

Cardiac autonomic responses in relation to cognitive workload during simulated military flight

Jukka Koskelo^{a,1}, Aleksi Lehmusaho^{b,1,*}, Tomi P. Laitinen^{b,c}, Juha E.K. Hartikainen^{b,d},
 Taija M.M. Lahtinen^e, Tuomo K. Leino^{f,g}, Kerttu Huttunen^{h,i,j}

^a Unit of Research and Development, A-Clinic Foundation, Helsinki, Finland

^b Institute of Clinical Medicine, University of Eastern Finland, Kuopio, Finland

^c Department of Clinical Physiology and Nuclear Medicine, Kuopio University Hospital, Finland

^d Heart Center, Kuopio University Hospital, Finland

^e Finnish Defence Forces, Centre for Military Medicine, Rovaniemi, Finland

^f National Defence University, Helsinki, Finland

^g Air Force Command Finland, Jyväskylä, Finland

^h Research Unit of Logopedics, University of Oulu, Finland

ⁱ Department of Otorhinolaryngology, Head and Neck Surgery, University Hospital of Oulu, Finland

^j Medical Research Center Oulu, Finland

ARTICLE INFO

Keywords:

Flight simulator
 Heart rate variability
 Mental workload

ABSTRACT

Understanding the operator's cognitive workload is crucial for efficiency and safety in human-machine systems. This study investigated how cognitive workload modulates cardiac autonomic regulation during a standardized military simulator flight. Military student pilots completed simulated flight tasks in a Hawk flight simulator. Continuous electrocardiography was recorded to analyze time and frequency domain heart rate variability (HRV). After the simulation, a flight instructor used a standardized method to evaluate student pilot's individual cognitive workload from video-recorded flight simulator data. Results indicated that HRV was able to differentiate flight phases that induced varying levels of cognitive workload; an increasing level of cognitive workload caused significant decreases in many HRV variables, mainly reflecting parasympathetic deactivation of cardiac autonomic regulation. In conclusion, autonomic physiological responses can be used to examine reactions to increased cognitive workload during simulated military flights. HRV could be beneficial in assessing individual responses to cognitive workload and pilot performance during simulator training.

1. Introduction

Knowledge about human performance and physiology is important in developing pilot training and flight safety procedures. Flying a military jet is an example of an extreme, multitask environment exposing the pilot to varying amounts of cognitive workload. A significant percentage (over 75%) of aircraft accidents are caused by human errors (Gramopadhye and Drury, 2000; Wiegmann and Shappell, 1999), of which some derive from pilot fatigue and cognitive overload (Caldwell et al., 2009). Human errors can induce technical, environmental, and organizational malfunctions that not only deteriorate performance independently from each other but also often accumulate and thereby

increase the risk of accidents in safety-critical systems (Dallat et al., 2019). For their part, researchers aim to increase the safety of human-machine systems to reduce the costs of operators' decreasing performance. This can be achieved by accumulating information about predictable human limitations, such as the effects of cognitive workload (Dehais et al., 2020; Giraudet et al., 2015; Lohani et al., 2019; Wang et al., 2024; Wilson, 2002). The present study explores how cognitive workload is reflected in autonomic nervous system when measured with cardiac monitoring during a simulated military flight.

1.1. Human assessment of cognitive workload

In psychophysiological studies and ergonomics, cognitive workload

* Corresponding author. Institute of Clinical Medicine, Faculty of Health Sciences, University of Eastern Finland, Kuopio, Yliopistonrinne 3, Medistudia building, 4th floor, FI-70211, Kuopio, Finland.

E-mail address: aleleh@uef.fi (A. Lehmusaho).

¹ Shared co-first authorship.

<https://doi.org/10.1016/j.apergo.2024.104370>

Received 8 April 2024; Received in revised form 22 July 2024; Accepted 19 August 2024

Available online 25 August 2024

0003-6870/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Abbreviations:

ANS	Autonomic nervous system
ATIS	Automatic terminal information service
ATC	Air traffic control
ECG	Electrocardiogram
HF	High Frequency
HRV	Heart rate variability
IBI	Interbeat interval
IFR	Instrument flight rules
ILS	Instrument landing system
IMC	Instrument meteorological conditions
LF	Low frequency
NASA-TLX	National Aeronautics and Space Administration Task Load Index

OM	Outer marker beacon
pNN50	Proportion of consecutive beat-to-beat intervals that differ by more than 50 ms
PNS	Parasympathetic nervous system
RMSSD	Root mean square of successive differences of interbeat intervals
RRI	R-R interval
SDNN	Standard deviation of the normal-to-normal interbeat interval
SNS	Sympathetic nervous system
VAS	Visual analog scale
VLF	Very low frequency
VOR	Very high frequency omnidirectional range station
WTT	Weapons tactics trainer

has long been of interest due to its impact on human performance (Aasman et al., 1987; Young et al., 2015). It has also been studied extensively within the aviation domain (Wang et al., 2024; Young et al., 2015). As concepts, cognitive and mental load have often been used interchangeably (Young et al., 2015), albeit not always, with even defining the workload being very challenging (Cain, 2007; de Waard and Lewis-Evans, 2014; Young et al., 2015). In the present study involving military aviation, with cognitive workload we consider task demand factors that are posed to a pilot. The nature and degree of the impact of the load, however, depend on an operator's characteristics, such as information-processing capacity, and environmental context. Indeed, according to Gaillard (1993), mental load refers to the relationship between environmental demands and the availability of resources to meet them.

Cognitive workload can be assessed using several methods, including self-reports and objective physiological and performance measures (Wang et al., 2024). There are self-report tools, such as the well-established and widely used NASA-TLX (Hart and Staveland, 1988), which was originally constructed for the aviation domain but is increasingly common in task load studies in a variety of other domains (Hart, 2006). Real-time probes, such as the NASA-TLX and the most widely used Situation Awareness Global Assessment Technique (SAGAT; Endsley, 1988) require the freezing of the ongoing activities for the participants to fill out self-reports. That may affect the accumulating effects of cognitive load and serve as a significant confounder when physiological measures, such as electrocardiogram (ECG) measurements, are used. The temporary suspension of the task may therefore make it difficult to interpret both the cognitive and the physiological data.

When using questionnaires in aviation, data are recommended to be collected after the trial (Tattersall and Foord, 1996), where the pilot is requested to self-reflect regarding flight events after completing the mission. For instance, Situation Awareness Rating Technique (SART) developed by Taylor (1990) is a well-known self-rating method administered post-trial, but more information is still needed about its validity and the risk of a memory bias. Self-reports are indeed prone to perception bias and memorizing errors (Annett, 2002; McKendrick and Cherry, 2018), and as a data source, they tend to provide a rather general-level evaluation of workload. Moreover, they might not be able to tap momentary fluctuations in workload during a flight (Mansikka et al., 2019).

In the study of Huttunen et al. (2011), real-time cognitive workload was assessed by a flight instructor who employed a standardized post-flight evaluation protocol. In the assessment, F/A-18 Hornet WTT simulator flight task data were used to examine cognitive workload and its relationship with speech prosody measurements. The present study uses the same protocol in evaluating the cognitive workload when

assessing the interrelationship between the results of a flight instructor's standardized evaluation of pilot cognitive workload and cardiac autonomic regulation responses to cognitive workload changes. Alongside cardiac measures, self-reports, and performance scores, Lehrer et al. (2010) used instructor-given ratings for the task load levels of flight simulator task segments, with professional airline pilots participating in their study.

1.2. Physiological measures of cognitive workload

Physiological measures can provide real-time information about the operator's status without interfering with primary task performance (Jorna, 1993; Tao et al., 2019). Acute mental stress factors (e.g., task demand) directly affect the dynamic balance of the operator's autonomic nervous system (ANS) activity by changing the mutual strength of the two subsystems of the ANS: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). Namely, increased level of cognitive load causes SNS activation, while PNS domination emerges during more restful situations (Weissman and Mendes, 2021). There are several standardized methods to study the balance of the ANS, and in aviation-related psychophysiological studies ANS testing is a good choice if it is non-invasive and easy to perform. However, few of the available measures are non-invasive and can be used such that a pilot's performance is not hindered. Cardiac-based assessments have been found to provide valid information about real-time changes in cognitive workload (Hughes et al., 2019). This is logical because mental load (task demand) affects ANS, and heart rate is regulated by ANS activity. SNS stimulation increases heart rate and shortens interbeat intervals (IBI), the time intervals between successive normal-to-normal (NN) heart rate peaks that can be seen in ECG data. PNS stimulation, in turn, which is related to vagus nerve activation (i.e., vagal tone), results in decreased heart rate and increased (longer) IBI. Measuring heart rate variability (HRV) involves extracting and analyzing IBIs from the collected ECG data. With mobile devices used for data collection, measurement of HRV is an established, non-intrusive method that has been found to be useable for measuring pilot responses to workload during simulated flights.

