Neurophysiological assessment of pilot arousal and engagement relative to in-flight task performance and control activity levels

Andrew Law, Sujoy Ghosh Hajra, Kris Ellis, Sion Jennings

Flight Research Laboratory, National Research Council Canada (NRC), Ottawa, ON, Canada

Introduction

Performance during an operational task depends on the level of physiological arousal and task engagement (Dehais et al, 2020). In particular, suboptimal mental states related to disengagement (e.g., mind wandering, effort withdrawal) or over-engagement (e.g., perseveration, attentional blindness/deafness) may occur when arousal levels are too low or too high. Neurophysiological monitoring of cardiac, brain, and/or ocular function may enable the detection and mitigation of mental states that compromise operational effectiveness and safety (Harrivel et al, 2017; Glaholt, 2014).

Previously, we have studied the electrocardiography (ECG) and electroencephalography (EEG) responses of helicopter pilots performing an in-flight target tracking task. We found that changes in task condition (i.e., target velocity) were correlated with changes in both heart rate (HR) and higher frequency measures of heart rate variability (HRV), suggesting an increase in physiological arousal with target velocity (Law et al, 2019). Moreover, HR and HRV measures showed a more linear response to task condition than EEG measures (Ghosh Hajra et al, 2020), which revealed potential non-linear effects of target motion on task engagement (Law et al, 2020).

In addition to the above measures, blink rate offers a complementary measure of task engagement (Ranti et al, 2020) and has been shown to decrease during visually demanding piloting tasks (Sirevaag et al, 1993; Wilson, 2002; Charles and Nixon, 2017). Blink signals are less sensitive than EEG to aircraft vibration and electromagnetic interference during helicopter flight. Here, we add blink rate (BR) as a secondary measure of task engagement, and then evaluate temporal variations in arousal (HR, HRV) and engagement (EEG engagement index and BR) relative to measures of helicopter pilot performance and control activity.

Methodology

Two NRC test pilots performed an in-flight target tracking task on the NRC's Bell 205 fly-by-wire (FBW) helicopter (Law et al, 2019). The FBW system was configured for attitude command, with aircraft height and heading hold enabled. The pilot used the cyclic to track a virtual target presented on two cockpit displays that provided aircraft-referenced and earth-referenced cues of target motion. Individual trials lasted for 120 seconds and target velocity started and ended at 0 knots for each trial. Target velocities peaked at 1.5 knots for the Level 1 (L1) condition, 9 knots for the L2 condition, and 18 knots for the L3 condition. Each pilot completed three flights (18 trials per flight, 6 trials per condition), during which ECG and EEG data were acquired using a BioSemi ActiveTwo system.

Performance, control movements, and neurophysiological data were evaluated separately in four time segments per trial: 0-30s, 30-60s, 60-90s, and 90-120s. Task performance was measured as target tracking root-mean-square error (RMSE), and cyclic control activity was quantified using the Dynamic Interface Modeling and Simulation System Product (DIMSS-PM; Roscoe and Wilkinson, 2002). ECG recordings were processed to compute HR from inter-beat intervals and HRV from the root mean square of successive differences (RMSSD) in inter-beat intervals. The EEG engagement index was computed as the inverse of normalized alpha power (8-13 Hz) recorded at Cz/F3/Fz/F4 electrodes (Law et al, 2020).

Finally, blink rate was derived from forehead EEG recordings using independent component analysis and blink waveform template matching.

To minimize the effect of learning on ECG, EEG, and blink responses, flight 1 for each pilot was treated as familiarization and flights 2 and 3 were used for data analysis. Non-stationarities in neurophysiological responses between flights 2 and 3 were resolved by z-score normalization within each flight and aggregation of z-scores across flights. For more details on the experimental protocol and ECG/EEG signal processing, please refer to Law et al, 2019; 2020.

Results

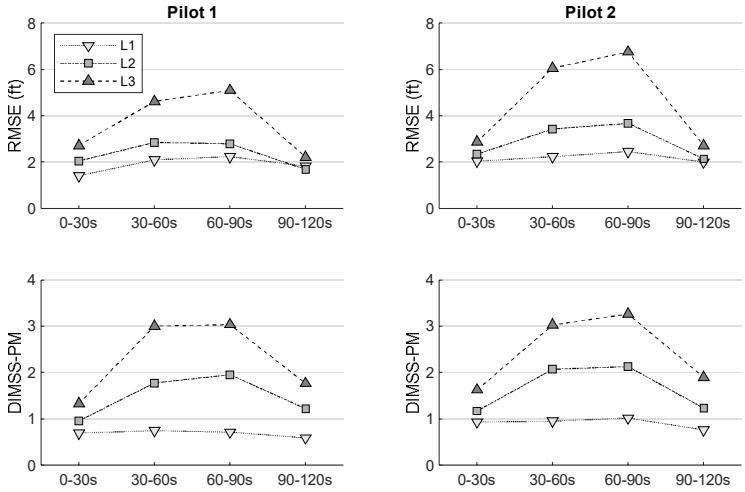
Task performance (RMSE) and control activity (DIMSS-PM) were proportional to target velocity, which peaked during the 30-60s and 60-90s segments (Figure 1). Condition- and time-dependent changes in DIMSS-PM reflected the more frequent and aggressive control movements required to track faster moving targets. Despite some differences in tracking performance, DIMSS-PM was very similar for both pilots across all three levels (L1, L2 & L3) and all four time segments. By comparison, ECG- and EEG-derived measures revealed distinct individual differences in physiological arousal and task engagement.

