocera et al, 2006)
- Wearable sensors have enabled us to reliably monitor cognitive workload in real time without interfering operational activity (e.g. Izzetoglu & Richards, 2019). However, a single sensor approach may not fully capture the multidimensionality aspect of cognitive workload (Kostenko et al, 2016).

Task complexity (operator-based)
Strategy
Ex. Number of commands

Task difficulty (activity-based)
Prescription and quantity of information to process
Ex. Number of aircrafts

Controller

Indicators (activity or operator-based)
Performance metrics, the participant's subjective experience with the task, and physiological measures

Operationalizing cognitive workload in terms of task complexity & difficulty.

Ex. Eye tracking

Uses infrared light to quantify pupil dilation & eye movements

Ex. Functional near infrared spectroscopy (fNIRS)

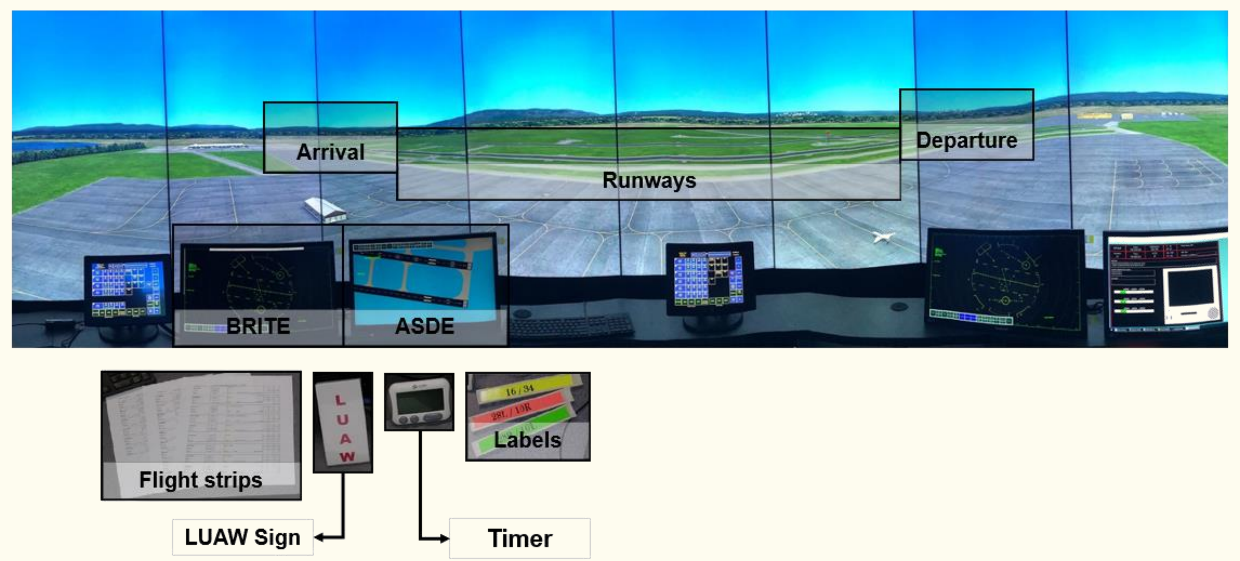
Uses near infrared light to quantify hemodynamic changes in the cortex

Proposed neuroergonomic multimodal methodology

Goal: Investigate the correlation between biometrics from eye-tracking and fNIRS, with task-load through complexity (defined as number of commands) and difficulty (number of aircraft), as well as with each other.

