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ORIGINAL PAPER

FROM NOVICE TO EXPERT: STUDYING THE PHYSIOLOGICAL ADAPTATION TO STRESS IN MILITARY PILOTS DURING FLIGHT

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Abstract

Introduction. Effective stress regulation and autonomic adaptation are critical for ensuring optimal performance and safety in military aviation.
The objective of this study was to investigate the physiological responses and autonomic regulation during flight of military pilots with different flight experience.
Material and methods. The study evaluates a comprehensive range of physiological parameters, including heart rate (HR), heart rate variability (HRV), autonomic nervous system (ANS) indices, and thermoregulation (forehead temperature), across three flight phases: pre-flight, during flight, and post-flight of three groups of participants: Group I (experienced pilot instructors), Group K (novice pilot students), and Group K2 (students after completing 50 flights).
Results. The study revealed significant differences between novice and experienced pilots in stress responses and recovery patterns. Group K consistently displayed higher HR, reduced HRV, and elevated sympathetic nervous system (SNS) indices across all phases, indicative of heightened sympathetic

Résumé

Du novice à l'expert : étudier l'adaptation physiologique au stress chez les pilotes militaires en vol

Introduction. Une régulation efficace du stress et une adaptation autonome sont essentielles pour garantir des performances et une sécurité optimales dans l'aviation militaire. L'objectif de cette étude était d'examiner les réponses physiologiques et la régulation autonome en vol de pilotes militaires ayant différentes expériences de vol.
Matériel et méthodes. L'étude évalue un large éventail de paramètres physiologiques, notamment la fréquence cardiaque (FC), la variabilité de la fréquence cardiaque (VFC), les indices du système nerveux autonome (SNA) et la thermorégulation (température frontale), sur trois phases de vol, avant, pendant et après le vol, auprès de trois groupes de participants: Groupe I (instructeurs pilotes expérimentés), Groupe K (élèves pilotes novices) et Groupe K2 (élèves ayant effectué 50 vols).
Résultats. Les résultats révèlent des différences significatives entre les pilotes novices et expérimentés

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dominance, anticipatory stress, and delayed recovery. Group I, in contrast, demonstrated balanced autonomic regulation, with lower HR, higher HRV, and efficient parasympathetic reactivation, reflecting superior stress resilience and workload management. Group K2 exhibited notable improvements in HR and HRV metrics, as well as enhanced thermoregulation, highlighting the adaptive effects of flight experience. The results underscore the importance of experience in enhancing autonomic flexibility and stress resilience.

Conclusions. This study highlights the potential of physiological monitoring as a tool for optimizing pilot training and identifying stress-prone individuals. By incorporating structured exposure and stress management techniques, training programs can foster greater autonomic stability, ensuring safety and performance in high-demand aviation environments.

Keywords: military pilots, flight training, heart rate variability, thermoregulation, stress regulation.

List of abbreviations:
ANOVA – analysis of variance
ANS – autonomic nervous system
ApEn – approximate entropy
bpm – beats per minute
HF – high frequency bands
HR – heart rate
HRV – heart rate variability
LF – low frequency bands
M – mean
PNS – parasympathetic nervous system
RMSSD – root mean square of successive differences in RR intervals
RR – duration of RR intervals in ECG record
SampEn – sample entropy
SCL – skin conductance level
SNS – sympathetic nervous system
STDHR – standard deviation of HR
STDRR – standard deviation of RR
VLF – very low frequency bands

en termes de réponses au stress et de schémas de récupération. Le groupe K a systématiquement affiché une FC plus élevée, une VFC réduite et des indices du système nerveux sympathique (SNS) élevés à toutes les phases, indiquant une dominance sympathique accrue, un stress anticipé et une récupération retardée. Le groupe I, en revanche, a démontré une régulation autonome équilibrée, avec une FC plus basse, une VFC plus élevée et une réactivation parasympathique efficace, reflétant une meilleure résilience au stress et une meilleure gestion de la charge de travail. Le groupe K2 a présenté des améliorations notables des paramètres de FC et de VFC, ainsi qu'une thermorégulation améliorée, soulignant les effets adaptatifs de l'expérience de vol. Les résultats soulignent l'importance de l'expérience pour améliorer la flexibilité autonome et la résilience au stress.

Conclusions. Cette étude met en évidence le potentiel du suivi physiologique comme outil d'optimisation de la formation des pilotes et d'identification des personnes sujettes au stress. En intégrant des techniques structurées d'exposition et de gestion du stress, les programmes de formation peuvent favoriser une plus grande stabilité autonome, garantissant sécurité et performance dans des environnements aéronautiques exigeants.

Mots-clés: pilotes militaires, formation au vol, variabilité de la fréquence cardiaque, thermorégulation, régulation du stress

Introduction

The aviation environment, particularly in military aviation, is characterized by high physical, cognitive, and emotional demands. Pilots must maintain exceptional performance under conditions that challenge their stress regulation, decision-making, and situational awareness. Understanding how flight experience influences autonomic regulation and physiological responses is critical for improving pilot training, reducing stress, and ensuring flight safety[1,2]. Heart rate variability (HRV), autonomic nervous system (ANS) indices, and thermoregulation have emerged as key physiological markers for assessing stress and adaptation in pilots[3,4].

The ANS plays a pivotal role in regulating physiological stress responses. The sympathetic nervous system (SNS) prepares the body for high-demand situations through the "fight-or-flight" response, increasing heart rate (HR) and reducing RR intervals, while the parasympathetic nervous system (PNS) promotes relaxation and recovery[5,6]. A balance between these systems ensures effective stress regulation, which is vital for pilot performance and recovery[7]. However,

the ability to maintain this balance depends largely on experience and repeated exposure to flight conditions[3,8].

Studies indicate that novice pilots face heightened physiological arousal during flight, reflected in elevated HR, reduced HRV, and increased sympathetic dominance[2,9]. For instance, Sharma et al. reported that first-year pilot students exhibit marked HR elevation and delayed PNS recovery, signaling a less adaptive autonomic response during training. This is attributed to high cognitive workload, situational stress, and lack of familiarity with complex flight tasks[10]. Similarly, Bair et al. found that novice pilots demonstrate limited stress modulation capabilities, as indicated by reduced HRV and persistent SNS activation during and after flight[11].

In contrast, experienced pilots demonstrate greater autonomic stability, including lower HR, higher HRV, and faster recovery post-flight[1,12]. The physiological markers in experienced pilots reflect an optimized autonomic balance, enabling them to manage stress effectively and maintain peak performance[13,14]. This finding aligns with the neurovisceral integration model, which proposes that greater vagal tone (PNS activation) is associated with improved cognitive flexibility and emotional regulation[1,6].

