# Cardiovascular Activity linked to the Emotional State and Cognitive Workload during a Flight Simulation

Antonio R. Hidalgo-Muñoz[1], Damien Mouratille[1], Nadine Matton[2], Mickaël Causse[3], Yves Rouillard[2], Radouane El-Yagoubi[1]

*[1]CLLE-LTC, University of Toulouse II – Jean Jaurès, 5 allées Antonio Machado, 31058, Toulouse, France*
*[2]École National de l'Aviation Civile, 7 Édouard-Belin, 31055, France*
*[3]Institut Supérieur de l'Aéronautique et de l'Espace, 10 Édouard-Belin, 31055, Toulouse, France*
*{antonio.hidalgo-munoz, radouane.el-yagoubi}@univ-tlse2.fr, damien.mouratille@etu.univ-tlse2.fr*
*{nadine.matton, yves.rouillard}@enac.fr, mickael.causse@isae.fr*

Keywords: Arousal, Cognitive Workload, ECG, Emotion, Heart Rate Variation, Flight Simulation.

Abstract: The identification of physiological markers of emotional and cognitive fluctuations during a flight can be useful to alert of risky situations due to their possible impact on pilot's mental state and performance. In this study, heart rate (HR) and other features, such as R-R peak interval variability and the spectral power of specific frequency bands, have been extracted from ECG recordings throughout flight simulations. The temporal variation of these features within different experimental conditions has been explored to verify their reliability to discriminate episodes of mental overload. Our results show that the monotonic decrease of HR reflects the emotional regulation, mainly under secondary low cognitive overload. Conversely, the increase of the root mean square successive differences was linked to higher cognitive workload situations. Furthermore, the habituation analysis reveals that these features are severely affected when an external cognitive demand is increased during a flight task and their temporal variation tendency depends on the emotional state.

## 1 INTRODUCTION

Investigating the emotional state and cognitive workload experienced by operators becomes a primordial concern in numerous domains where the human factor is critical. This is the case in aviation where pilots are commonly exposed to different sources of emotional and cognitive stressors (Blogut, 2015), and not surprisingly, approximately 70 % of the accidents are due, at least partially, to erroneous decisions or distraction of the crew (Salas, Maurino & Curtis, 2010). Therefore, integrating an efficient and objective online monitoring to assess the emotional and/or the cognitive variations into the cockpit would be largely desirable. To this aim, reliable and cost-effective physiological measures are required.

As it is well known, emotion and cognition have both an impact on the autonomic nervous system (ANS). Either way, the combined effect of emotional state and cognitive demand facing complex tasks, such as the control of a plane, has been hardly considered in the literature and remains challenging. Usually, research works have focused mainly, or even exclusively, on one of these factors by neglecting a possible interaction between them.

For example, in the case of emotion, the effect of anxiety during simulation training has been explored by Tichon et al. (2012). They found larger muscle activation for anxious states, while ocular measurements did not show significant variations, except for the fixation time. Differently, in Causse et al. (2013) the influence of emotion on pilot decision-making has been studied by using functional magnetic resonance imaging, necessarily out of a cockpit. In that case, the emotion was generated by rewarding the participants according to the relevance of their landing decisions in different situations. Interestingly, Allsop & Gray (2014) have analyzed the effects of anxiety on attention and gaze behavior in aviation, using social stress to increment the level of arousal and causing impairment in attentional control. Similarly, Gray, Gaska & Winterbottom

(2016) have applied the same method to elicit stress on the participants and to disentangle the particular influences on specific attentional processes.

On the other side, the objective measurement of the cognitive (sometimes called mental) workload is a topic raising more and more interest in diverse domains, such as ergonomics in general (Young et al. 2014, for a review) or aviation in particular (Vecchiato et al. 2016) and its physiological correlates have become essential. For instance, regarding the measures of the central nervous system, electroencephalography (EEG) has been widely used to assess cognitive overload and to discriminate specific psychological processes involved in multi-task resolution with different applications (Stikic et al. 2014). Another application, but using peripheral measures, can be found in Gaetan et al. (2015), who have studied the physiological markers referring to distinct levels of workload in helicopter pilots by using electromyography and skin conductance. However, they could not draw definitive conclusions due to large individual differences.