Earlier, cardiac IBIs as reflectors of flight instructor-assessed cognitive workload were studied by Hannula et al. (2008). In that study, neural networks and regression models were used to analyze the variation in cognitive workload and heart rate of qualified pilots during training in an F/A-18 Hornet WTT flight simulator. Several other studies have also used HRV to detect the pilot's cognitive workload during aircraft simulator trials. They have been able to differentiate the task stimulus from rest conditions (Jorna, 1992; Veltman and Gaillard, 1996; Wei et al., 2014) and HRV levels among separate flights with different task demands (Mansikka et al., 2016a; Wei et al., 2014). Mansikka et al.

(2016a) examined pilots' mental workload and successfully differentiated the rest phase from task conditions but also different levels of load by intentionally increasing the degree of flight task difficulty (instrument landing system [ILS] approaches were used in the study). Furthermore, Mansikka et al. (2016b) found significant differences in mental workload, measured with HRV, between different flight phases. The present study aims to replicate previous findings and fill the existing information gaps in the field by investigating whether a dynamic change in cognitive workload during a simulated, standard military flight modulates cardiac autonomic regulation. It is still uncertain which HRV variables are the most effective and useful indicators of dynamic cognitive workload changes. The literature-based descriptions, interpretations, and expected behaviors of the multiple HRV variables used in this study, related to increased cognitive workload, are described in Table 1.

The present study aims to provide information about HRV as a method for measuring cardiac autonomic regulation during student pilot training, while also informing general ergonomics.

2. Methods

2.1. Participants

Thirteen male pilot students participated in the present simulator study. They had adequate instrument flight experience with a BAe Hawk Mk 51 (mean of 70 flight hours, range 55–80) and were instrument flight

certified. All participants had passed an aeromedical prescreen and an extensive physical examination within the previous 12 months. Individual capacity to perform given tasks influences the impacts of workload on a pilot's physiology and thereby mediates the relationship between cognitive workload and physiological reactions to it. Therefore, to guarantee a homogeneous skill level in the study population, the participants were recruited from the same student pilot course of the Finnish Air Force. Characteristics of the participants are shown in Table 2. The study protocol was approved in advance by the Medical Ethics Committee of the Northern Ostrobothnia Hospital District, Finland. Written informed consent was obtained from all participants.

2.2. Study protocol

This study was a part of a series of studies conducted in the Finnish Air Force (see, e.g., Lohi et al., 2007). Five simulator flight phases were planned to achieve various levels of cognitive workload without being too demanding for the pilot students. English was used for all communication during the mission.

On the morning of the simulator flights, garrison wake-up was at 06:00 a.m. All the simulator flights were performed between 9:00 a.m. and 12:00 noon. The participants performed an instrument flight rules (IFR) flight with the BAe Hawk Mk 51 (HWS-002) simulator, which does not have an autopilot. Simulated airport weather conditions were cloud overcast at 500 ft, wind calm, and visibility 3.5 km.

The participants' actions for operating the aircraft simulator and executing flight tasks required constant multitasking and intensive information processing. The demanded actions varied across different flight phases. The simulated flights consisted of the en-route flight phase, initial approach, intermediate approach, and final approach under IFR, using radar vectors and an ILS approach, performed according to routine, standardized protocols described in the Aeronautical Information Publication and commonly used in aviation.

2.3. Flight phases

Phase 1 (P1): Flight started airborne at 1500 ft with instrument meteorological conditions (IMC), i.e., there was no visual information of the surrounding environment outside the cockpit. Using the very high frequency omnidirectional range (VOR) system, participants first navigated toward the route turning point and climbed to 10,000 ft (flight level 100). Actions included adjustments of flight controls and throttle simultaneously with constant crosschecking of instruments.

Phase 2 (P2): Participants began initial approach by flying toward VOR nearby the destination airport at flight level 100. They copied the destination airport information (ATIS) on the radio and adjusted the instruments accordingly. They also communicated with air traffic control (ATC) for vectors toward the ILS base leg and simultaneously started to descend. There was a time limit set for self-briefing of ILS information from a flipbook.

Phase 3 (P3): Participants operated the controls and descended to 2300 ft, reducing airspeed with a speed brake to 250 knots during the IFR base leg. They then communicated with ATC for ILS approach clearance and turned to the localizer beam. Anticipation of turning to the final approach heading was needed with consideration of a light

Table 1
Expected behaviour of HRV variables due to increased cognitive workload.

HRV variable	Description	Effect	Reference
MEAN RRI (ms)	Mean of RRI intervals	↓	Henelius et al. (2009); Tjolleng et al. (2017); Veltman and Gaillard (1996)
SDNN (ms)	Standard deviation of all normal-to-normal (NN) intervals	↓	Cao et al. (2019); Fallahi et al. (2016); Wei et al. (2014)
RMSSD (ms)	Square root of the mean of the sum of the squares of differences between successive NN intervals	↓	Cao et al. (2019); Cinaz et al. (2013); Fallahi et al. (2016); Fernández-Morales et al. (2022); Grassmann et al. (2017); Tjolleng et al. (2017); Wang et al. (2020)
pNN50 (%)	Proportion of normal-to-normal intervals greater than 50 ms (NN50) divided by the total number of all NN intervals	↓	Cinaz et al. (2013); Fernández-Morales et al. (2022); Grassmann et al. (2017)
RRI LF (ms ²)	Low frequency (.04–.15 Hz)	↑↓	↓: Aasman et al. (1987); Grassmann et al. (2017); Veltman and Gaillard (1993, 1998), ↑: Herlambang et al. (2021); Wang et al. (2020)
RRI HF (ms ²)	High frequency (.15–.40 Hz)	↓	Grassmann et al. (2017); Hjortkov et al. (2004); Veltman and Gaillard (1998); Wang et al. (2020); Yu et al. (2009)
RRI LF/HF	Ratio between LF and HF, overall autonomic activity	↑	Cinaz et al. (2013); Hjortkov et al. (2004); Wang et al. (2016); Wang et al. (2020); Yu et al. (2009)
RRI nLF (n.u.)	Normalized low frequency = LF/(total power – VLF)	↑	Garde et al. (2002); Wang et al. (2016); Yu et al. (2009)
RRI nHF (n.u.)	Normalized high frequency = HF/(total power – VLF)	↓	Garde et al. (2002); Yu et al. (2009)

Table 2
Participant characteristics (N = 13).

Characteristic	M (SD)	Range
Age (years)	23.50 (.52)	23–24
Height (cm)	180.00 (5.41)	170.00–190.00
Weight (kg)	77.00 (6.29)	70.00–87.00
Total flight experience (h)	190 (11.65)	170–210

crosswind component.

Phase 4 (P4): After the ILS localizer was established, the participants began the descent to 1700 ft. After that, they adjusted the relevant aircraft system controls, e.g., took the landing gear down and flaps halfway out. They also communicated with ATC after the outer marker (OM) inbound sound and contacted the Tower radio frequency.

Phase 5 (P5): Sufficient situation awareness and anticipating of future events were essential for starting the ILS descending glide at the right moment – simultaneously with adjusting flaps full, air speed reduction, trimming, and heading adjustments. As a safety protocol, participants had to recall the decision altitude and threshold air speed according to the weight of the aircraft while simultaneously maintaining the heading and attitude. Maintaining these parameters becomes progressively more difficult when the runway is approached. At the decision altitude, after a quick check of the weather conditions, the final decision about landing was made; proceeding to land was allowed only if there was visual contact with the runway. If not, IFR go-around was performed instead. Finally, landing was performed with the plane requiring subtle multi-control handling.