Despite significant advancements, there remain critical gaps in understanding the transition from novice to experienced pilot physiology. Most studies focus on novice and experienced groups in isolation, without tracking the progression of physiological markers over specific training milestones[8,15]. Additionally, limited studies compare autonomic regulation across before flight, during flight, and after flight conditions, which are crucial for assessing anticipatory stress in-flight adaptation, and recovery[10,16]. The transition from novice to experienced pilot involves significant improvements in autonomic regulation and stress adaptation. Repeated exposure to flight conditions enhances autonomic flexibility, as evidenced by improvements in HRV parameters, reduced SNS dominance, and better thermoregulation[4,16]. Geisler et al. demonstrated that pilots with higher flight experience show greater parasympathetic recovery post-stress and increased HR complexity (measured via approximate entropy). These findings highlight the plasticity of the ANS and its ability to adapt through targeted training.

Thermoregulatory stability also improves with experience. Novice pilots exhibit greater variability in core body temperature under stress due to autonomic dysregulation, while experienced pilots maintain more consistent thermoregulatory control[12,16]. Thermoregulation is particularly sensitive during flight conditions due to environmental stressors such as G-forces, vibration, and cognitive workload[17].

However, stress adaptation is gradual and non-uniform. Kamath and Fallen reported that while HR parameters (e.g., mean HR, RR intervals) stabilize early with experience, other markers such as very low frequency (VLF) power and HR complexity require prolonged exposure to achieve significant improvements. VLF power reflects long-term sympathetic modulation and is associated with sustained stress responses[3,9]. High VLF power in novice pilots suggests a prolonged sympathetic influence, while experienced pilots exhibit better modulation of these responses[7,8]. By addressing these gaps, it will be better to explore how flight exposure influences physiological markers in military pilot students and compare them with experienced instructors as a control group.

The objective of the study was to investigate the physiological responses and autonomic regulation during flight of military pilots with different flight experience and to identify the most sensitive physiological parameters for monitoring pilot readiness and training effectiveness.

Material and methods

The study was approved by the Committee on Ethics of Scientific Research of the Medical University – Pleven (Bulgaria). All the procedures and experiments of the study were performed in conformity with the ethical standards in the Helsinki Declaration of 1975, as revised in 2000, for biomedical research involving human subjects. Written informed consent was obtained from all participants prior to participation.

This study employed a quasi-experimental design to evaluate the physiological responses and stress regulation mechanisms of military pilots with varying levels of experience across three flight conditions: pre-flight, during flight, and post-flight. Participants (n=23) were divided into three groups:

- Group I: pilot instructors (n=5) with extensive flight experience with at least 2 000 flight hours.
- Group K: first-year pilot students (n=9) beginning their training.
- Group K2: the same students reassessed after completing 50 flights with and without instructors (n = 9).

Inclusion criteria: the participants were required to be healthy, with no history of cardiovascular, respiratory or neurological disorders.

Exclusion criteria: chronic illnesses, medications affecting ANS function or substance use.

The flights were conducted with a training aircraft model "Zlin 242 L", light aircraft with piston engine, group 3. The measurements were made in the time range between 06:00 – 08:00 in the morning, taking into account the circadian rhythm of the subjects, in order to reduce potential differences in the state of alertness and fatigue.

The physiological responses were measured using the Gp8Amp System (Somatic Vision Inc., USA), a validated multi-channel amplifier known for its precision in monitoring real-time autonomic activity during dynamic operations[4].

The following sensors were used:

1. ECG electrodes, placed on the chest to monitor HR and RR intervals, reflecting autonomic activity[7].
2. Temperature sensor – affixed to the forehead to measure skin temperature, indicative of thermoregulation[16].
3. Skin conductance sensors – attached to the forehead to monitor skin conductance level (SCL) as a measure of sympathetic nervous system activation[12].

The Alive Pioneer Software (Somatic Vision Inc., USA) was used for real-time processing, visualization, and storage of physiological signals. The platform provided reliable data on HR, HR variability (HRV), temperature, and skin conductance[3].

The experimental procedure was standardized across all participants and included three phases:

- *Pre-flight phase*
  - Timing**:** from boarding until just before airplane takeoff.
  - Participants were equipped with sensors, and physiological recordings commenced upon boarding.
  - Data collected in this phase reflected anticipatory stress and baseline autonomic activity.
- *During flight phase*
  - Timing: from takeoff to landing.
  - Physiological responses were continuously recorded during flight, capturing autonomic and stress-related changes during active maneuvers.
- *Post-flight phase*
  - Timing: from landing to engine shutdown.
  - Recordings continued after landing to capture recovery patterns during taxiing and concluded once the airplane engines were turned off.

Consistent recording conditions across groups minimized variability caused by external factors[9]. Physiological and autonomic parameters were recorded to evaluate stress responses, autonomic regulation, and recovery[3]. These included:

- Skin and temperature metrics:
  - Skin sweat level: indicator of sympathetic activation through skin conductance.
  - Temperature (absolute value): forehead temperature to assess thermoregulation[16].
  - Sweat stability: measures the consistency of sweat patterns under stress.
- Autonomic indices:
  - PNS index – parasympathetic nervous system activity.
  - SNS index – sympathetic nervous system activity.
  - Stress index – combined autonomic measures of overall stress load.
- Time-domain HRV metrics:
  - Mean RR (ms) – average time between heartbeats, reflecting autonomic tone.
  - STDRR (ms) – standard deviation of RR intervals.
  - RMSSD (ms) – root mean square of successive differences in RR intervals, linked to parasympathetic modulation.
- Frequency-domain HRV metrics:
  - VLF, LF, HF (Hz) – frequency bands reflecting the balance between sympathetic and parasympathetic activity[7].
  - LF/HF ratio – indicator of autonomic balance and stress response.
- Nonlinear HRV metrics:
  - Approximate entropy (ApEn) – complexity of heart rate dynamics, linked to physiological adaptability[5].

Data were preprocessed using Alive Pioneer software to remove artifacts and segment recordings into the three flight phases.

Statistical methods

Data were analyzed using SPSS "Statistics 26" and Python for advanced visualization. Statistical tests included:

1. Normality testing:
2. Shapiro-Wilk test to evaluate the normality of distributions.
3. Homogeneity of variance:
   - Levene's test to assess variance equality across groups.
4. Post-hoc analysis:
   - Tukey HSD tests for pairwise comparisons in variables with equal variances.
   - Games-Howell test for variables with unequal variances (e.g., temperature).
5. Repeated measures ANOVA to assess differences across flight conditions and between groups.
6. Effect size (η^2):
   - Calculated to measure the strength of observed differences[9].

A p-value < 0.05 was considered statistically significant.

Results

This section presents the detailed analysis of physiological parameters for pilot instructors (Group I), novice pilot students (Group K), and experienced pilot students after 50 flights (Group K2). Comparisons were made across the three flight phases: pre-flight, during flight, and post-flight. Statistical analyses were conducted using repeated measures ANOVA, with post-hoc Tukey HSD for equal variances and Games-Howell for unequal variances (temperature).