Nonetheless, despite the numerous possibilities of physiological measures linked to emotion and cognition, electrocardiography (ECG) is still considered among the most suitable options, even for complex computational model integrating both psychological factors, e.g. in Besson et al. (2012), providing powerful and discriminant features for classifier implementation. Heart rate (HR) and heart rate variation (HRV) are two fundamental ECG parameters (Massaro & Pecchia, 2016), often taken into account in studies focusing on the relationship between cardiovascular activity and emotion/cognition in ergonomics. Concretely, in the aviation domain, Durantin et al. (2013) have included HRV measures together with functional near infrared spectroscopy (fNIRS) measurements, to detect mental overload during a computing-based piloting task for remotely operated vehicle applications. Wei et al. (2014) have also shown the suitability of HRV measures to distinguish among three levels of mental workload. Mansikka et al. (2016) have studied HR and HRV features for differentiating between high performances of instrument landing system approach from sub-standard-performance in fighter pilots. Following this line, other applications can be found in car drivers, where HR and HRV have also received a particular attention (Heine et al. 2017; Mehler, Reimen & Coughlin, 2012; Stuiver et al., 2014).

Recently, emerging research works started analyzing mental workload under stressing situations or different personality profiles in tasks requiring a high level of performance. Specifically, in the field of aeronautics, Grassman et al. (2016) have analyzed the correlation between cardiorespiratory measures and personality factors in pilots while performing a demanding multi-task covering perceptual speed, orientation and working memory. Their results suggest the importance of considering emotional coping strategies when measuring mental workload. From a more technical standpoint, Mandrick et al. (2016), by means of pupillometry, fNIRS and cardiovascular measurements, have investigated the physiological correlates of human performance under a high level of workload when threatened by unpredictable auditory stressors.

The satisfactory results from the mentioned studies encourage a deeper exploration of the ECG markers of the relation between emotional state and cognitive demand during piloting. Furthermore, in order to reach a good external validity, the experiment has been designed to be as ecological as possible, approaching as closely as possible a real flight situation, in spite of the inherent difficulties of this kind of neuro-ergonomics researches. Finally, the habituation effect has been also considered to determine the phases where ECG parameters were the more stable, in order to use them to feed an eventual online classifier of user’s mental state.

# 2 MATERIALS AND METHODS

## 2.1 Participants

Eleven healthy volunteers were recruited from the National Civil Aviation School (ENAC) in Toulouse, France. All participants had normal auditory acuity and normal or corrected to normal vision and none of them declared a history of severe medical treatment, neither psychological disorder nor any cardiac or neurological trouble. They assessed to be relaxed and lucid before the session. A signed informed consent was obtained from each participant two days before carrying out the experiment. All of them were in possession of the Private Pilot License having at least a flying experience of 60 flight hours (132.9 ± 51.9 hours), were familiar to simulator environments and fluent in English.

Three of the participants were discarded due to technical problems in data acquisition or inefficient performances. The 8 resting participants were considered in the physiological analysis (male; 20.8

± 3.2 years). The study was conducted in accordance with the Declaration of Helsinki.

## 2.2 Experimental Setting

The experiment took place in an AL-50 simulator, located in a room with artificial dimmed lighting which was kept at a comfortable temperature. The experiment consisted in completing two dual-task scenarios. Each dual-task scenario required the simultaneous accomplishment of a pre-established flight plan with a flight simulator and a secondary task based on target stimulus discrimination, aiming at modulating the level of cognitive workload (low or high). Furthermore, dual-task scenarios were carried out in two different conditions (with or without social stressor). This 2 x 2 design enabled to assess the interaction between cognitive workload and emotional state. While mental workload varied within the two dual task scenarios, the social stressor was administered during the second dual task scenario.

### 2.2.1 Flight Plans

Two flight scenarios analogous in terms of difficulty, one for each emotional condition of the experiment (with or without social stressor), were designed by an expert instructor. The established flight paths required various changes in heading, speed, and altitude, and tilt specifications to vary the course. The strict timing of this variation was specified in the flight plan.

Favourable weather conditions were set and technical unexpected events were not included. Each flight lasted approximately 35 minutes from take-off to landing.

The trajectories and parameters from both flight tasks were recorded and examined by a professional in order to verify the completion of the instructions. The performance was considered as acceptable when the deviations of the expected parameters fell into a margin adjusted to the pilot expertise.