2.4. Assessment of cognitive workload

To evaluate cognitive workload, the present study used the multifaceted, research-based method constructed by [Huttunen et al. \(2011\)](#). In focus were non-interrupted flight performance and the task demand factors posed to the pilots. Therefore, post-flight assessment of the cognitive workload during the simulated flights was performed by an experienced flight instructor who, in the ratings, used versatile video-recorded flight simulator data obtained during the data collection. The same instructor had also instructed and supervised the pilot students during the simulator flights. When enquired before starting the cognitive workload assessments, the instructor reported being somewhat familiar with all the participants; he had worked with each of them more often than just occasionally, though not very frequently.

Post-flight cognitive workload assessment was selected because often-used real-time self-evaluations using a questionnaire, such as NASA-TXL, distract pilots' concentrating on the tasks. In addition, situation awareness was only one of the three areas to be measured in the present study. Of interest were also the effects of the information load and the decision load on the operator. Neither SART nor SAGAT, for instance, would have sufficed for that purpose. Additionally, according to [de Waard and Lewis-Evans \(2014\)](#), self-evaluation is too simplistic a procedure to capture the multifaceted nature of mental workload.

The flight instructor was given detailed written instructions on and definitions of different parameters for the evaluations, separately in each flight phase, of the load in 1) situation awareness load 2) information processing load, and 3) decision making load. These three cognitive workload types were requested to be rated using a visual analog scale (VAS), a 100 mm horizontal line on which the scores of the cognitive workload components ranged from 0 (indicating no cognitive workload at all) to 100 (the highest imaginable load). Before analyzing the data from the video recordings, the instructor was familiarized with using a VAS. Data analysis was executed using the video recordings to allow time for thorough assessment and to give more accurate information compared to real-time analysis during the simulation.

These three load components were selected to operationalize the task load and to reflect the nature of cognitive processing needed during the simulator flight. They were based on multiple publications. In particular, the assessment of situation awareness was based on the very influential situation awareness model proposed by Endsley over 30 years ago ([Endsley, 1988, 1993, 1994, 1995, 2000](#)) but which is still widely used, e.g., in aviation, military, human performance/safety, automation, medical research and elsewhere. A more detailed description of the different constituents of the cognitive workload concept adopted in the present study is presented in Supplementary Material. The assessment protocol for cognitive workload used by the flight instructor was based

on that description.

The three cognitive workload types showed excellent internal consistency when looked at together; within each flight phase, Cronbach's alpha ranged from .74 to .95. Additionally, concerning the five flight phases in focus, 13 out of the altogether 15 pairwise comparisons of the different load types were significantly correlated, with Spearman correlation coefficients ranging from .70 to .99. Therefore, there was good grounds for combining the three load types. The arithmetic mean of the three cognitive workload types was therefore calculated for a variable representing the total cognitive workload. Hereon the term cognitive workload will be used when referring to it.

2.5. Heart rate variability recording and data analysis

ECG data were collected with an ambulatory digital 3-lead ECG recorder (Oxford Medilog FD-4, Oxford Instruments Medical System, Abingdon, UK). The ECG electrodes were attached on the participant's chest according to the manufacturer's instructions. Electronic representations of leads V1, V5, and aVF were used. Before the simulation, ECG was recorded for 5 min in supine position, and ECG recording continued throughout the simulator flight.

Artifacts were checked with care by using beat-to-beat visual checks and manual corrections. After removing artifacts and noisy data, the ECG data samples were analyzed with a WinCPRS program (Absolute Aliens Inc., Turku, Finland). ECG recording, manipulation, and interpretation were conducted according to the standards of Task Force of The European Society of Cardiology and The North American Society of Pacing and Electrophysiology ([Camm et al., 1996](#)). The ECG data were time-synchronized with the flight simulator clock. Multiple time and frequency domain variables (see [Table 1](#)) were calculated across the simulator flight phases to obtain the longest possible time intervals and short-term variability in different flight phases and to avoid missing data segments.

2.6. Statistical analysis

All statistical analyses were performed with SPSS 27.0. Because of multicollinearity, a linear mixed effects model for repeated measures, using restricted maximum likelihood and Satterthwaite approximation, was employed for all statistical analyses of HRV variables. The normality of distribution of the ECG variables and cognitive workload was assessed using histograms with normal curves and Kolmogorov-Smirnov test. To ensure statistical validity of the analysis, variables having skewed distributions (i.e., cognitive workload, pNN50, SDNN, RMSSD, RRI HF, RRI LF, and RRI LF/HF ratio) underwent natural logarithmic (Ln) transformation. MEAN RRI, nHF, and nLF were normally distributed and therefore analyzed without logarithmic transformation. Scatter plots with LOESS curves revealed linear associations between cognitive workload and the HRV variables. All residual values were also analyzed and found to be normally distributed.

Akaike's information criterion was checked to determine the most suitable covariance structure for each analysis. It showed that, in the linear mixed model for the data, an unstructured covariance structure had the best fit for all pairwise flight phase comparisons. An autoregressive structure was used in the analysis of the relationship between cognitive workload and HRV. The pairwise comparisons of flight phases were conducted with linear mixed effects model for repeated measures, where, in separate analyses, cognitive workload and each HRV variable were assumed as dependent variables with the flight phase as a fixed factor. The same model was used to analyze the relationship between cognitive workload and HRV. The analysis was performed separately for each HRV variable, which were assumed as dependent variables, whereas cognitive workload was set as covariate. Based on the significant results found in the mixed model, a Pearson correlation analysis was subsequently conducted for studying correlations between some selected variables. The standard statistical significance criterion ($p <$

.05) was adopted in the mixed model and correlation analyses.

3. RESULTS

Mean durations of the flight phases (in seconds) were: P1 175 (*SD* 21, range 125–240); P2 126 (*SD* 39, range 60–180); P3 95 (*SD* 31, range 60–145); P4 87 (*SD* 30, range 25–150); P5 125 (*SD* 24, range 75–170).

3.1. Cognitive workload

Across the flight task phases P1–5, the mean total cognitive workload among the 13 participants was 14.23 (*SD* 9.45, range 3.80–37.33), indicating relatively low levels on a scale of 0–100. For the mean values per flight phases, see Figs. 1 and 2. The mean values for the three load components were as follows: mean situation awareness load was 15 (*SD* 14, range 2–76), mean information load was 15 (*SD* 13, range 1–52), and mean decision load was 12 (*SD* 13, range 1–80). Cognitive workload changed significantly across the whole flight (Figs. 1 and 2, dotted line) ($p = .015$), although not between the single flight phases. In terms of cognitive workload, the easiest flight phase was Phase 1 (climb), and the most demanding one was Phase 5 (final ILS approach and landing).

3.2. Heart rate variability

Significant differences were found between the five flight phases in

all time and frequency domain HRV variables (Table 3). Both time and frequency domain HRV variables, related to cardiac autonomic regulation, revealed a withdrawal of parasympathetic control. In pairwise comparisons, statistically significant differences were found in both time (Fig. 1) and frequency domain (Fig. 2) HRV parameters between all other flight phase pairs except between Phase 3 (IFR base leg) and Phase 5 (final ILS approach and landing), and between Phase 4 (ILS localizer established and approach) and Phase 5 (final ILS approach and landing), respectively.