HR parameters:

- Maximum (Max) HR was highest in Group K during all phases, reflecting higher stress responses, while Group K2 showed partial adaptation (Fig.1).
  - During pre-flight condition, Group K demonstrated significantly higher max HR (M = 125 bpm) compared to Group I (M = 85 bpm), $p < 0.01$,

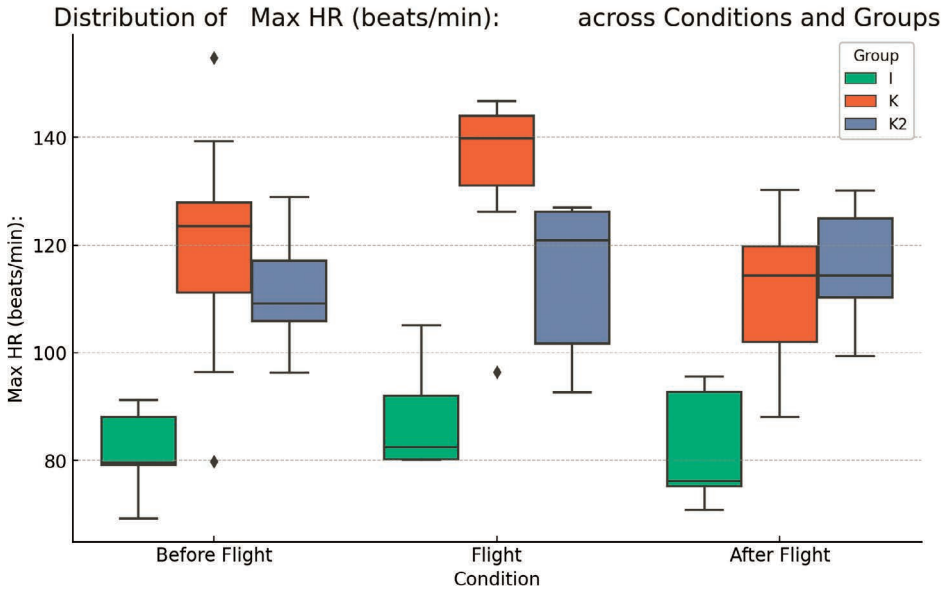


Fig. 1. Distribution of maximum heart rate across groups and conditions as mean±SD in beats /min. Abbreviations: Max HR – maximum heart rate; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

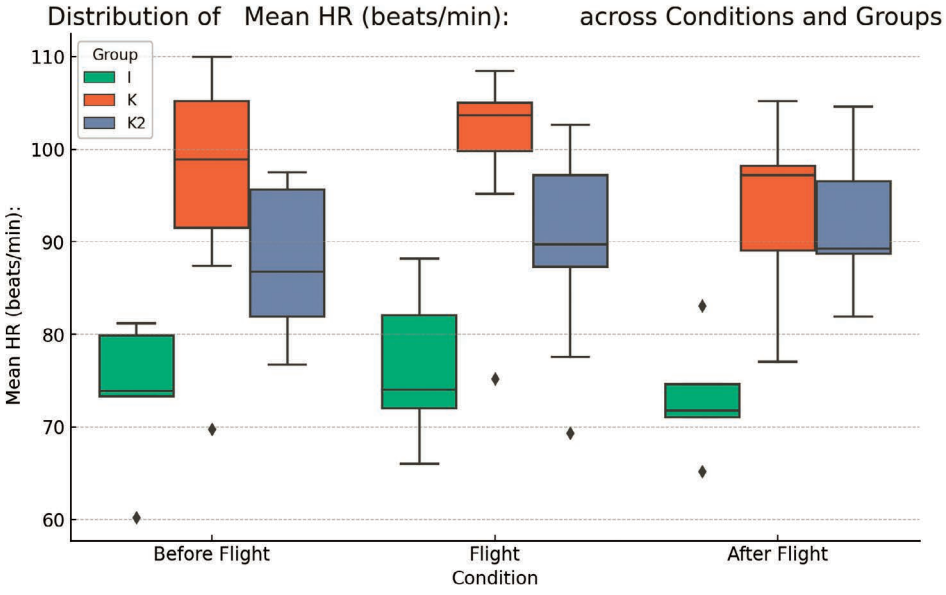


Fig. 2. Mean heart rate across groups and conditions as mean±SD in beats /min. Abbreviations: HR – heart rate; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

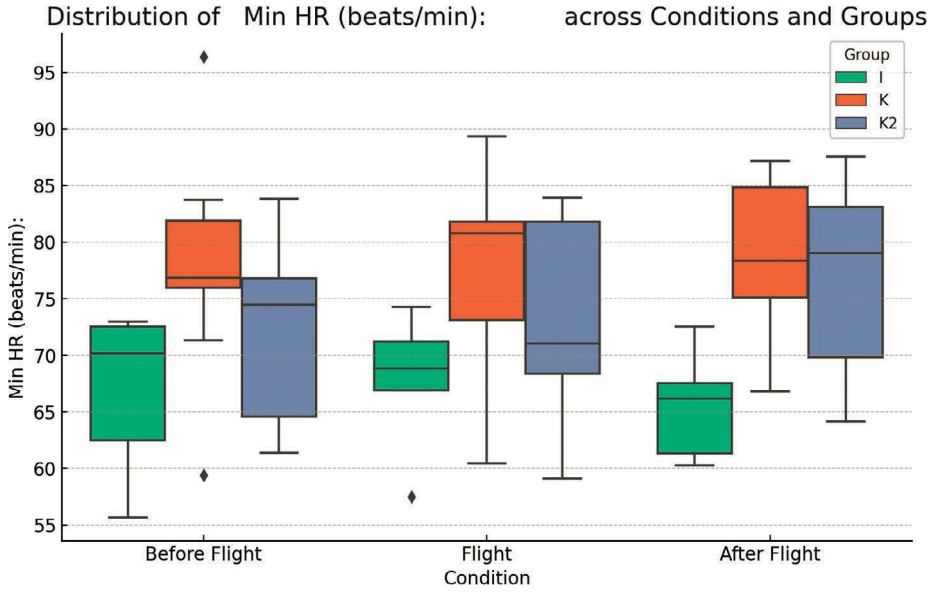


Fig. 3. Minimum heart rate across groups and conditions as mean±SD in beats /min.
Abbreviations: Min HR – minimum heart rate; I – Pilot instructors; K – First-year pilot students beginning their training; K2 – The same experienced pilot students, after completing 50 flights

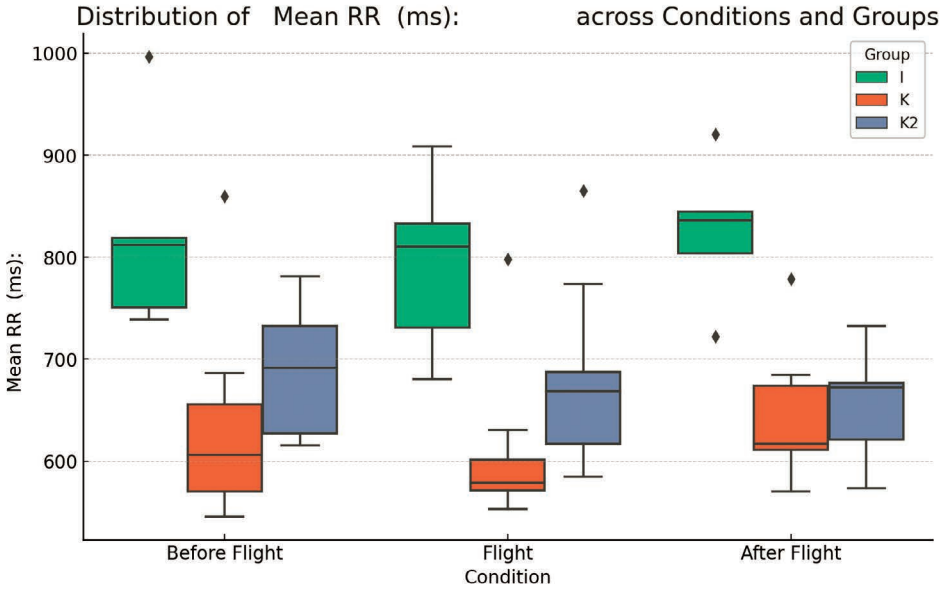


Fig. 4. Mean RR intervals across groups and conditions as mean±SD in ms.
Abbreviations: Mean RR – duration of RR intervals in ECG record; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

indicating higher anticipatory stress, while Group K2 exhibited intermediate values (M =110 bpm).