### 2.2.2 Emotional State Manipulation

While some research works consider that adverse weather conditions increase the difficulty of the flight tasks and consequently increase emotional activation, we have considered that this type of manipulation rather increases cognitive workload in a simulator, where no vital threat exist. Therefore, we choose to modulate emotional state thanks to the method depicted in the study of Allsop and Gray (2014). During the first dual-task scenario (including a complete flight plan and the two versions of the cognitive secondary task explained below), considered as the low arousal (LA) condition, the participant was left alone in the simulator without interruption. On the contrary, during the execution of the second dual-task scenario, considered as the high arousal (HA) condition, the participant was filmed by two cameras and his voice was recorded with a microphone. Also, he was thoroughly monitored by two researchers, and he was supposedly involved in a competition with the other participants. This mock competition would consist in a public nominative classification of the individual results from the experiment. In addition, free access for two hours to a bigger simulator (A320 model) in the case of obtaining the best performance was used as incentive. The truth about the competition and filming was disclosed at the end of the experiment, just before leaving.

Note that for the HA condition, the arousal can be increased due to the motivation or/and to the social stress of feeling evaluated. Two questionnaires (French version) were used to find out the origin of the emotional state for ulterior analysis out of scope of this study. The former, the Competitive State Anxiety Inventory-2R (Martinent et al. 2010) to measure the anxiety linked to the competition, was delivered just before the HA condition, whereas the latter, the State-Trait Anxiety Inventory (form Y) (Spielberger et al. 1993) to measure the general anxiety, was given when the second dual-task scenario was finished.

### 2.2.3 Cognitive Workload Manipulation

A 7 inches tactile screen (TFT LCD, resolution 800 × 480) having built-in speakers was employed to implement the secondary task. The screen was integrated on the left of the control board and accessible comfortably by the pilots.

Essentially, this task consisted of pressing the screen as quick as possible after hearing some isolated numbers integrated among Air Traffic Control (ATC) instructions, which were not related to the flight plan and were used only as distractors, making the environment more realistic.

The task was implemented using E-prime 2.0 (© Psychology Software Tool, Inc., PA, USA). The stimuli presentation took 24 minutes, avoiding the take-off and landing periods. The secondary task was subdivided in two phases of same duration (12 minutes and separated by a bell sound), allowing to manipulate the additional cognitive workload:

- Low Cognitive Workload (LCW): The participant was instructed to press the screen if the heard numbers met a simple rule. For the first dual-task scenario, the number ought to be greater than five, while for the second flight plan, during the

LCW, the rule consisted in pressing the screen if the heard numbers were even. Simultaneous to ATC and numbers playing, a series of random numbers in black was displayed on the screen. The two numbers (heard and visualized) could present equal or different values.

- High Cognitive Workload (HCW): Similarly to the previous phase, the participant was instructed to press the screen according to the value of the heard numbers. However, for this condition, the attribute value on which attention had to be directed depended on the color of the number displayed on the screen. In other words, the color of the visualized number discriminated if the property to evaluate was the magnitude or the parity of the previous heard number. The colors used were red and green for the first dual-task scenario and magenta and blue for the second dual-task scenario. In these cases, the participant had to look at the screen, at least to look sideways, in order to see the colors and to decide to press or not after hearing the number. This instruction increased the working memory demands, likely intensifying the effect of the congruence or incongruence between the heard number and the number displayed on the screen.

Participants showing too low performance, less than 50 % of correct responses as implying a misunderstanding, were discarded for behavioral-based mean comparisons.

## 2.3 ECG Measurement

ECG signal was recorded along the whole experiment by placing two electrodes on the clavicle and left pectoral of the participants. BrainVision Recorder 1.21 (© Brain Products GmbH, Gilching, Germany) was used for signal acquisition. Ground reference signal was taken from the electroencephalography montage, employed for ulterior analysis.

All ECG features were computed in Matlab 2016a (© The Mathworks, Inc., MA, USA) by taking three 4-minutes segments referring to the different parts of the experiment as detailed in previous sections (LCW and HCW for LA and HA). The meaning of every feature was as follow:

- HR: Heart rate corresponds to the number of beats (by counting the R-peaks) per minute (bpm).

- RR: Interval length between two consecutives R-peaks. Note that incomplete RR intervals next to the segment limits were not considered.

To evaluate HRV:

- Ratio (RR): Difference between the maximum and the minimum R-R interval length within the considered 4-min segment. Note that, for convenience, the RR and Ratio (RR) results are showed in milliseconds (ms), whereas the following parameters are computed based on the original measures in seconds.