Mixed model analysis showed that cognitive workload had a significant inverse relationship with three HRV variables: the time domain variables RMSSD and pNN50, and the frequency domain variable HF. As described in the methods section, the analysis regarding these variables was conducted by using Ln-conversions. Therefore, the interpretation of the estimation follows a formula: when the cognitive workload (L) increases exponentially to $L \times e$ (e = base of the Ln, ~ 2.72), the HRV variable presumably decreases to e^x (where x is the estimate, i.e., the regression coefficient). Interpretation of the results obtained using the logarithmic values with exponentiated regression coefficients is logical in the view of the original values, as the results indicate changes in the ratio of the expected original outcome means. The regression coefficient between the cognitive workload and the pNN50 was $-.42$, $F(10,61)$, $t = -3.23$, $p = .002$; for the HF $-.32$, $F(7,59)$, $t = -2.619$, $p = .011$; and for the RMSSD $-.119$, $F(7,61)$, $t = -2.57$, $p = .013$. Therefore, when the cognitive workload increased $L \times e$, the pNN50 decreased to .66 times its

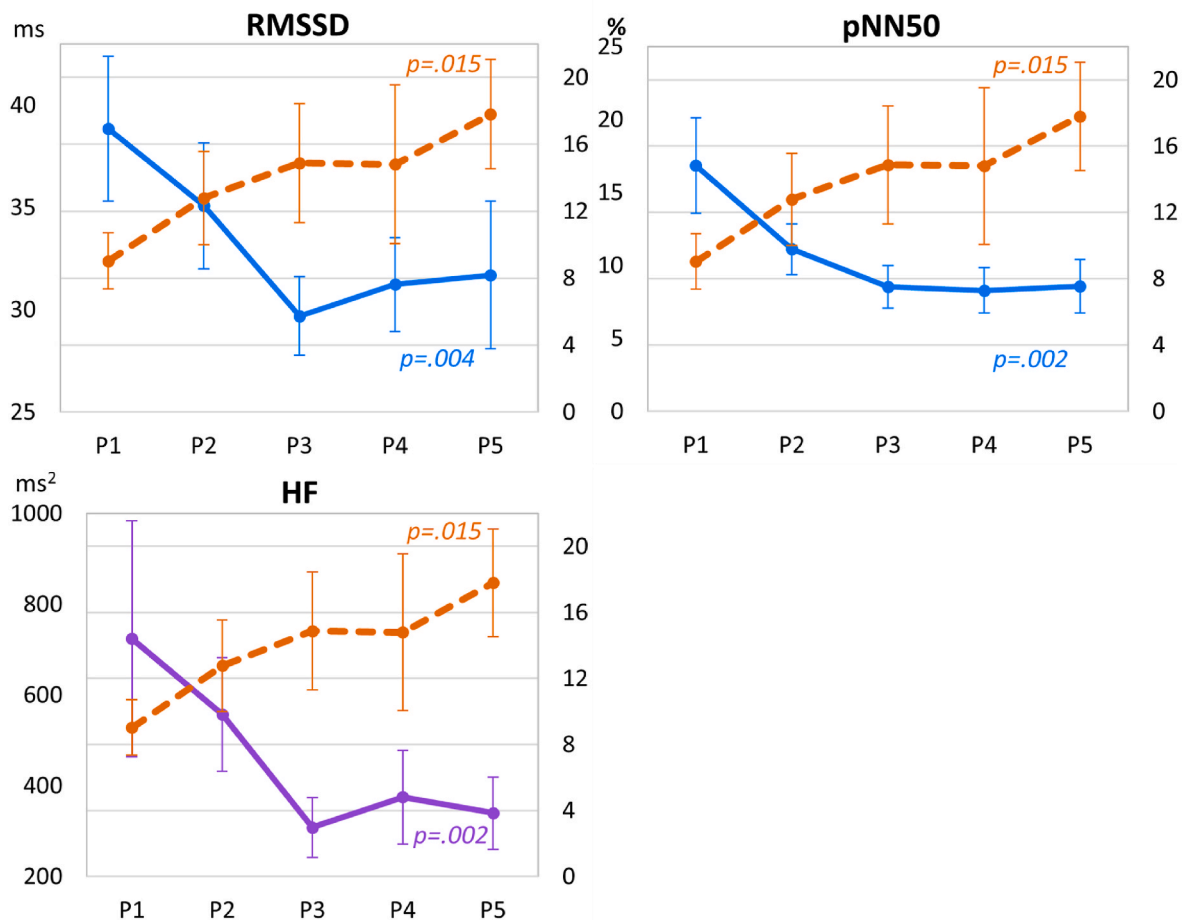


Fig. 1. The three HRV measures (RMSSD, pNN50 and HF; solid line; see the scale on the left Y-axis) which had statistically significant relationship with cognitive workload (dashed line; see the scale on the right Y-axis) in the five simulator flight phases ($N = 13$).

Note. Mean $\pm$ SEM. Cognitive workload is presented on a VAS (Y-axis, mm). X-axis: flight phases P1 = climb, P2 = radar vectors for ILS approach, P3 = IFR base leg, P4 = ILS localizer established and approach, P5 = final ILS and landing. P-values represent the significance of the overall change in the variables across the five flight phases.

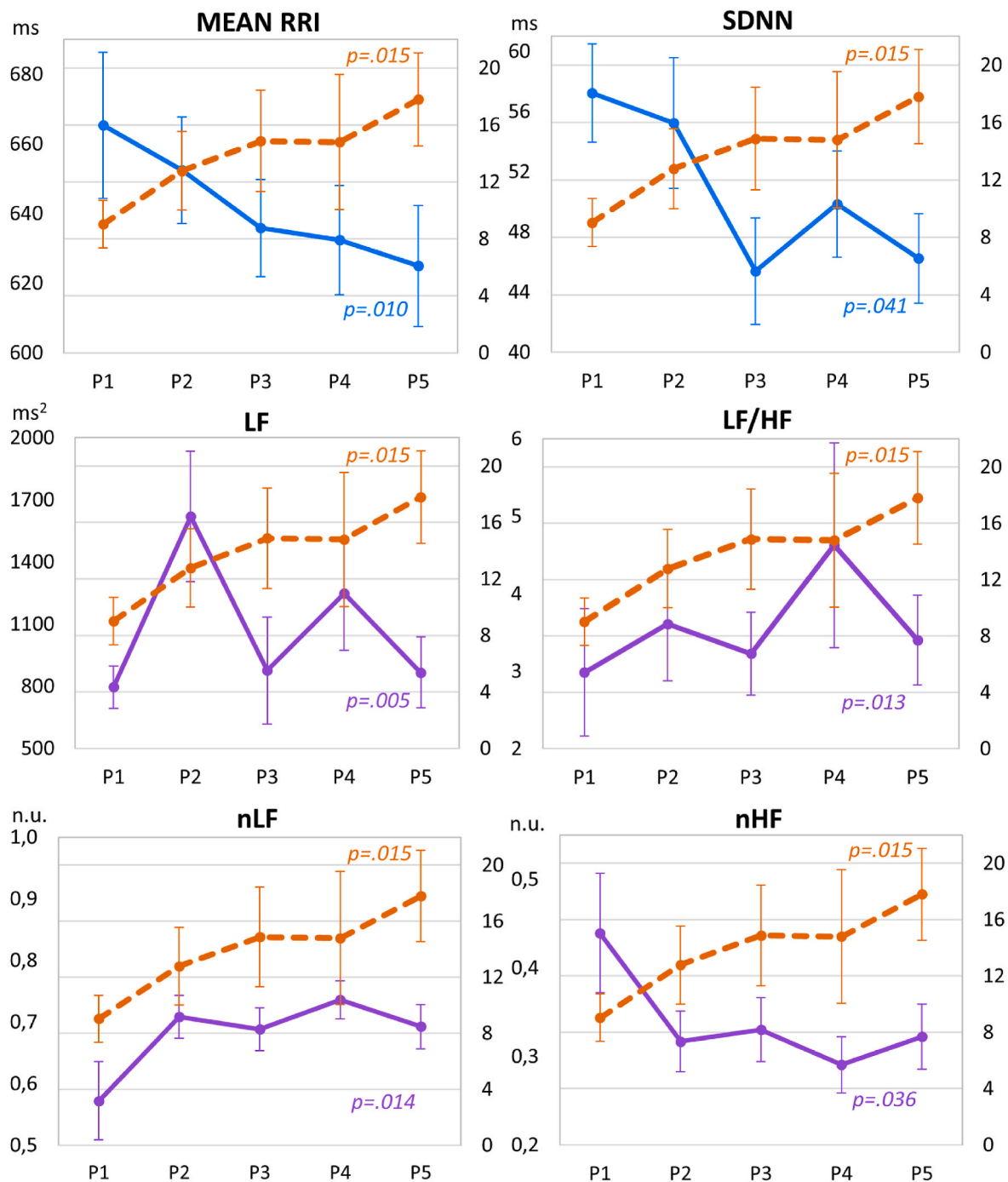


Fig. 2. The six HRV measures (MEAN RRI, SDNN, LF, LF/HF, nLF and nHF; solid line; see the scale on the left Y-axis) which did not have statistically significant relationship with cognitive workload (dashed line; see the scale on the right Y-axis) in the five simulator flight phases (N = 13).