For both pilots, RMSE and DIMSS-PM were positively correlated with HR and negatively correlated with RMSSD during the 30-60s and 60-90s segments (Figure 1, Table 1), though individual differences were observed in the timing of peak correlation. HR and HRV measures were generally more strongly correlated with DIMSS-PM than RMSE. By comparison, RMSE and DIMSS-PM were only weakly correlated with the EEG engagement index over all time windows, reflecting the non-linear and overlapping EEG responses to task condition. Likewise, BR was only weakly correlated with RMSE and DIMSS-PM for pilot 1, who rarely blinked during the tracking task (average blinks/min: 1.5 for L1 trials, 1.1 for L2 trials, and 1.0 for L3 trials). For pilot 2 (average blinks/min: 9.4 for L1 trials, 9.2 for L2 trials, and 8.4 for L3 trials), a strong negative correlation between blink rate and RMSE and DIMSS-PM was observed during the 30-60s segment, suggesting a higher level of visual engagement during this time window. Interestingly, BR correlations with DIMSS-PM for both pilots were negative during the 30-60s and 60-90s windows, but positive during the 90-120s window. This may indicate a relative decrease in task engagement as target motion diminished toward the end of L2 and L3 trials.

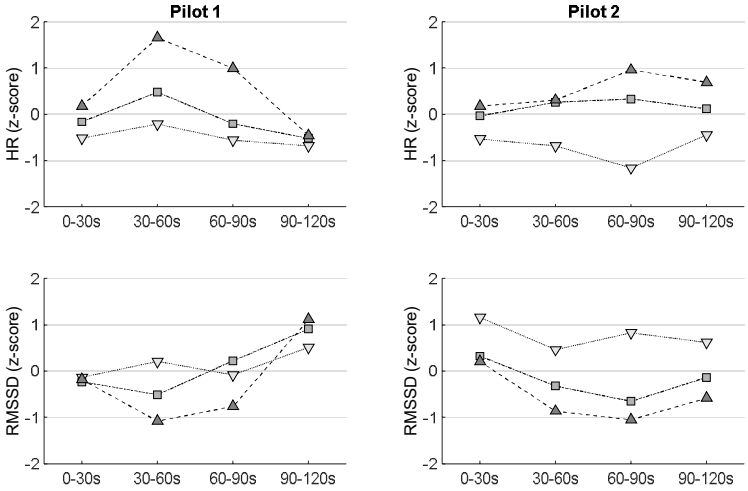
Conclusions

This case study demonstrated that ECG, EEG, and blink measures reveal distinct differences in physiological arousal and task engagement among helicopter pilots who had very similar in-flight performance and control activity. Furthermore, HR and HRV measures of physiological arousal were significantly correlated with tracking task performance and control movements, whereas EEG and blink rate measures indicated that task conditions had non-linear effects on task engagement. This may be partly attributable to the visual demands of the task, which required the pilots to detect subtle symbology cues of target motion while compensating for minor handling quality deficiencies (e.g., variable cyclic trim position) and environmental factors (e.g., gusts). Future work will involve in-flight neurophysiological measurements during modified piloting tasks (e.g., supervised autonomy) to investigate a wider range of arousal and engagement states.