- SD (RR): Standard deviation of R-R interval lengths for each 4-min segment.

- RMSSD: Root mean squared of the successive differences between adjacent R-R intervals. It is associated with fast (parasympathetic) variability.

- pNN-*x*: Proportion of R-R intervals which differ more than *x* ms respect to the adjacent previous R-R interval. When $x$ = SD, the SD refers to the standard deviation of R-R interval lengths taking the whole recording as reference, i.e. it deals with an intra-subject specific measure.

To evaluate the spectral variations in the cardiac activity two spectral bands were analyzed:

- $f_{\mathrm{LF}}$: Energy in 0.05Hz – 0.15Hz band, related to parasympathetic and sympathetic activity (Chanel et al. 2011).

- $f_{\mathrm{HF}}$: Energy in 0.15Hz – 1Hz band, related to parasympathetic (vagal) activity (Chanel et al. 2011).

- $f_{\mathrm{LF/HF}}$: Ratio of energy in the LF and HF bands. A decrease in this score might point to either decrease in sympathetic or increase in parasympathetic tone.

## 2.4 Statistical Analysis

For the multivariate analysis, normality was first checked for the variables under examination by means of the Shapiro-Wilk's. Then, an analysis of variance (ANOVA) of repeated measures was performed including three within-subject factors: emotion (2 levels of arousal: LA and HA) × cognition (2 levels of cognitive workload: LCW and HCW) × habituation *intra-condition* (3 levels: {1:= (0 – 4 min), 2:= (4 – 8 min), 3:= (8 – 12 min)}).

To verify any statistically significant differences between conditions a maximum *p*-value of .05 was set. Greenhouse-Geisser's correction was applied if sphericity could not be assumed. Post hoc analysis was based on LSD Fisher criterion.

All statistical analyses were carried out using STASTICA version 12 (© StatSoft Inc., OK, USA).

# 3 RESULTS

## 3.1 Reaction Time and Accuracy

The performance for the secondary task, measured for 9 participants, showed significant main effects for both emotion and cognition, with faster RT (less time invested to respond) for HA compared to LA condition ($p$ = .003) and for LCW compared to

HCW ($p < .001$) condition. No interaction between cognition and emotion was found. Figure 3 represents the means of RT.

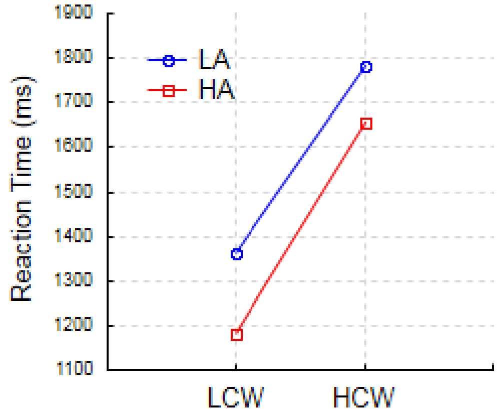


Figure 1: Reaction times for the secondary task. LCW: low cognitive workload; HCW: high cognitive workload. LA: low arousal; HA: high arousal.

In regard to the accuracy, two sources of errors have been considered, commission errors when an unexpected response is given and omission errors when the subject did not react to the target stimulus. No significant differences were found in terms of global errors, i.e. the addition of commission and omission errors, between any conditions (93.4 % of accuracy on average). However, a main effect of emotion for omission errors was found, i.e. between LA and HA condition, ($p = .03$) showing a higher number of lost expected responses in LA compared to HA (12.5 % and 5.99 % of omissions, respectively), yielding to a reduction of 49.2 % on the omission rate when HA is considered.

Furthermore, a significant correlation of $r = .914$ ($p = .01$) between commission and omission errors rates was found for HCW in LA, whereas a weaker correlation of $r = .733$ ($p = .025$) between the same error rates was found for HCW in HA.

Finally, by means of a linear regression analysis of every single trial (x axis = trial position; y axis = RT), by comparing the derivative values of the adjusted line to a horizontal line (derivative = 0), an improvement in the RT was observed for HCW ($p = .029$ and $p = .022$ for LA and HA condition, respectively). No significant improvement in RT was demonstrated for LCW conditions.

## 3.2 ECG features

Interestingly, a main effect of cognition was found for RMSSD, showing a greater value for HCW (mean = 0.0219) compared to LCW (mean = 0.0208) condition ($p = 0.014$). No main effect of emotion was found.