Note. Mean $\pm$ SEM. Cognitive workload presented on a VAS (mm). X-axis: flight phases P1 = climb, P2 = radar vectors for ILS approach, P3 = IFR base leg, P4 = ILS localizer established and approach, P5 = final ILS and landing. P-values represent the significance of the overall change in the variables across the five flight phases.

original value; the HF decreased to .73; the RMSSD decreased to .89. It should be noted that the complex nature of the mixed model, including the chosen estimation measures and covariance structures, resulted in higher and variable degrees of freedom, which, however, is common with this method.

Pearson correlation analysis was conducted for the three aforementioned HRV variables and the cognitive workload across the flight task. All three HRV variables correlated significantly with each other: RMSSD and pNN50 ($r = .82, p < .001$); RMSSD and HF ($r = .61, p < .001$), and pNN50 and HF ($r = .43, p < .001$). The analysis showed a

significant negative correlation between pNN50 and cognitive workload ($r = -.22, p = .042$) and HF and cognitive workload ($r = -.32, p = .005$). RMSSD also had a negative correlation with cognitive workload ($r = -.193, p = .063$), but it was not statistically significant.

4. Discussion

4.1. Findings of the present study

To ensure training safety and adequate performance capabilities of

Table 3
HRV during simulator flight (N = 13).

HRV variable	P1 M	P2 M	P3 M	P4 M	P5 M	Overall effect significance
MEAN RRI (ms)	665 (21.0)	653 (15.3)	636 (14.0) ^{\$\$}	632 (15.7) ^{# \$\$}	625 (17.4) ^{# \$\$}	.010
SDNN (ms)	57 (3.3)	55 (4.3)	45 (3.5) ^{## \$}	50 (3.5)	46 (3.0) ^{# \$}	.041
RMSSD (ms)	39 (3.5)	35 (3.1)	30 (1.9) ^{## \$}	31 (2.3) [#]	32 (3.6)	.004
pNN50 (%)	17 (3.3)	11 (1.7)	9 (1.5) ^{## \$\$}	8 (1.6) ^{##}	9 (1.8) [#]	.002
RRI LF (ms ²)	796 (103)	1620 (315) ^{##}	876 (258) ^{\$}	1248 (274) ^{\$ ^}	866 (171) ^{\$}	.005
RRI HF (ms ²)	724 (260)	557 (125)	308 (66) ^{# \$\$}	375 (103) ^{\$\$}	340 (80) ^{# \$\$}	.002
RRI LF/HF	3.0 (.83)	3.6 (.73) [#]	3.2 (.73)	4.6 (.132) ^{##}	3.4 (.58) [#]	.013
RRI nLF (n.u.)	.57 (.06)	.71 (.03) ^{##}	.69 (.03)	.74 (.03) ^{##}	.69 (.04) ^{##}	.014
RRI nHF (n.u.)	.39 (.07)	.27 (.03) [#]	.28 (.04)	.24 (.03) [#]	.27 (.04) [#]	.036

Note. Standard error of the mean (SEM) is presented in parenthesis. P1 = climb, P2 = radar vectors for ILS approach, P3 = IFR base leg, P4 = ILS localizer established and approach, P5 = final ILS and landing. Significances between flight phases: [#] = $p < .05$ and ^{##} $p < .01$ vs. P1 phase; ^{\$} = $p < .05$ and ^{\$\$} $p < .01$ vs. P2 phase; [^] = $p < .05$ vs. P3 phase.

military pilots, it is crucial to investigate the physiological mechanisms resulting from various risk factors, such as changes in cognitive workload. Potential physiological markers found can be utilized in developing real-time feedback monitoring for assessing the operator's status. The results of the present study indicated that participants' cognitive workload varied during the simulated military flight, with HRV reflecting the workload. Furthermore, HRV metrics were able to discriminate the challenging flight phases for varying ANS responses and task demands. However, the results indicated that some variables were more sensitive to dynamic changes of cognitive workload. Higher cognitive workload led to decrement of HRV, especially in variables known to reflect cardiac PNS activity. Linear mixed model analysis indicated a statistically significant inverse relationship between cognitive workload and three of the HRV variables analyzed, namely RMSSD, pNN50 and HF. A significant negative correlation was also found between cognitive workload and HRV (pNN50, HF). The RMSSD, pNN50 and HF have previously been found to strongly correlate (Cao et al., 2019; Shaffer and Ginsberg, 2017), and our results support that, as in the present study all those HRV variables correlated significantly with each other. These variables reflect cardiac PNS (i.e., vagal) modulation (Berntson et al., 1997; Brindle et al., 2014; Camm et al., 1996). Thus, the present findings suggest that an increase in cognitive workload leads to PNS withdrawal. Specifically, rapid changes in HRV due to varying stress factors are initially caused by changes in PNS activity.

In contrast, cardiac effects due to changes in LF occur with a delay (Berntson et al., 1997). Although it used to be thought that SNS predominantly contributes to LF, it is not an accurate measure of purely SNS activity for various reasons. Firstly, a series of previous studies have provided inconsistent evidence of its validity. Without normalization, LF has not consistently been shown to reflect SNS activity in response to increased cognitive workload, but rather a baroreflex function (Goldstein et al., 2011). Additionally, current understanding suggests that SNS activation reduces the total HRV power, including both HF and LF. Furthermore, PNS modulation alone also influences changes in LF (Hedman et al., 1998). Therefore, LF cannot be assumed to indicate pure

SNS activity, nor can LF/HF be considered to serve as an accurate indicator of sympathovagal (ANS) balance (Billman, 2013). However, nLF is thought to provide more reliable indication of SNS modulation, as the effect of total HRV power is suppressed (Camm et al., 1996). Our results indicated that neither LF (with or without normalization) nor LF/HF had a significant relationship with increasing cognitive workload. However, they did reveal significant differences between flight phases, with nLF showing a more logical direction of change. LF and LF/HF, on the other hand, exhibited somewhat oscillatory changes. Time domain variable SDNN did not show a significant relationship or correlation with increasing cognitive workload. Longer period measurements of SDNN are known to indicate total power HRV and are therefore used in the medical field with 24-h measurements as an index of pathologies and cardiac risks. In contrast, short-term measurement of SDNN has been found to indicate more PNS activity, but it is not as reliable measure as RMSSD and pNN50, respectively (Shaffer and Ginsberg, 2017).

Although Henelius et al. (2009) stated that a liberal workload classifier could potentially be used as a part of a pre-overload alarm mechanism in a safety-critical system, there is a shared understanding that no single physiological measure, e.g., an HRV variable, typically suffices to capture all dimensions of cognitive workload (Ayres et al., 2021; Lehrer et al., 2010; Lohani et al., 2019; Mansikka et al., 2016a; Wilson, 2002). Therefore, multiple HRV variables, such as the ones used in the present study, should be used to estimate rapid, i.e., parasympathetic, regulation of the heart.

During the flight task, the cognitive workload increased as a function of the later flight phases with peaking at the fifth phase (P5). The last flight phases included the ILS final approach and landing, which expectedly demanded the greatest situation awareness, anticipation, and decision-making abilities with simultaneous time pressure. HRV measurement was able to distinguish this increased cognitive demand with logical cardiac responses, as the time domain variables and also HF decreased. The first flight phase (P1), in turn, differed from the other phases, as it had only a minor task demand. Thus, the cognitive workload appeared to gradually increase during the task. Therefore, towards

the end of the flight, there most probably was an effect of accumulating strain that was induced by cognitive workload. Had there been a full take-off phase included in the light, it could have been more demanding with notable physiological responses induced because, in the same way as landing, take-off is considered to represent a high task demand during a flight (Lacabanne et al., 2012; Lee and Liu, 2003; Wilson, 2002).