- All groups showed an increase in max HR during flight, reaching the highest values (M = 145 bpm) in Group K, while Group I remained lowest value (M=105 bpm), $p < 0.01$. Group K2 showed moderate levels (M = 125 bpm).
- After landing, Group K retained elevated max HR (M = 120 bpm), while Group K2 showed improvement (M = 115 bpm). Group I returned to baseline values (M = 90 bpm).

▸ Mean HR

Group K showed persistently elevated mean HR, while Group K2 demonstrated significant improvement after 50 flights. The mean HR trends are illustrated in Fig. 2.

- Pre-flight – Group K exhibited significantly higher mean HR (M = 100 bpm) compared to Group I

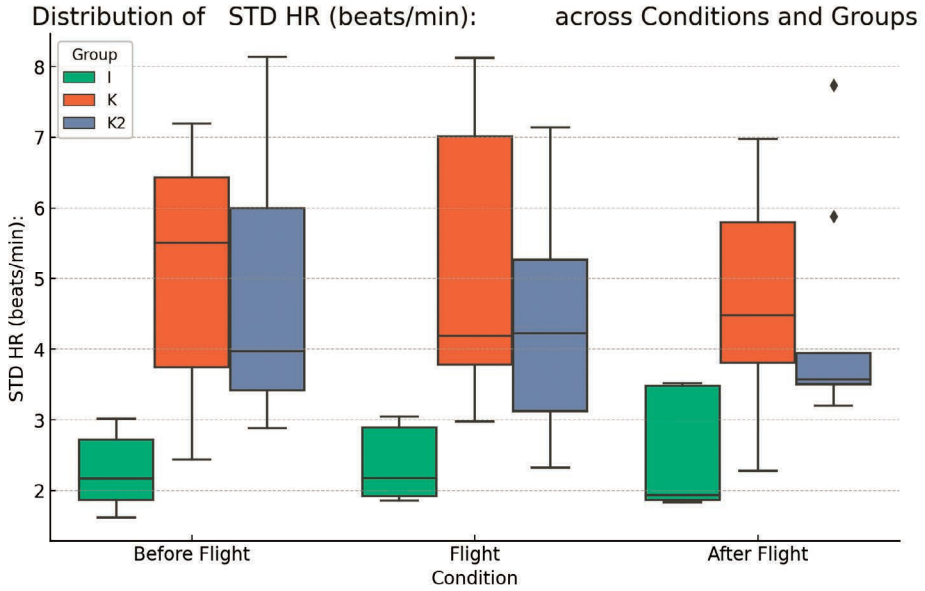


Fig. 5. Standard deviation of heart rate across groups and conditions as mean±SD in beats /min. Abbreviations: STD HR – standard deviation of heart rate; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

(M = 75 bpm, $p < 0.01$). Group K2 showed partial improvement (M = 90 bpm).

- During flight – mean HR peaked in Group K (M = 105 bpm), followed by Group K2 (M = 95 bpm) and Group I (M = 85 bpm).
- Post-flight – Group K showed slower HR recovery (M = 95 bpm) compared to Group K2 (M = 85 bpm) and Group I (M = 70 bpm, $p < 0.01$).

▸ Minimum (min) HR

Fig. 3 highlights the min HR across conditions.

- Pre-flight – Group K exhibited higher min HR (M = 80 bpm) compared to Group I (M = 70 bpm, $p < 0.05$). Group K2 showed intermediate values (M = 75 bpm).
- During flight – min HR values increased slightly, with Group K and K2 maintaining higher levels (M = 80 bpm) compared to Group I (M = 70 bpm).
- Post-flight – min HR for Group K remained elevated (M = 78 bpm), while Group K2 recovered closer to Group I (M = 65 bpm).

Group K exhibited higher min HR across phases, with Group K2 showing recovery toward Group I levels.

HRV parameters:

▸ Mean RR interval (mean RR):

The mean RR intervals reflect the time between heartbeats and are inversely related to HR (Fig. 4).

- Pre-flight – Group I exhibited the highest mean RR (M = 800 ms), while Group K had the lowest (M = 600 ms, $p < 0.01$). Group K2 showed intermediate values (M = 700 ms).
- During flight – mean RR decreased for all groups, showing the most significant reduction (M = 580 ms) in Group K, indicating higher stress.
- Post-flight- Group K2 demonstrated partial recovery (M = 650 ms) but remained lower than Group I (M = 800 ms).

Group K showed significantly lower mean RR, indicating higher heart rate. Group K2 displayed partial recovery.

▸ Standard deviation of HR (STD HR), an indicator of HRV, is presented in Fig. 5.

- Pre-flight – Group I exhibited the lowest STD HR (M = 2 bpm) compared to Group K (M = 7 bpm), $p < 0.01$).
- During flight – STD HR variability remained lowest in Group I (M = 2 bpm), while Group K2 showed higher variability (M = 5 bpm) but still below Group K levels (M = 7 bpm).
- Post-flight – Group K2 showed improved HR variability (M = 4 bpm), approaching Group I values.

STD HR was lowest in Group K2 after flight, showing significant improvements in variability, as compared to Group K.

▸ Very Low Frequency (VLF) Power

The VLF power (log) reflects longer-term HRV regulation and is shown in Fig. 6.