Concerning HR measure, despite the lack of main effects in cognition or emotion, an interaction between these two factors was found ($F = 7.69$; $p = .028$). LSD Fisher post hoc test showed smaller HR for HA compared to LA condition only for LCW ($p = .049$). Regarding HRV features, no interaction between emotion and cognition was evidenced.

Table 1 shows the statistics (mean ± standard error) for all ECG features for both emotional state and cognitive workload conditions, averaging the results of the three 4-min segments intra-condition.

Table 1: Mean values of ECG features

| Feature | Low Arousal | | High Arousal | |
|---|---|---|---|---|
| | LCW | HCW | LCW | HCW |
| HR(bpm) | 93.7±6.0 | 92.4±5.5 | 91.9±6.2 | 93.6±6.0 |
| RR (ms) | 661 ± 42 | 668 ± 40 | 676 ± 46 | 662 ± 43 |
| Ratio(RR) | 1423 ± 43 | 1507 ± 91 | 1444 ± 42 | 1452 ± 53 |
| SD(RR) | .045±.008 | .050±.012 | .047±.009 | .047±.010 |
| RMSSD | .020±.003 | .021±.002 | .021±.003 | .022±.004 |
| pNN-20 | .349±.066 | .361±.061 | .362±.069 | .367±.084 |
| pNN-50 | .078±.038 | .073±.035 | .074±.032 | .102±.059 |
| pNN-SD | .059±.016 | .054±.012 | .056±.013 | .073±.028 |
| $f_{LF/HF}$ | 2.05±.188 | 2.19±.237 | 1.98±.285 | 1.83±.165 |

Concerning the habituation factor, a main effect of was found in HR ($F = 4.80$; $p = .026$) and Ratio (RR) ($F = 4.53$; $p = .03$). An interaction between habituation and emotion was found in HR ($F = 10.10$; $p = .002$), RMSSD ($F = 13.53$; $p < .001$), and pNN-20 ($F = 5.07$; $p = .022$) and a triple interaction among the three factors was found in HR ($F = 7.20$; $p = .007$). No simple interaction between cognition and habituation was statistically significant. Note that the concept of habituation makes sense strictly intra-condition, thus it is necessary to be cautious for drawing conclusions.

In the case of HR, post hoc analyses revealed significant differences between the beginnings of the two dual-task scenarios, i.e. between LA and HA for the first and the second segments during the LCW condition ($p = .002$; $p = .006$, respectively) being greater for the start of LA (coinciding with the start of the experimental session). The HR slowed down significantly from the first and second segments compared to the last one within LCW under the LA condition ($p < .001$; $p = .007$, respectively), yielding to a more than 5 bpm of total reduction in HR, in contrast to HA condition, where no differences were found in this direction. Concerning the HCW periods, only a difference between the first and the last segment again in LA condition was observed ($p$ = .013). Furthermore, there were significant differences between the end of LCW (third segment) and the beginning of HCW phases for both LA and HA conditions ($p$ = .005; $p$ = .019, respectively).

For visualization purposes, the most relevant results for HR and for RMSSD are depicted in Figures 1 and 2, respectively.

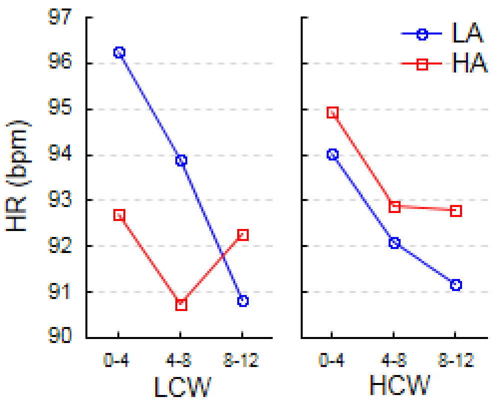


Figure 2: Means of HR for Low (LA) and High (HA) Arousal conditions (blue and red lines, respectively) for Low (LCW) and High (HCW) Cognitive Workload (left and right plots) for the three consecutive 4-min segments belonging to each condition (axes x). Note that HA follows LA condition along the experiment.