Methodology

High-fidelity simulated tower environment



Experimental methodology

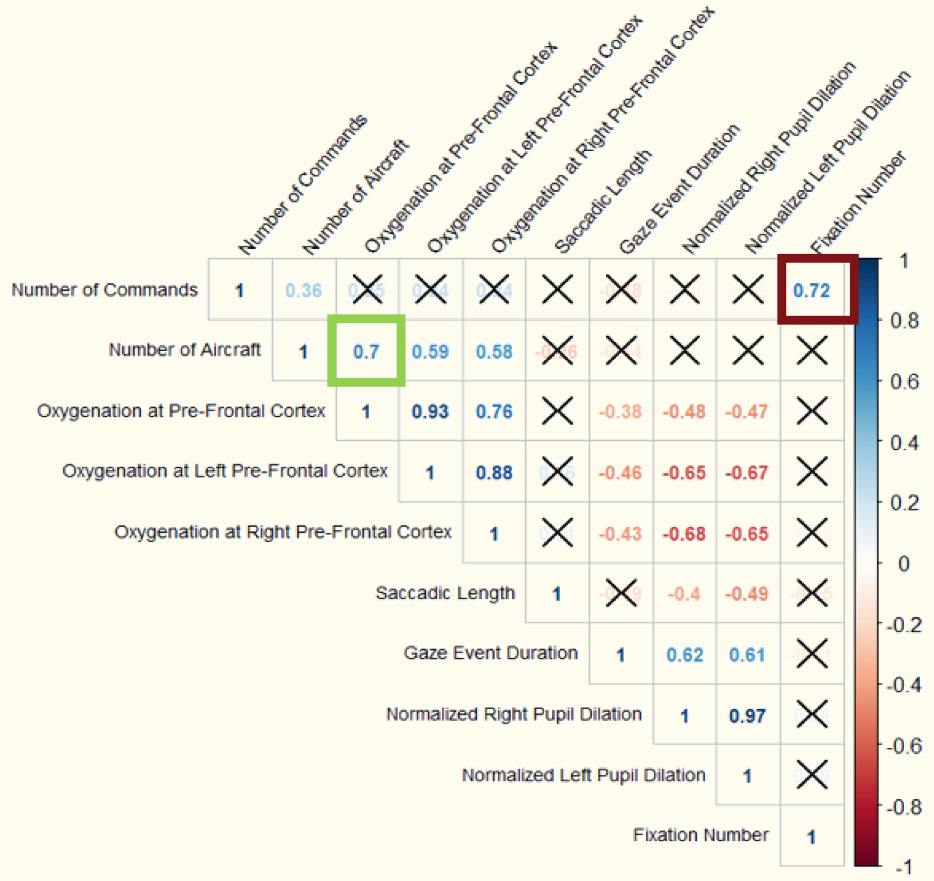
Number of commands
Task Complexity
Task Difficulty
Number of aircraft