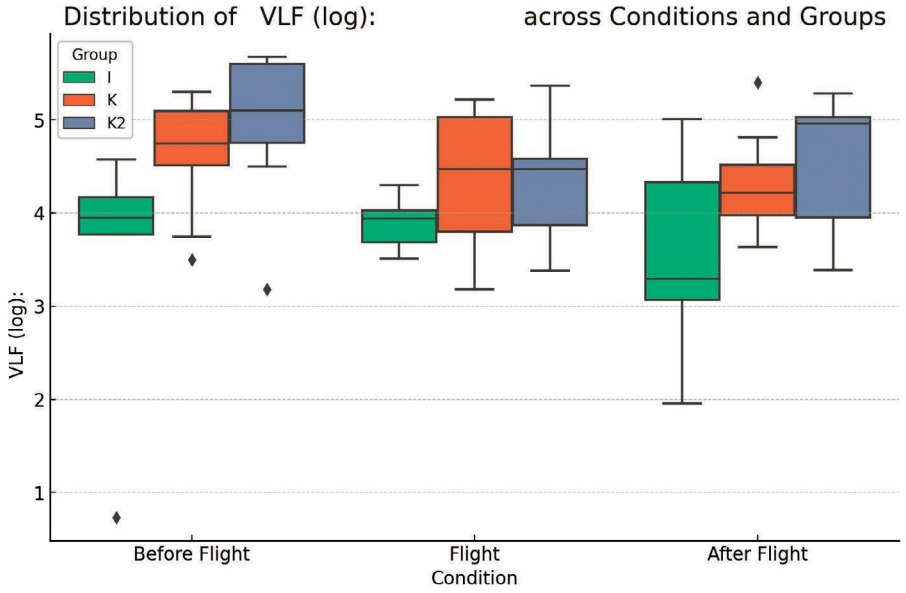


Fig. 6. Very low frequency power across groups and conditions as mean±SD in log.
Abbreviations: VLF – very low frequency power; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

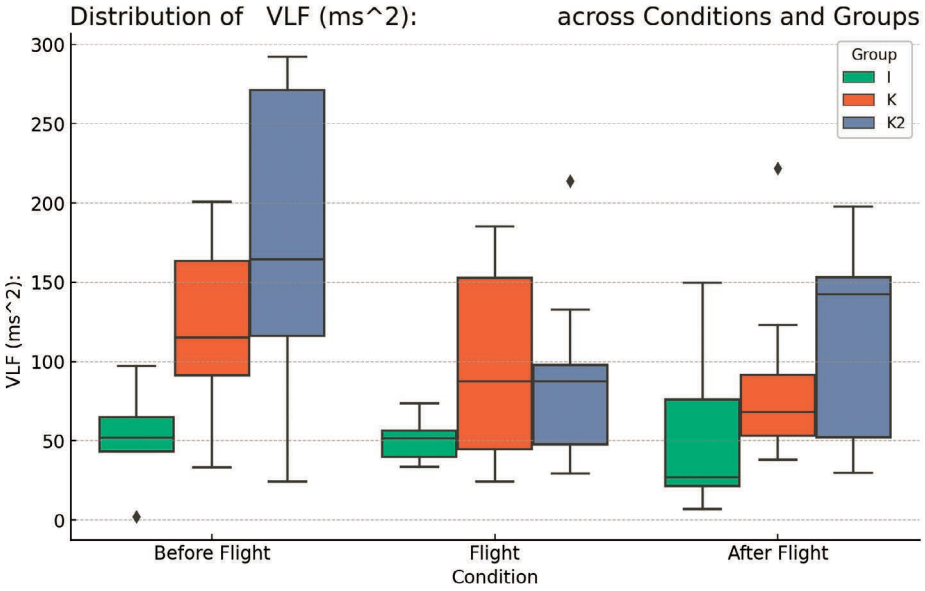


Fig. 7. Very low frequency power across groups and conditions as mean±SD in ms².
Abbreviations: VLF – very low frequency power; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

- Pre-flight – Group I exhibited lower VLF power (M = 4 log units) compared to Group K (M = 4.8 log units, $p < 0.01$), and Group K2 (M = 5 log units, $p < 0.01$).
- During flight – VLF power decreased across all groups, with Group K remaining the most elevated.
- Post-flight – Group K demonstrated recovery in VLF power, approaching Group I values.

Group K showed higher VLF power across all conditions, indicating prolonged sympathetic activation.

- The VLF power (ms²) trends are presented in Fig.7.
  - Pre-flight – Group K exhibited higher VLF values (M = 150 ms²) compared to Group I (M = 50 ms², $p < 0.01$). Group K2 demonstrated greater variability (M = 200 ms², $p < 0.01$).
  - During flight – VLF power decreased across all groups but remained elevated in Group K.

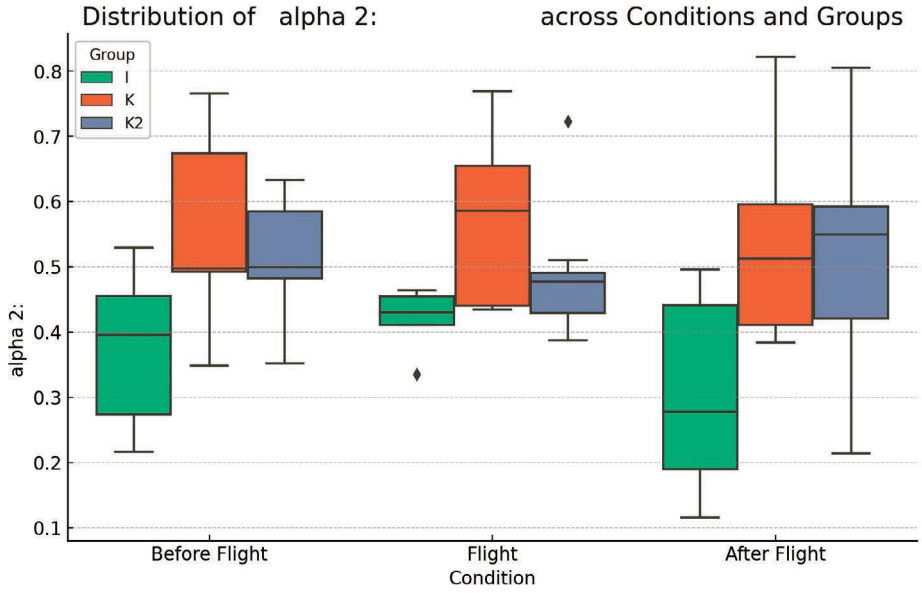


Fig. 8. Heart rate variability alpha 2 Parameter across groups and phases as mean±SD.
Abbreviations: HRV alfa 2 – heart rate variability alpha 2 parameter; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

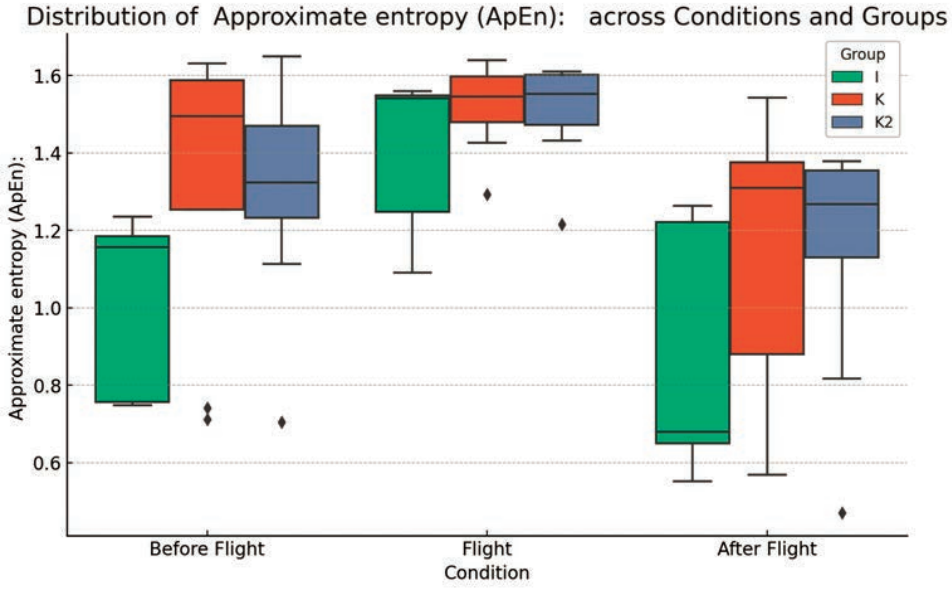


Fig. 9. Approximate entropy across groups and phases as mean±SD.
Abbreviations: ApEn – approximate entropy; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

- Post-flight – Group K2 displayed partial recovery, with values approaching Group I.