To measure cognitive workload via HRV assessment, essential requirements to minimize irrelevant burden on the cardiovascular system are an undisturbed recording environment and a negligible amount of physical effort by the participant. During real military flights, depending on the nature of the flight mission and equipment used, military pilots are often required to exert physical effort and endure external physical factors, such as constantly varying gravitation forces, vibration, high temperature, noise, humidity, light, and hypoxia. However, these factors may still be manageable and minimized with proper study design. Studies involving real-flight tasks have reported significant changes in cognitive workload and cardiac measures. Some researchers suggest that these findings might partly be caused by greater excitation and perception of real risks (Fuentes-García et al., 2021; Jorna, 1993; Roscoe, 1993). However, the physical effort required to operate the controls of modern combat aircrafts, as in the simulator, is minimal and does not cause confounding heart rate responses (Roscoe, 1993; Wilson, 2002). This makes a simulator environment suitable for investigating cognitive workload using HRV measurements.

Based on the findings of the present study, the flight task we used can be interpreted as rather basic for the military student pilots, as the cognitive workload values (measured by using VAS) did not reach overload levels and, on average, fell on the lower half of the scale. Nevertheless, HRV measures were still reactive to the changes seen in the cognitive workload. Hughes et al. (2019) noted that a participant's experience or skill level in a particular task is a substantial factor affecting physiological responses to cognitive workload. Compared to novices, more experienced participants usually have more efficient information-processing skills during a task because fewer cognitive resources need to be invested in the primary task (Abernethy et al., 2007; Borghini et al., 2014). Although our participants were air force pilot students who, in the selection phase of pilot training, had been tested for advanced cognitive abilities, it is arguable that a sample of more experienced pilots would show fewer HRV fluctuations during the same flight task. The present study indicates that HRV can be sensitive to changes in cognitive workload below the overload threshold. In future studies, HRV measures should be investigated with raising the simulator task difficulty close to the potential overload level.

It can be argued that the sample size of the present study was rather limited. Partly due to this, some borderline results emerged. For instance, in comparisons of the MEAN RRI (in literature also referred to as mean IBI) and cognitive workload, the distinct and expected inverse relationship was not statistically significant. In fact, MEAN RRI has previously showed validity for revealing changes in cognitive workload during computer, flight, and driving tasks (Henelius et al., 2009; Mansikka et al., 2016b; Tjolleng et al., 2017; Veltman and Gaillard, 1996). In this study, the same limitation also concerns the cognitive workload as it did not significantly differ between the single flight phases, albeit the overall change was significant.

4.2. Conclusions, applications, and further research

Indeed, individual physiological responses to cognitive workload should be analyzed and used in training when one learns to operate complex, safety-critical systems like an aircraft. By quantifying individual processing range and limits for workload and using that information alongside additional objective or subjective methods, overload instances might be avoided, and piloting errors thereby prevented. HRV measurements also have the potential to be used as an evaluation method for cognitive capacity in pilot training.

The results of the present study are in line with previous findings on

the association between cognitive workload and HRV as a cardiac autonomic activity measure (Alaimo et al., 2020; Hjortskov et al., 2004; Lehrer et al., 2010; Mansikka et al., 2016b; Mohanavelu et al., 2020; Tjolleng et al., 2017). In the future, it would be beneficial to integrate biometric monitoring into the cockpit environment to enhance flight safety (Alaimo et al., 2020). Also, cognitive workload assessment with a non-invasive appliance would be beneficial to include in pilot training programs, e.g., in proficiency flight tasks performed in a simulator. It would give valuable information about cognitive effort and residual capacity. Based on that, better solutions, considering training and system development, could be made (Lehrer et al., 2010; Santos et al., 2022). Although there is no single cognitive workload threshold level that applies for all individuals collectively, an individual baseline could possibly be assessed and defined for physiological measures. The relative changes in levels, caused by changes in cognitive workload, would be informative in detecting non-optimal cognitive workload levels (Lohani et al., 2019).

In summary, in the present study several HRV variables indicating parasympathetic downregulation of heart rate were in line with each other and mirrored cognitive workload during a military simulator flight.

CRedit authorship contribution statement

Jukka Koskelo: Writing – original draft, Visualization, Software, Project administration, Methodology, Data curation. **Aleksi Lehmu-saho:** Writing – original draft, Formal analysis. **Tomi P. Laitinen:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Data curation, Conceptualization. **Juha E.K. Hartikainen:** Writing – review & editing, Validation, Supervision. **Taija M.M. Lahtinen:** Writing – review & editing, Funding acquisition, Data curation. **Tuomo K. Leino:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **Kerttu Huttunen:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors acknowledge flight instructors Matti Mustanoja and Toni Ovaskainen for their valuable help during data collection and analysis in Hawk simulator. This work was supported by grants from the Ministry of Defence/Scientific Advisory Board of Defence. The Finnish Defence Forces and Oulu University Hospital have also financially supported this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apergo.2024.104370>.

References

- Aasman, J., Mulder, G., Mulder, L.J.M., 1987. Operator effort and the measurement of heart rate variability. *Hum. Factors* 29 (2), 161–170. <https://doi.org/10.1177/001872088702900204>.
- Abernethy, B., Maxwell, J.P., Masters, R.S.W., Van Der Kamp, J., Jackson, R.C., 2007. Attentional processes in skill learning and expert performance. In: Tenenbaum, G., Eklund, R.C. (Eds.), *Handbook of Sport Psychology*, third ed. Wiley Press, New York, NY, pp. 245–263. <https://doi.org/10.1002/9781118270011.ch11>.
- Alaimo, A., Esposito, A., Orlando, C., Simoncini, A., 2020. Aircraft pilots workload analysis: heart rate variability objective measures and NASA-task load index