Fixation number, gaze event duration, saccadic length, oxygenation

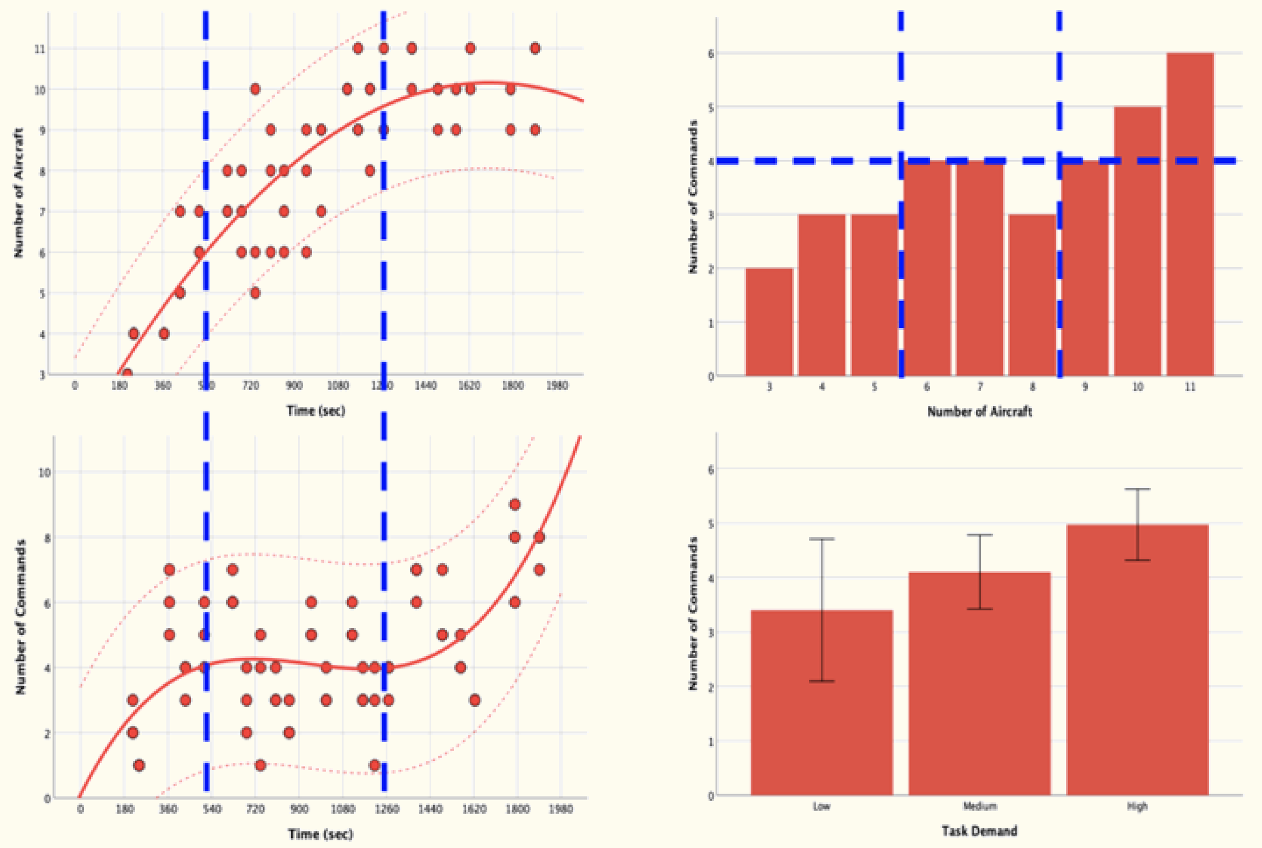
Local Controller
Ground Controller
Observer

- Three retired ATCT specialists (with over 20 years of experience) participated in a 32 minutes scenario, switching and performing three different roles: (1) observer; (2) operating the local control position; (3) operating the ground control position.
- Biometrics from the devices were averaged for the time duration in which the number of aircraft controlled remained constant.
- Eye-tracking metrics, such as fixation durations & counts, saccadic lengths, gaze event durations, and pupil dilation have is used to quantify the effort, information processing capabilities, attention, and decision-making ability of participants.
- fNIRS measures changes in oxyhemoglobin (HbO), deoxyhemoglobin (HbR) and oxygenation (HbO + HbR), which are directly associated with changes in brain activity associated with attention and working memory.