VLF power was significantly elevated in Group K, while Group K2 demonstrated improvements toward Group I levels.

▸ HRV alpha 2 parameter

The alpha 2 parameter, reflecting long-term correlations in HRV, was analyzed across groups and phases (Fig. 8).

- Pre-flight – Group I had the highest alpha 2 values (M = 0.80), indicating stable autonomic regulation. Group K showed significantly lower values (M = 0.50, $p < 0.01$), while Group K2 exhibited intermediate levels (M = 0.65).
- During flight – Group K experienced further suppression of alpha 2 (M = 0.40), reflecting greater autonomic imbalance under stress. Group K2 showed improved alpha 2 levels (M = 0.60), though not reaching Group I levels (M = 0.75).

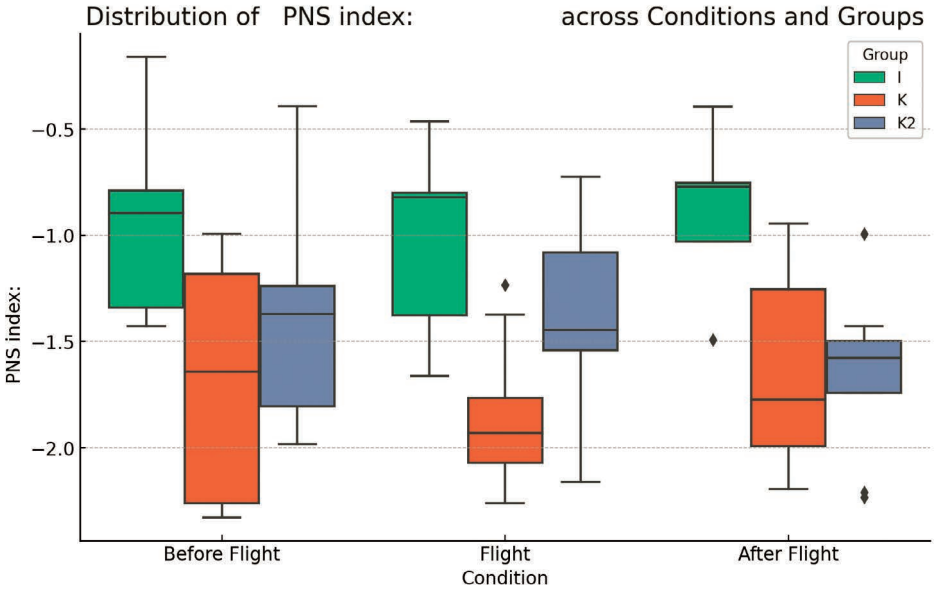


Fig. 10. Parasympathetic nervous system index across groups and phases as mean±SD.
Abbreviations: PNS Index – parasympathetic nervous system index; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

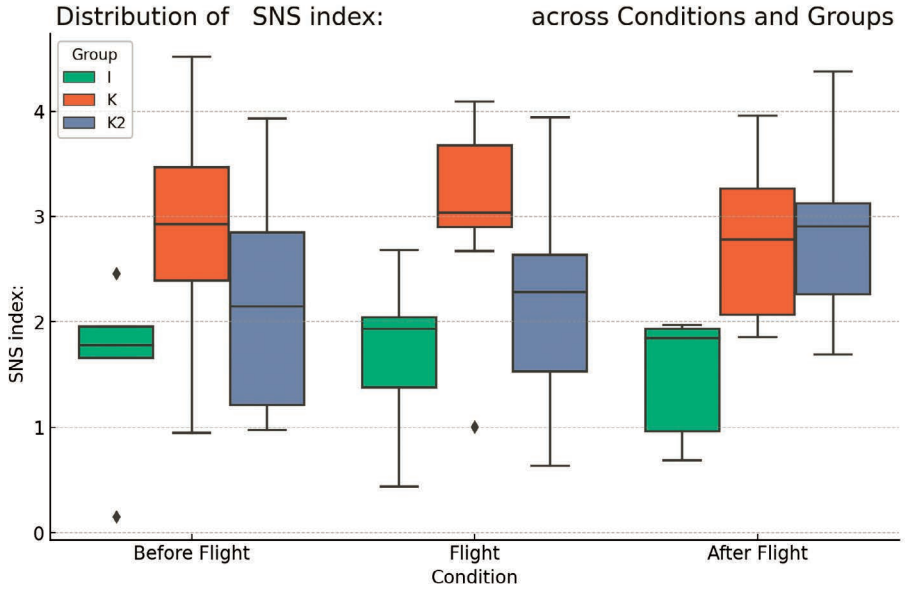


Fig. 11. Sympathetic nervous system index across groups and phases as mean±SD.
Abbreviations: SNS Index – sympathetic nervous system index; I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

- Post-flight – Group K2 demonstrated significant recovery (M = 0.70) compared to Group K (M = 0.45, $p < 0.01$), approaching Group I values (M = 0.78).

Group K demonstrates consistently higher alpha 2 values, while Group K2 shows improvement, approaching the stability observed in Group I.

▸ Approximate entropy (ApEn).

Approximate entropy (ApEn) quantifies HR complexity and adaptability, with higher values indicating greater autonomic flexibility (Fig. 9).

- Pre-flight – Group K exhibited the highest ApEn values (M = 1.6), while Group I had significantly lower values (M = 0.8). Group K2 showed intermediate values (M = 1.2) – $p < 0.01$.
- During flight – ApEn values increased for all groups due to the demands of flight. Group