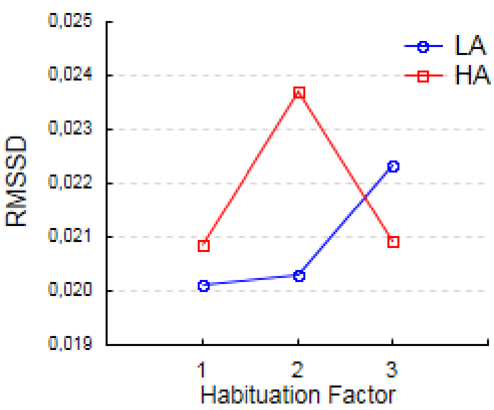


Figure 3: Means of RMSSD for Low (LA) and High (HA) Arousal conditions (blue and red lines, respectively) for the three levels of the habituation factor.

Post hoc analyses showed that for RMSSD value increases significantly from the first and second segment to the last segment within LA condition ($p$ = .004 and $p$ = .007, respectively). This result was analogous, but in opposed direction, to the result obtained for HR. In contrast to the tendency for LA, during the HA condition, the RMSSD value obtained in the middle segment was significantly greater than the next others ($p < .001$ in both cases).

No significant results were found for the spectral features.

## 4 DISCUSSION

Before discussing the results, it is fair to remind the comment of Mansikka et al. (2016) assuring that while a simulator mission can be designed to be mentally extremely demanding, it will inherently lack the stressors of a real flying mission such as the sense of risk and the fear of collision or injury of death. According to this conclusive argument, the assessment of the generated emotional state is crucial to draw reliable conclusions.

The results concerning the RT for the secondary task, where main effects of emotion and cognition were obtained, permitted to suppose that the emotional state and the cognitive demand were manipulated separately in the experimental setting. Indeed, this was the objective of the task, i.e. to generate different and objectively measurable levels of emotional activation and cognitive workload to check their influence on cardiovascular activity. In addition, the significant difference in omission errors between LA and HA conditions could also support the idea of an increment in the motivation during HA, prioritizing the flight plan to the detriment of the secondary task. Moreover, the regression analysis of trial position on RT suggests the influence of training for the secondary task for HCW, which can consequently make difficult to obtain main effects of the cognition on the HR measure.

In any case, the interaction between cognition and emotion, exhibited in HR measure, suggests that these two factors do not have a cumulative impact on the sympathetic nervous system. Contrary to other research works (Mandrick et al. 2016), HR was not impacted neither by emotional arousal nor cognitive demand independently. Maybe, this lack of main effect could be related to the presence of only two difficulty levels in the secondary task and to the absence of direct sensorial stimulation for the emotional activation.

According to the comparisons between the four combined conditions (post hoc analysis on emotion and cognition), LCW makes pilot more sensitive to HR modulations caused by the emotional influence. At first sight, this fact could lead to the assumption of an independency between cognitive processing of stimuli and emotional regulation. However, an intrinsic frustration generated by the HCW, which is considered as an influent factor for mental workload (Hsu et al. 2015), might have biased the results. A similar interaction has been described in Patel et al. (2016) where the authors showed that induced arousal affected working memory differently according to the task difficulty and, to the contrary, the increase of cognitive demand lightened the physiological responses linked to anxiety.

On the other hand, it is important to take into account the HR evolution along time periods during the flight simulation. There is a difference after the change of instructions (switching LCW for HCW) that could be related to the stress and insecurity facing new tasks. Probably, this non-stationarity of HR prevents to find the global differences related to emotional state or cognitive workload. Therefore, it is convenient to incorporate HRV features to complement and refine the information provided by the HR.

Concerning HRV, RMSSD was presented as the most discriminant feature for cognitive workload level estimation, since a significant difference in RMSSD has been found between two levels of cognitive demand. This feature had already shown good results for discriminating task difficulty by employing more than two levels (Mandrick et al. 2016). Furthermore, conversely to HR, when the habituation factor was analyzed, RMSSD showed a monotone increase during the LA compared to the HA condition, where the maximum was reached at the middle of time course. This result could be due to a more efficient emotional regulation when the level of arousal is low (Appelhans & Luecken, 2006), while an eventual feeling of temporal pressure just before the end of the dual-task scenario could affect this regulation under HA. Hence, our results suggest the suitability of RMSSD for the calibration of weak emotions along time and to determine cognitive workload variations.