- subjective evaluation. *Aerospace* 7 (9), 137. <https://doi.org/10.3390/aerospace7090137>.
- Annett, J., 2002. Subjective rating scales: science or art? *Ergonomics* 45 (14), 966–987. <https://doi.org/10.1080/00140130210166951>.
- Ayres, P., Lee, J.Y., Paas, F., van Merriënboer, J.J.G., 2021. The validity of physiological measures to identify differences in intrinsic cognitive load. *Front. Psychol.* 12, 702538 <https://doi.org/10.3389/fpsyg.2021.702538>.
- Berntson, G.G., Bigger Jr, J.T., Eckberg, D.L., Grossman, P., Kaufmann, P.G., Malik, M., Nagaraja, H.N., Porges, S.W., Saul, J.P., Stone, P.H., Van Der Molen, M.W., 1997. Heart rate variability: origins, methods, and interpretive caveats. *Psychophysiology* 34 (6), 623–648. <https://doi.org/10.1111/j.1469-8986.1997.tb02140.x>.
- Billman, G.E., 2013. The LF/HF ratio does not accurately measure cardiac sympathovagal balance. *Front. Physiol.* 4, 26. <https://doi.org/10.3389/fphys.2013.00026>.
- Borghini, G., Astolfi, L., Vecchiato, G., Mattia, D., Babiloni, F., 2014. Measuring neurophysiological signals in aircraft pilots and car drivers for the assessment of mental workload, fatigue and drowsiness. *Neurosci. Biobehav. Rev.* 44, 58–75. <https://doi.org/10.1016/j.neubiorev.2012.10.003>.
- Brindle, R.C., Ginty, A.T., Phillips, A.C., Carroll, D., 2014. Autonomic basis of cardiovascular reactivity. *Psychophysiology* 51, 964–976. <https://doi.org/10.1111/psyp.12248>.
- Caldwell, J.A., Mallis, M.M., Caldwell, J.L., Paul, M.A., Miller, J.C., Neri, D.F., 2009. Fatigue countermeasures in aviation. *Aviat. Space. Environ. Med.* 80 (1), 29–59. <https://doi.org/10.3357/asm.2435.2009>.
- Camm, A.J., Malik, M., Bigger, J.T., Breithardt, G., Cerutti, S., Cohen, R.J., Coumel, P., Fallen, E.L., Kennedy, H.L., Kleiger, R.E., 1996. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the Eur. Soc. of Cardiol. the North Am. Soc. of Pacing Electrophysiol. *Circ.* 93 (5), 1043–1065. <https://doi.org/10.1161/01.CIR.93.5.1043>.
- Cain, B., 2007. A Review of the Mental Workload Literature. Technical Report RTO-TR-HFM-121-Part-II. Defence Research and Development, Toronto, Canada.
- Cao, X., MacNaughton, P., Cadet, L.R., Cedeno-Laurent, J.G., Flanagan, S., Vellarino, J., Donnelly-McLay, D., Christiani, D.C., Spengler, J.D., Allen, J.G., 2019. Heart rate variability and performance of commercial airline pilots during flight simulations. *Int. J. Environ. Res. Publ. Health* 16 (2), 237. <https://doi.org/10.3390/ijerph16020237>.
- Cinaz, B., Arrnrich, B., La Marca, R., et al., 2013. Monitoring of mental workload levels during an everyday life office-work scenario. *Personal Ubiquitous Comput.* 17, 229–239. <https://doi.org/10.1007/s00779-011-0466-1>.
- Dallat, C., Salmon, P.M., Goode, N., 2019. Risky systems versus risky people: to what extent do risk assessment methods consider the systems approach to accident causation? A review of the literature. *Saf. Sci.* 119, 266–279. <https://doi.org/10.1016/j.ssci.2017.03.012>.
- Dehais, F., Lafont, A., Roy, R., Fairclough, S., 2020. A neuroergonomics approach to mental workload, engagement and human performance. *Front. Neurosci.* 14, 268. <https://doi.org/10.3389/fnins.2020.00268>.
- de Waard, D., Lewis-Evans, B., 2014. Self-report scales alone cannot capture mental workload. *Cognit. Technol. Work* 16, 303–305. <https://doi.org/10.1007/s10111-014-0277-z>.
- Endsley, M.R., 1988. Situation awareness global assessment Technique (SAGAT). In: *Proc. IEEE 1988 Nat. Aerosp. Electr. Conf.*, vol. 3. IEEE, Piscataway, pp. 789–795. <https://doi.org/10.1109/NAECON.1988.195097>.
- Endsley, M.R., 1993. A survey of situation awareness requirements in air-to-air combat fighters. *Int. J. Aviat. Psychol.* 3 (2), 157–168. https://doi.org/10.1207/s15327108ijap0302_5.
- Endsley, M.R., 1994. Situation awareness: some reflections and comments. In: Gilson, R. D., Garland, D.J., Koonce, J.M. (Eds.), *Situational Awareness in Complex Systems*. Embury-Riddle Aeronautical University Press, Daytona Beach, pp. 315–317.
- Endsley, M.R., 1995. Toward a theory of situation awareness in dynamic systems. *Hum. Factors* 37 (1), 32–64. <https://doi.org/10.1518/001872095779049543>.
- Endsley, M.R., 2000. Theoretical underpinnings of situation awareness. In: Endsley, M. R., Garlands, D.J. (Eds.), *Situation Awareness Analysis and Measurement*. Lawrence Erlbaum Associates, Mahwah, pp. 1–21. <https://doi.org/10.1201/b12461>.
- Fallahi, M., Motamedzade, M., Heidari Moghadam, R., Soltanian, A.R., Miyake, S., 2016. Effects of mental workload on physiological and subjective responses during traffic density monitoring: a field study. *Appl. Ergon.* 52, 95103 <https://doi.org/10.1016/j.apergo.2015.07.009>.
- Fernández-Morales, C., Espejo-Antúnez, L., Clemente-Suárez, V.J., Tabla-Hinojosa, F.B., Alborno-Cabello, M., 2022. Analysis of heart rate variability during emergency flight simulator missions in fighter pilots. *BMJ Mil. Health*, e002242. <https://doi.org/10.1136/military-2022-002242>.
- Fuentes-García, J.P., Clemente-Suárez, V.J., Marazuela-Martínez, M.A., Tórner-Aguilera, J.F., Villafaina, S., 2021. Impact of real and simulated flights on psychophysiological response of military pilots. *Int. J. Environ. Res. Publ. Health* 18 (2), 787. <https://doi.org/10.3390/ijerph18020787>.
- Gaillard, A.W.K., 1993. Comparing the concepts of mental load and stress. *Ergonomics* 36 (9), 991–1005. <https://doi.org/10.1080/00140139308967972>.
- Garde, A., Laursen, B., Jørgensen, A., Jensen, B., 2002. Effects of mental and physical demands on heart rate variability during computer work. *Eur. J. Appl. Physiol.* 87 (4–5), 456–461. <https://doi.org/10.1007/s00421-002-0656-7>.
- Giraudet, L., Imbert, J.P., Bérenger, M., Tremblay, S., Causse, M., 2015. The neuroergonomic evaluation of human machine interface design in air traffic control using behavioral and EEG/ERP measures. *Behav. Brain Res.* 294, 246–253. <https://doi.org/10.1016/j.bbr.2015.07.041>.
- Goldstein, D.S., Benthos, O., Park, M.Y., Sharabi, Y., 2011. Low-frequency power of heart rate variability is not a measure of cardiac sympathetic tone but may be a measure of modulation of cardiac autonomic outflows by baroreflexes. *Exp. Physiol.* 96 (12), 1255–1261. <https://doi.org/10.1113/expphysiol.2010.056259>.
- Gramopadhye, A.K., Drury, C.G., 2000. Human factors in aviation maintenance: how we got to where we are. *Int. J. Ind. Ergon.* 26 (2), 125–131. [https://doi.org/10.1016/S0169-8141\(99\)00062-1](https://doi.org/10.1016/S0169-8141(99)00062-1).
- Grassmann, M., Vlemmincx, E., von Leupoldt, A., Van den Bergh, O., 2017. Individual differences in cardiorespiratory measures of mental workload: an investigation of negative affectivity and cognitive avoidant coping in pilot candidates. *Appl. Ergon.* 59 (Pt A), 274–282. <https://doi.org/10.1016/j.apergo.2016.09.006>.
- Hannula, A.M., Huttunen, K., Koskela, J., Laitinen, T., Leino, T., 2008. Comparison between artificial neural network and multilinear regression models in an evaluation of cognitive workload in a flight simulator. *Comput. Biol. Med.* 38 (11–12), 1163–1170. <https://doi.org/10.1016/j.compbiomed.2008.09.007>.
- Hart, S.G., 2006. NASA-task load index (NASA-TLX); 20 years later. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 50 (9), 904–908. <https://doi.org/10.1177/154193120605000909>.
- Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (task load index): results of empirical and theoretical research. In: Hancock, P.A., Meshkati, N. (Eds.), *Advances in Psychology*, pp. 139–183. [https://doi.org/10.1016/S0166-4115\(08\)62386-9](https://doi.org/10.1016/S0166-4115(08)62386-9). North-Holland, Amsterdam.
- Henelius, A., Hirvonen, K., Holm, A., Korpela, J., Muller, K., 2009. Mental workload classification using heart rate metrics. *Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. IEEE, Piscataway*, pp. 1836–1839. <https://doi.org/10.1109/IEMBS.2009.5332602>.
- Hedman, A., Hartikainen, J., Hakumäki, M., 1998. Physiological background underlying short-term heart rate variability. *Ann. Noninvasive Electrocardiol.* 3 (3), 267–280. <https://doi.org/10.1111/j.1542-474X.1998.tb00354.x>.
- Herlambang, M.B., Nossens, F., Taatgen, N.A., 2021. The effects of intrinsic motivation on mental fatigue. *PLoS One* 16 (1), e0243754. <https://doi.org/10.1371/journal.pone.0243754>.
- Hjortskov, N., Rissén, D., Blangsted, A.K., Fallentin, N., Lundberg, U., Søgaard, K., 2004. The effect of mental stress on heart rate variability and blood pressure during computer work. *Eur. J. Appl. Physiol.* 92 (1–2), 84–89. <https://doi.org/10.1007/s00421-004-1055-z>.
- Hughes, A.M., Hancock, G.M., Marlow, S.L., Stowers, K., Salas, E., 2019. Cardiac measures of cognitive workload: a meta-analysis. *Hum. Factors* 61 (3), 393–414. <https://doi.org/10.1177/0018720819830553>.
- Huttunen, K., Keränen, H., Väyrynen, E., Pääkkönen, R., Leino, T., 2011. Effect of cognitive load on speech prosody in aviation: evidence from military simulator flights. *Appl. Ergon.* 42 (2), 348–357. <https://doi.org/10.1016/j.apergo.2010.08.005>.
- Jorna, P.G., 1992. Spectral analysis of heart rate and psychological state: a review of its validity as a workload index. *Biol. Psychol.* 34 (2–3), 237–257. [https://doi.org/10.1016/0301-0511\(92\)90017-o](https://doi.org/10.1016/0301-0511(92)90017-o).
- Jorna, P.G., 1993. Heart rate and workload variations in actual and simulated flight. *Ergonomics* 36 (9), 1043–1054. <https://doi.org/10.1080/00140139308967976>.
- Lacabanne, M., Amadiou, F., Tricot, A., Spanghero-Gaillard, N., 2012. Analysis of the flight task around different types of aircraft. *International Conference on Human-Computer Interaction in Aerospace (HCI-Aero)* 1–6. <https://hal.science/hal-01627366>. Bruxelles, Belgium.
- Lee, Y.H., Liu, B.S., 2003. Inflight workload assessment: comparison of subjective and physiological measurements. *Aviat Space Environ. Med.* 74 (10), 1078–1084.
- Lehrer, P., Karavadas, M., Lu, S.-E., Vasschillo, E., Vasschillo, B., Cheng, A., 2010. Cardiac data increase association between self-report and both expert ratings of task load and task performance in flight simulator tasks: an exploratory study. *Int. J. Psychophysiol.* 76 (2), 80–87. <https://doi.org/10.1016/j.ijpsycho.2010.02.006>.
- Lohani, M., Payne, B.R., Strayer, D.L., 2019. A review of psychophysiological measures to assess cognitive states in real-world driving. *Front. Hum. Neurosci.* 13 <https://doi.org/10.3389/fnhum.2019.00057>.
- Lohi, J.J., Huttunen, K.H., Lahtinen, T.M., Kilpeläinen, A.A., Muhli, A.A., Leino, T.K., 2007. Effect of caffeine on simulator flight performance in sleep-deprived military pilot students. *Mil. Med.* 172 (9), 982–987. <https://doi.org/10.7202/MILMED.172.9.982>.
- Mansikka, H., Simola, P., Virtanen, K., Harris, D., Oksama, L., 2016a. Fighter pilots' heart rate, heart rate variation and performance during instrument approaches. *Ergonomics* 59 (10), 1344–1352. <https://doi.org/10.1080/00140139.2015.1136699>.
- Mansikka, H., Virtanen, K., Harris, D., Simola, P., 2016b. Fighter pilots' heart rate, heart rate variation and performance during an instrument flight rules proficiency test. *Appl. Ergon.* 56, 213–219. <https://doi.org/10.1016/j.apergo.2016.04.006>.
- Mansikka, H., Virtanen, K., Harris, D., 2019. Comparison of NASA-TLX scale, modified Cooper-Harper scale and mean inter-beat interval as measures of pilot mental workload during simulated flight tasks. *Ergonomics* 62 (2), 246–254. <https://doi.org/10.1080/00140139.2018.1471159>.
- McKendrick, R.D., Cherry, E., 2018. A deeper look at the NASA TLX and where it falls short. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* 62 (1), 44–48. <https://doi.org/10.1177/1541931218621010>.
- Mohanavelu, K., Poonguzhali, S., Ravi, D., Singh, P., Mahajabin, M., Ramachandran, K., Singh, U., Jayaraman, S., 2020. Cognitive workload analysis of fighter aircraft pilots in flight simulator environment. *Defence Sci. J.* 70, 131–139. <https://doi.org/10.14429/dsj.70.14539>.
- Roscoe, A.H., 1993. Heart rate as a psychophysiological measure for in-flight workload assessment. *Ergonomics* 36 (9), 1055–1062. <https://doi.org/10.1080/00140139308967977>.
- Santos, S., Parraca, J.A., Fernandes, O., Villafaina, S., Clemente-Suarez, V.J., Melo, F., 2022. The effect of expertise during simulated flight emergencies on the autonomic