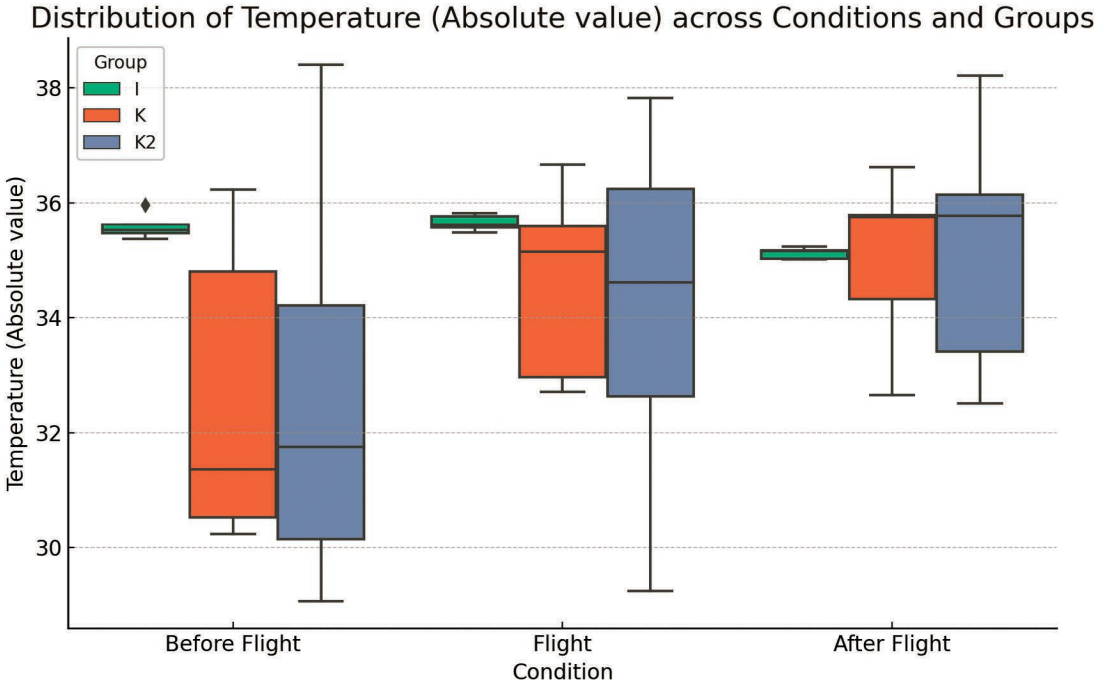


Fig. 12. Forehead temperature across groups and phases as mean±SD in degrees of Celsius. Abbreviations: I – pilot instructors; K – first-year pilot students beginning their training; K2 – the same experienced pilot students, after completing 50 flights

K showed minimal complexity, whereas Group I maintained higher ApEn (M = 1.4), reflecting their better autonomic balance ($p < 0.01$).

- Post-flight – Group K demonstrated near-complete recovery (M = 1.3), approaching Group I levels (M = 1.0, $p = 0.08$), while Group K2 remained significantly lowering (M = 1.1).

Group K demonstrates consistently higher HR complexity. Group K2 shows significant improvement, nearing the levels of Group I, while Group K lags behind.

ANS indices:

▸ PNS index

The PNS index, reflecting parasympathetic tone, varied significantly across groups and conditions (Fig. 10).

- Pre-flight – Group I had the highest PNS index (M = –0.5), significantly higher than Group K (M = –2.2, $p < 0.01$).
- During flight – all groups exhibited suppression of PNS activity, significantly lower value had Group K (M = –2.0), $p < 0.01$, as compared with Group I maintaining relatively higher levels (M = –1.0).
- Post-flight – Group I recovered to baseline levels (M = –0.3), while Group K2 demonstrated moderate recovery (M = –1.0) compared to Group K (M = –1.8, $p < 0.05$).

Group K exhibits consistently suppressed parasympathetic activity. Group K2 shows improvement, but Group I demonstrates the fastest recovery.

▸ SNS index

The SNS index, reflecting sympathetic activity and stress, showed the following trends (Fig. 11):

- Pre-flight – Group K exhibited the highest SNS activation (M = 3.2), significantly higher than Group I (M = 1.8, $p < 0.01$). Group K2 demonstrated intermediate values (M = 2.5).
- During Flight – SNS activation peaked in Group K (M = 3.8), followed by Group K2 (M = 3.0) and Group I (M = 2.0).
- Post-flight – Group I rapidly returned to baseline levels (M = 1.5), while Group K2 demonstrated improved recovery (M = 2.2) compared to Group K (M = 3.0, $p < 0.05$).

Thermoregulation (forehead temperature variability):

▸ Temperature variability, reflecting thermoregulatory control, was highest in Group K across all phases (Fig. 12):

- In the pre-flight phase, Group K exhibited the lowest forehead temperature values (M = 31.5°C) compared to Group I (M = 35.5°C, $p < 0.01$).
- During flight – Group K displayed the greatest reduction (M = 30.5°C) compared to Group I (M = 34.0°C, $p < 0.01$) and Group K2 (M = 32.0°C).

- In the post-flight phase, Group I demonstrated the fastest return to baseline forehead temperature (M = 35.6°C).

Group K shows significant temperature instability across all phases, whether Group K2 demonstrates improvement in thermoregulatory control.

Discussion

The findings underscore the critical role of experience in shaping stress regulation, autonomic control, and recovery in aviation settings.

The HR results highlight significant distinctions in autonomic regulation and stress resilience. Novice pilots (Group K) exhibited the highest mean HR, max HR, and min HR values across all phases. They demonstrated heightened physiological stress, anticipatory arousal, and delayed recovery[12,18]. Experienced pilots (Group I) maintained stable HR parameters, reflecting superior autonomic regulation and stress resilience, and recovered rapidly across phases[19]. Intermediate Group (Group K2) showed significant HR improvements after 50 flights, supporting the role of training in enhancing stress adaptation and reducing autonomic strain[20]. These findings align with prior research showing that repeated stress exposure improves autonomic regulation, lowers HR responses, and enhances parasympathetic recovery[3,21].

The HR findings suggest practical applications for optimizing pilot training programs: monitoring of HR metrics can serve as indicators of stress reactivity and recovery delays, helping identify stress-prone individuals during training; gradual exposure to flight stressors, combined with stress-management techniques (e.g., biofeedback and mindfulness), can improve autonomic balance and recovery; it can guide training progression, ensuring that novice pilots achieve sufficient autonomic stability before advancing to more complex tasks[20,22].

HRV parameters, including mean RR, STD HR, VLF (log), VLF (ms^2), ApEn and alpha 2 values provide comprehensive insights into autonomic regulation, including parasympathetic activity, sympathetic dominance, and overall stress responses during flight.

The findings from HRV parameters highlight the following: novice pilots demonstrated reduced HRV (lower mean RR, STD HR, ApEn, and alpha 2), reflecting increased sympathetic activation, reduced HR complexity, and poor recovery. Experienced pilots (Group I) exhibited higher HRV, reflecting balanced autonomic regulation, higher HR complexity, and faster recovery under all flight conditions. Intermediate Group (Group K2) showed significant improvements in all HRV parameters, including ApEn and Alpha 2, demonstrating progressive autonomic adaptation after repeated flight exposure. These results emphasize the importance of HRV parameters in monitoring stress regulation and recovery. HRV metrics can serve as biomarkers to identify stress-prone pilots and evaluate the effectiveness of training programs in enhancing autonomic resilience[3,9].

We examined the ANS indices, specifically the PNS index, the SNS index, and the LF/HF ratio, across the three flight conditions (pre-flight, during flight, and post-flight) for the three pilot groups. These indices provide essential insights into autonomic regulation, stress reactivity, and recovery in pilots of varying experience levels.