In addition, pNN-20 seemed to be another accurate option to investigate the interaction between emotion and habituation. In agreement with the conclusions reported in Mietus et al. (2002) for pathological populations, pNN-20 is revealed to be more useful than pNN-50 to determine inter-condition differences. Given that our population is constituted by healthy people and the crucial comparisons were intra-subject, no more values were tested to avoid over-fitted results. Nevertheless, in order to get an equitable, but intra-subject customized measure, pNN-SD was also analyzed, where SD was adaptive to individual differences. Either way, no relevant results were found, returning to the use of fixed time intervals as a better option. Therefore, taking 20 ms as threshold appears as a good trade-off for emotional process analysis.

Following the line of previous findings, revisited by Thayer et al. (2012), the lack of signification of HRV parameters for HA condition could be linked to a worse performance on the mentioned emotional regulation when pilots are evaluated. In any case, as mentioned, the HRV parameters should be taken together to the HR to verify its relative magnitudes.

Apart from HR and HRV features, spectral measures have been analyzed, but no conclusions can be drawn from them, since no signification was evidenced. Likely, the complex tasks involved in our experiment did not allow to distinguish between sympathetic and parasympathetic contributions (Chanel et al. 2011), encouraging the selection of more general parameters as predictor variables in similar environments.

# 5 CONCLUSIONS

Flying an aircraft is a very complex task demanding a huge amount of cognitive resources, and is also dependent on the emotions felt by the pilot. The interaction found in the ECG parameters in our study hints that the emotional state and the cognitive demand have not a simple cumulative impact on the ANS, but they interact together. Furthermore, the habituation and the instructions change of a secondary task, parallel to the flight plan, influences notably HR and RMSSD features. This fact shows habituation as an important factor to take into consideration for online calibration and ECG-based classifiers.

A higher monotony in HR decrease was observed during a low cognitive demanding task under conditions generating low arousal. An inverse patron was found for HRV showing the control of nervous system resources, particularly evident in RMSSD when the cognitive demand increases. The inclusion of other physiological signals such as electro-dermal activity, which could be feasible to incorporate into a cockpit, would be desirable in order to extract additional robust features representing the general mental state of pilots.

## ACKNOWLEDGEMENTS

This work was supported by the French Research National Agency and the French Defence Procurement Agency via the Accompagnement Spécifique des travaux de Recherches et d'innovation Défense (ASTRID), project ANR-13-ASTR-0036.

## REFERENCES

Allsop, J. and Gray, R., 2014. Flying under pressure: Effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition*, *3*(2), pp.63-71.

Appelhans, B.M. and Luecken, L.J., 2006. Heart rate variability as an index of regulated emotional responding. *Review of general psychology*, *10*(3), p.229.

Besson, P., Maiano, C., Bringoux, L., Marqueste, T., Mestre, D.R., Bourdin, C., Dousset, E., Durand, M. and Vercher, J., 2012, September. Cognitive workload and affective state: A computational study using Bayesian networks. In *Intelligent Systems (IS), 2012 6th IEEE International Conference* (pp. 140-145). IEEE.

Blogut, A. (2015). Stressing factors in aviation. Scientific Research & Education in the Air Force – AFASES.

Causse, M., Dehais, F., Péran, P., Sabatini, U. and Pastor, J., 2013. The effects of emotion on pilot decision-making: A neuroergonomic approach to aviation safety. *Transportation research part C: emerging technologies*, *33*, pp.272-281.

Chanel, G., Rebetez, C., Bétrancourt, M. and Pun, T., 2011. Emotion assessment from physiological signals for adaptation of game difficulty. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, *41*(6), pp.1052-1063.

Durantin, G., Gagnon, J.F., Tremblay, S. and Dehais, F., 2014. Using near infrared spectroscopy and heart rate variability to detect mental overload. *Behavioural brain research*, *259*, pp.16-23.

Gaetan, S., Dousset, E., Marqueste, T., Bringoux, L., Bourdin, C., Vercher, J.L. and Besson, P., 2015. Cognitive workload and psychophysiological parameters during multitask activity in helicopter pilots. *Aerospace medicine and human performance*, *86*(12), pp.1052-1057.

Grassmann, M., Vlemincx, E., von Leupoldt, A. and 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. *Applied Ergonomics*, *59*, pp.274-282.

Gray, R., Gaska, J. and Winterbottom, M., 2016. Relationship between sustained, orientated, divided, and selective attention and simulated aviation performance: Training & pressure effects. *Journal of Applied Research in Memory and Cognition*, *5*(1), pp.34-42.