- response and operative performance in military pilots. *Int. J. Environ. Res. Publ. Health* 19 (15), 9141. <https://doi.org/10.3390/ijerph19159141>.
- Shaffer, F., Ginsberg, J.P., 2017. An overview of heart rate variability metrics and norms. *Front. Public Health* 5, 258. <https://doi.org/10.3389/fpubh.2017.00258>.
- Tao, D., Tan, H., Wang, H., Zhang, X., Qu, X., Zhang, T.A., 2019. Systematic review of physiological measures of mental workload. *Int. J. Environ. Res. Publ. Health* 16 (15), 2716. <https://doi.org/10.3390/ijerph16152716>.
- Tattersall, A.J., Foord, P.S., 1996. An experimental evaluation of instantaneous self-assessment as a measure of workload. *Ergonomics* 39 (5), 740–748. <https://doi.org/10.1080/00140139608964495>.
- Taylor, R.M., 1990. Situational Awareness Rating Technique (SART): the development of a tool for aircrew systems design. In: *Situational Awareness in Aerospace Operations (AGARD-CP-478)*, vol. 3. Neuilly-Sur-Seine, France, NATO-Advisory Group for Aerospace Research and Development, pp. 1–17.
- Tjolleng, A., Jung, K., Hong, W., Lee, W., Lee, B., You, H., Son, J., Park, S., 2017. Classification of a driver's cognitive workload levels using artificial neural network on ECG signals. *Appl. Ergon.* 59 (Pt A), 326–332. <https://doi.org/10.1016/j.apergo.2016.09.013>.
- Veltman, J.A., Gaillard, A.W.K., 1993. Indices of mental workload in a complex task environment. *Neuropsychobiology* 28, 72–75.
- Veltman, J.A., Gaillard, A.W.K., 1996. Physiological indices of workload in a simulated flight task. *Biol. Psychol.* 42 (3), 323–342. [https://doi.org/10.1016/0301-0511\(95\)05165-1](https://doi.org/10.1016/0301-0511(95)05165-1).
- Veltman, J.A., Gaillard, A.W.K., 1998. Physiological workload reactions to increasing levels of task difficulty. *Ergonomics* 41 (5), 656–669. <https://doi.org/10.1080/001401398186829>.
- Wang, H., Jiang, N., Pan, T., Si, H., Li, Y., Zou, W., 2020. Cognitive load identification of pilots based on physiological-psychological characteristics in complex environments. *J. Adv. Transp.* 5640784 <https://doi.org/10.1155/2020/5640784>, 2020.
- Wang, P., Houghton, R., Majumdar, A., 2024. Detecting and predicting pilot mental workload using heart rate variability: a systematic review. *Sensors* 24, 3723. <https://doi.org/10.3390/s24123723>.
- Wang, X., Liu, B., Xie, L., Yu, X., Li, M., Zhang, J., 2016. Cerebral and neural regulation of cardiovascular activity during mental stress. *Biomed. Eng. Online* 15 (Suppl. 2), 160. <https://doi.org/10.1186/s12938-016-0255-1>.
- Wei, Z., Zhuang, D., Wanyan, X., Liu, C., Zhuang, H., 2014. A model for discrimination and prediction of mental workload of aircraft cockpit display interface. *Chin. J. Aeronaut.* 27, 1070–1077. <https://doi.org/10.1016/j.cja.2014.09.002>.
- Weissman, D.G., Mendes, W.B., 2021. Correlation of sympathetic and parasympathetic nervous system activity during rest and acute stress tasks. *Int. J. Psychophysiol.* 162, 60–68. <https://doi.org/10.1016/j.ijpsycho.2021.01.015>.
- Wiegmann, D.A., Shappell, S.A., 1999. Human error and crew resource management failures in Naval aviation mishaps: a review of U.S. Naval Safety Center data, 1990–96. *Aviat. Space Environ. Med.* 70 (12), 1147–1151.
- Wilson, G.F., 2002. An analysis of mental workload in pilots during flight using multiple psychophysiological measures. *Int. J. Aviat. Psychol.* 12, 3–18. https://doi.org/10.1207/S15327108IJAP1201_2.
- Young, M.S., Brookhuis, K.A., Wickens, C.D., Hancock, P.A., 2015. State of science: mental workload in ergonomics. *Ergonomics* 58 (1), 1–17. <https://doi.org/10.1080/00140139.2014.956151>.
- Yu, X., Zhang, J., Xie, D., Wang, J., Zhang, C., 2009. Relationship between scalp potential and autonomic nervous activity during a mental arithmetic task. *Auton. Neurosci.* 146 (1–2), 81–86. <https://doi.org/10.1016/j.autneu.2008.12.005>.