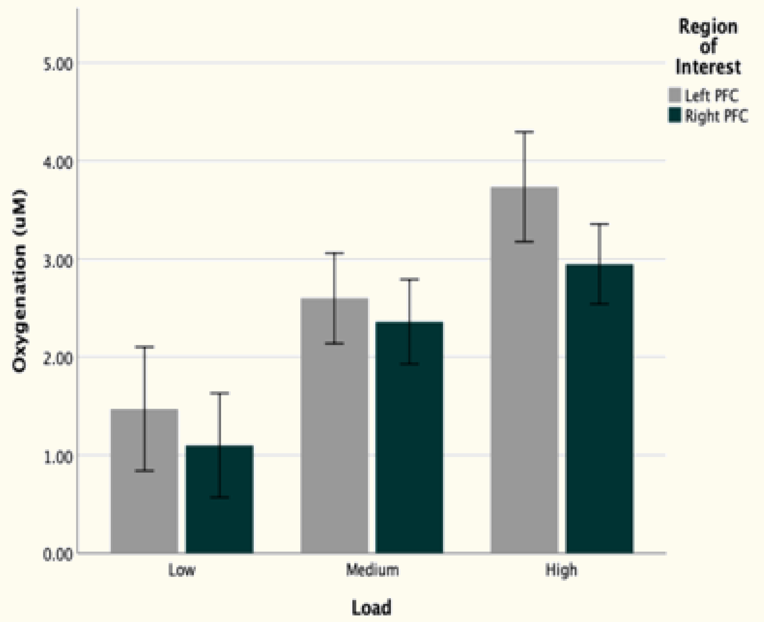
Results



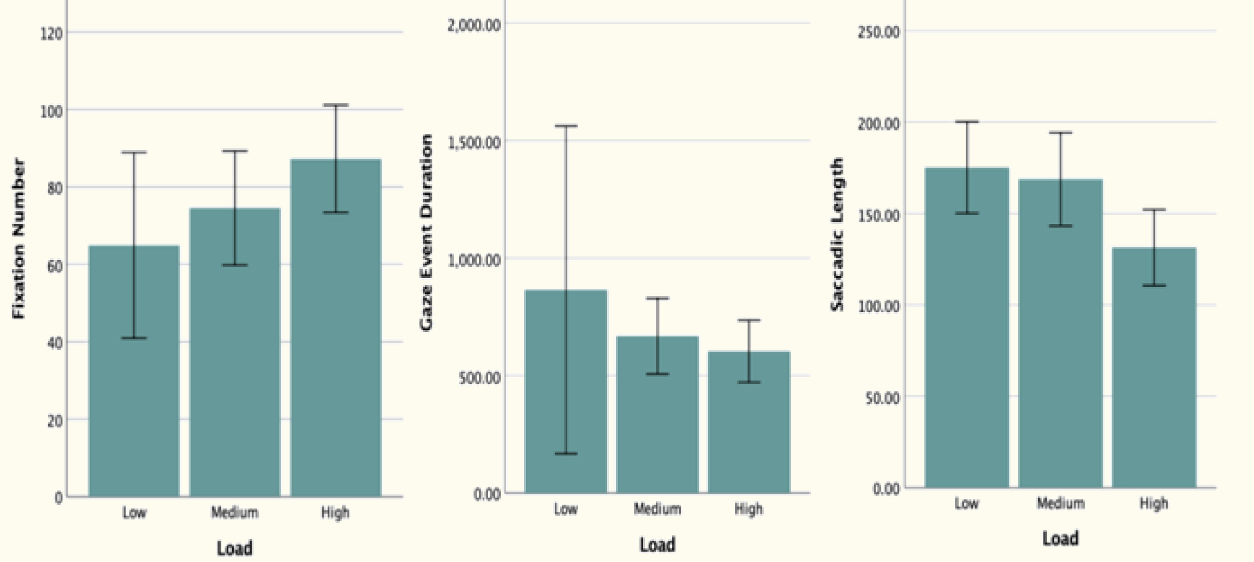
- Eye tracking metrics (i.e. fixation number) correlated with task complexity but not with task difficulty (red box).
- fNIRS metrics (i.e. blood oxygenation at PFC) correlated highly with task difficulty, but not complexity (green box).
- Negative relationship between some eye tracking measures (gaze duration & pupil dilation) and fNIRS metrics.



- The number of aircraft (top left) and clearances (bottom left) over time were combined (top right) in order to operationalize task demand as a single variable with three levels: low, medium, and high (bottom right).
- The dashed blue lines represent the relationship between complexity and demand: (1) Increasing number of aircraft & commands; (2) Increasing number of aircraft but steady number of commands; (3) Steady number of aircraft but increasing number of commands.



- Significant effect of workload on the left ($F_{2,62} = 10.61$, $p < 0.01$) and on the right ($F_{2,62} = 10.29$, $p < 0.01$) PFC, with differences across all load levels per region of interest.



- A non-parametric Kruskal–Wallis test was used to examine the effect of workload on eye-tracking measures. Only saccadic length showed significant decrease ($\chi_2 = 9.3$, $p = 0.01$, $df = 2$) across task load.

Conclusions

Correlation between physiological and neurophysiological measures → Eye-tracking and fNIRS measures are sensitive to effective methods at assessing human performance

Relationship between intrinsic and extrinsic task factors → Task difficulty (number of aircraft) and complexity (number of commands) don't appear to follow a linear trend.

Eye-tracking and fNIRS variables are both sensitive to different performance metrics ← **Capture the complex multidimensionality of cognitive workload**

The implementation of multiple measures will allow for improved assessment of human performance in complex environments ← **Efficacy of a multimodal approach to reliably evaluate performance**