(A) Performance and control activity



(B) Heart rate and RMSSD



(C) EEG engagement index and blink rate

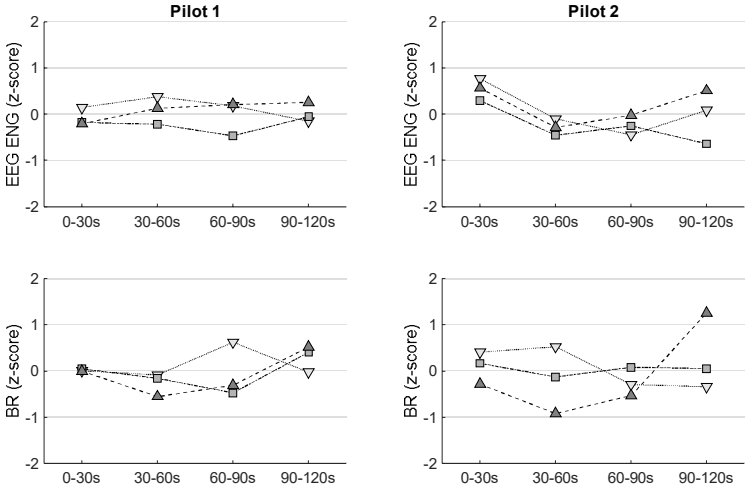


Figure 1. Comparison of task performance, control activity, heart rate, RMSSD, EEG engagement index, and blink rate across target velocity conditions and time windows. Markers indicate the mean value for each condition and time window.

Table 1: Rank correlations of heart rate, RMSSD, EEG engagement index, and blink rate with tracking error (left coefficient) and control activity (right coefficient). Significant correlations ($p < 0.05$) are highlighted in gray.

		Time into trial			
		0-30s	30-60s	60-90s	90-120s
Heart rate	Pilot 1	0.33 / 0.43	0.67 / 0.65	0.64 / 0.73	0.11 / 0.23
	Pilot 2	0.01 / 0.41	0.34 / 0.37	0.60 / 0.75	-0.06 / 0.40
RMSSD	Pilot 1	-0.06 / -0.12	-0.49 / -0.45	-0.33 / -0.38	-0.11 / 0.20
	Pilot 2	-0.28 / -0.37	-0.40 / -0.56	-0.64 / -0.78	-0.31 / -0.65
EEG-ENG	Pilot 1	-0.23 / -0.13	-0.11 / -0.08	0.12 / 0.18	-0.24 / 0.11
	Pilot 2	-0.22 / -0.09	-0.13 / -0.19	0.07 / 0.23	-0.04 / 0.24
Blink Rate	Pilot 1	-0.07 / -0.00	-0.32 / -0.26	-0.15 / -0.29	-0.12 / 0.12
	Pilot 2	-0.25 / -0.11	-0.62 / -0.62	-0.07 / -0.27	0.14 / 0.41

References:

Dehais, F., Lafont, A., Roy, R., and Fairclough, S. (2020). A neuroergonomics approach to mental workload, engagement and human performance. Frontiers in neuroscience, 14, 268.

Harrivel, A. R., Stephens, C. L., Milletich, R. J., Heinich, C. M., Last, M. C., Napoli, N. J., Abraham, N., Prinzel, L. J., Motter, M.A. and Pope, A. T. (2017). Prediction of cognitive states during flight simulation using multimodal psychophysiological sensing. In AIAA Information Systems-AIAA Infotech@ Aerospace.

Glaholt, M. G. (2014). Eye tracking in the cockpit: a review of the relationships between eye movements and the aviator's cognitive state. DRDC Scientific Report DRDC-RDDC-2014-R153.

Sirevaag, E. J., Kramer, A. F., Reisweber, C. D. W. M., Strayer, D. L., and Grenell, J. F. (1993). Assessment of pilot performance and mental workload in rotary wing aircraft. Ergonomics, 36(9), 1121-1140.

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

Charles, R., and Nixon, J. (2017). Blink counts can differentiate between task type and load. Proceedings of Contemporary Ergonomics and Human Factors, 257-265.

Ranti, C., Jones, W., Klin, A., and Shultz, S. (2020). Blink rate patterns provide a reliable measure of individual engagement with scene content. Scientific reports, 10(1), 1-10.

Law, A., Jennings, S., and Ellis, K. (2019). A Comparison of Control Activity and Heart Rate as Measures of Pilot Workload in a Helicopter Tracking Task. In Vertical Flight Society 75th Annual Forum Proceedings, Philadelphia, PA, May 2019.

Law, A., Ghosh Hajra, S., Jennings, S., and Ellis, K. (2020). An Evaluation of Pilot Electroencephalographic Activity during a Helicopter Tracking Task. In Vertical Flight Society 76th Annual Forum Proceedings, Virginia Beach, VA, Oct 2020.

Ghosh Hajra, S., Xi, P., and Law, A. (2020). A comparison of ECG and EEG metrics for in-flight monitoring of helicopter pilot workload. In 2020 IEEE International Conference on Systems, Man, and Cybernetics (SMC) (pp. 4012-4019). IEEE.

Roscoe, M. F., and Wilkinson, C. (2002). DIMSS- JSHIP's modeling and simulation process for ship/helicopter testing and training. In AIAA Modeling and Simulation Technologies Conference and Exhibit Conference Proceedings, Monterey, CA, 2002.