The PNS index reflects the activity of the PNS, which is critical for rest, recovery, and autonomic balance. Higher values indicate greater parasympathetic dominance, reflecting a relaxed physiological state and efficient recovery[3].

The analysis of ANS indices highlights significant differences in autonomic regulation between groups: novice pilots (Group K) displayed heightened SNS activation, reduced PNS activity, and elevated LF/HF ratios across all phases, and showed slower recovery post-flight, indicating prolonged sympathetic dominance. Experienced pilots (Group I) maintained balanced autonomic modulation, with lower SNS indices, higher PNS indices, and lower LF/HF ratios across all phase, and demonstrated efficient recovery post-flight, reflecting superior autonomic flexibility and resilience. Intermediate group (Group K2) exhibited significant improvement in autonomic modulation after 50 flights, with reduced SNS activation, improved PNS recovery, and lower LF/HF ratios compared to Group K. Despite improvements, autonomic regulation in Group K2 did not fully match the stability observed in Group I.

These findings emphasize the critical role of experience and training in autonomic regulation. Monitoring ANS indices can help identify pilots with heightened stress responses and delayed recovery, enabling targeted interventions to improve autonomic balance and stress resilience[3,5,9].

Forehead temperature reflects aspects of thermoregulation and peripheral blood flow, both of which are influenced by ANS activity, particularly the SNS[24].

The results of forehead temperature analysis provide valuable insights into autonomic stress responses and recovery mechanisms in pilots: novice pilots showed significant reductions in forehead temperature during pre-flight and flight phases, reflecting heightened sympathetic activation and vasoconstriction due to stress, and exhibited delayed recovery

post-flight, indicative of prolonged sympathetic dominance. Experienced pilots maintained relatively stable forehead temperature across all phases, demonstrating superior autonomic regulation and stress resilience, and showed rapid post-flight recovery, highlighting efficient parasympathetic activation. Group K2 demonstrated improvements in thermoregulation after 50 flights, with partial stabilization of forehead temperature during flight and post-flight phases, and despite progress, did not fully reach the levels of Group I, suggesting the need for continued exposure and stress adaptation training. These findings align with existing literature that links peripheral temperature to sympathetic activation during stress[24,25]. Temperature, as a thermoregulatory indicator, can serve as a non-invasive biomarker for monitoring stress responses and autonomic recovery in pilots[9,16].

The analysis of forehead temperature offers practical applications for pilot training and stress monitoring:

- Stress assessment – forehead temperature can be used as a real-time stress marker during training and operational flights, helping to identify pilots with heightened stress responses.
- Improving stress recovery – training interventions such as biofeedback**,** breathing techniques, and progressive exposure to stressors can help mitigate sympathetic over activation and improve thermoregulation in novice pilots[3,21].
- Performance optimization – monitoring temperature trends can inform training protocols ensuring pilots achieve autonomic stability and stress resilience before advancing to more complex flight operations.

These results reinforce the importance of monitoring thermoregulation as a physiological marker of stress and autonomic control during pilot training and flight operations.

The results highlight the profound impact of flight experience on physiological stress responses and autonomic regulation:

- Experienced pilots (Group I) consistently demonstrated lower HR values, higher HRV metrics, and efficient stress recovery, balanced sympathetic and parasympathetic nervous system activity, reflected in ANS indices, superior thermoregulation, indicating stable vasomotor control under stress.
- In contrast, novice pilots (Group K) exhibited heightened physiological arousal, suppressed HRV, and delayed autonomic recovery, particularly during pre-flight and post-flight phases. These responses reflect increased sympathetic dominance, reduced parasympathetic activity, and limited stress resilience.
- Students after 50 flights (Group K2) showed clear signs of autonomic adaptation, with improvements in HR, HRV, ANS indices, and thermoregulation. However, their responses did not yet fully match the levels observed in experienced instructors, suggesting that continued exposure and advanced training are necessary to achieve optimal autonomic regulation.

The findings of this study offer valuable implications for pilot training and stress management programs:

1. Monitoring Stress and Recovery:

- Continuous physiological monitoring of HR, HRV, and thermoregulation can identify pilots experiencing heightened stress and delayed recovery.
- HRV metrics such as mean RR, ApEn, and LF/HF ratio serve as reliable indicators of autonomic balance and stress resilience.

2. Targeted Stress Management Interventions:

- Implementing stress management strategies, such as biofeedback, breathing exercises, and progressive relaxation techniques, can help novice pilots regulate sympathetic activation and enhance parasympathetic recovery.
- Regular exposure to real-world flight scenarios with incremental workload increases can improve stress tolerance and autonomic flexibility.

3. Progressive Training Programs:

- Structured flight training programs should include gradual exposure to flight-related stressors, focusing on building mental resilience and autonomic stability in novice pilots.
- Advanced pilots can benefit from tailored interventions to further optimize autonomic balance and stress recovery.

While this study provides significant insights, certain limitations must be acknowledged:

- The sample size was relatively small, particularly for Group I, which may limit the generalizability of findings.
- Environmental factors such as cabin conditions, noise, and temperature were not explicitly controlled and may have influenced thermoregulatory responses.
- Longitudinal studies involving extended flight exposure would help further validate the observed autonomic adaptations over time.

Future research should focus on:

1. Exploring gender differences in stress responses among pilots.
2. Investigating the long-term effects of advanced stress-management interventions.
3. Expanding the sample size to include pilots across diverse aviation disciplines and experience levels.

This study contributes to the growing body of literature on pilot physiology and stress adaptation by:

- Identifying key autonomic markers that distinguish novice, transitioning, and experienced pilots.
- Providing evidence for the role of experience in improving stress regulation during flight conditions.
- Offering insights into training interventions to enhance parasympathetic recovery, reduce sympathetic dominance, and accelerate autonomic adaptation.

Conclusions

This study underscores the pivotal role of experience in modulating physiological stress responses and autonomic regulation among pilots. Novice pilots experience pronounced sympathetic activation, reduced HRV, and impaired recovery, particularly during pre-flight and flight phases. However, cumulative flight exposure significantly improves these parameters, as evidenced by the progress observed in Group K2. Experienced pilots demonstrate a highly adaptive autonomic response, with balanced sympathetic-parasympathetic activity, stable HRV metrics, and efficient thermoregulation under stress. These findings emphasize the need for structured training programs and stress management interventions to optimize autonomic regulation, enhance pilot performance, and ensure flight safety. By integrating physiological monitoring into pilot training programs, aviation professionals can identify stress-prone individuals, implement targeted interventions, and foster the development of stress resilience – essential for safe and effective flight operations.

Author contributions

S.R.V. and B.K.R. participated in the conception and design of the study, analysis of the data and article writing; S.R.V.; V.R.M., L.V.T. and I.I.M. recorded the data and made computer analysis of recorded parameters; P.T.T made statistical analysis and presented figures; U.G.R. ensured organization of the flights of the studied groups of persons.

Compliance with Ethics Requirements:

"The authors declare no conflict of interest regarding this article"

"The authors declare that all the procedures and experiments of this study respect the ethical standards in the Helsinki Declaration of 1975, as revised in 2008(5), as well as the national law. Informed consent was obtained from all the patients included in the study"

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