Heine, T., Lenis, G., Reichensperger, P., Beran, T., Doessel, O. and Deml, B., 2017. Electrocardiographic features for the measurement of drivers' mental workload. *Applied Ergonomics*, *61*, pp.31-43.

Hsu, B.W., Wang, M.J.J., Chen, C.Y. and Chen, F., 2015. Effective indices for monitoring mental workload while performing multiple tasks. *Perceptual and motor skills*, *121*(1), pp.94-117.

Mandrick, K., Peysakhovich, V., Rémy, F., Lepron, E. and Causse, M., 2016. Neural and psychophysiological correlates of human performance under stress and high mental workload. *Biological psychology*, *121*, pp.62-73.

Mansikka, H., Simola, P., Virtanen, K., Harris, D. and Oksama, L., 2016. Fighter pilots' heart rate, heart rate variation and performance during instrument approaches. *Ergonomics*, *59*(10), pp.1344-1352.

Martinent, G., Ferrand, C., Guillet, E. and Gautheur, S., 2010. Validation of the French version of the Competitive State Anxiety Inventory-2 Revised (CSAI-2R) including frequency and direction scales. *Psychology of Sport and exercise*, *11*(1), pp.51-57.

Massaro, S. and Pecchia, L., 2016. Heart Rate Variability (HRV) Analysis A Methodology for Organizational Neuroscience. *Organizational Research Methods*, p.1094428116681072.

Mehler, B., Reimer, B. and Coughlin, J.F., 2012. Sensitivity of physiological measures for detecting systematic variations in cognitive demand from a working memory task: an on-road study across three age groups. *Human factors*, *54*(3), pp.396-412.

Mietus, J.E., Peng, C.K., Henry, I., Goldsmith, R.L. and Goldberger, A.L., 2002. The pNNx files: re-examining a widely used heart rate variability measure. *Heart*, *88*(4), pp.378-380.

Patel, N., Vytal, K., Pavletic, N., Stoodley, C., Pine, D.S., Grillon, C. and Ernst, M., 2015. Interaction of threat and verbal working memory in adolescents. *Psychophysiology 53*(4), pp. 518-526.

Salas, E., Maurino, D., & Curtis, M. (Eds.). (2010). Human Factors in Aviation, 2nd Edition. Academic Press.

Spielberger, C.D., Gorsuch, R.L., Lushene, R., Vagg, P.R. and Jacobs, G., 1983. *Manual for the state-trait anxiety inventory (form Y): self-evaluation questionnaire*. Palo Alto, CA: Consulting Psychologists Press.

Stikic, M., Berka, C., Levendowski, D.J., Rubio, R.F., Tan, V., Korszen, S., Barba, D. and Wurzer, D., 2014. Modeling temporal sequences of cognitive state changes based on a combination of EEG-engagement, EEG-workload, and heart rate metrics. *Frontiers in Neuroscience*, *8*, pp.242-255.

Stuiver, A., Brookhuis, K.A., de Waard, D. and Mulder, B., 2014. Short-term cardiovascular measures for driver support: increasing sensitivity for detecting

changes in mental workload. *International Journal of Psychophysiology*, *92*(1), pp.35-41.
Thayer, J.F., Åhs, F., Fredrikson, M., Sollers, J.J. and Wager, T.D., 2012. A meta-analysis of heart rate variability and neuroimaging studies: implications for heart rate variability as a marker of stress and health. *Neuroscience & Biobehavioral Reviews*, *36*(2), pp.747-756.
Tichon, J.G., Wallis, G., Riek, S. and Mavin, T., 2014. Physiological measurement of anxiety to evaluate performance in simulation training. *Cognition, technology & work*, *16*(2), pp.203-210.
Vecchiato, G., Borghini, G., Aricò, P., Graziani, I., Maglione, A.G., Cherubino, P. and Babiloni, F., 2016. Investigation of the effect of EEG-BCI on the simultaneous execution of flight simulation and attentional tasks. *Medical & biological engineering & computing*, *54*(10), pp.1503-1513.
Wei, Z., Zhuang, D., Wanyan, X., Liu, C. and Zhuang, H., 2014. A model for discrimination and prediction of mental workload of aircraft cockpit display interface. *Chinese Journal of Aeronautics*, *27*(5), pp.1070-1077.
Young, M.S., Brookhuis, K.A., Wickens, C.D. and Hancock, P.A., 2015. State of science: mental workload in ergonomics. *Ergonomics*, *58*(1), pp.1-17.