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PILOT FATIGUE DETECTION VIA SPEECH ANALYSIS, ELECTROCARDIOGRAM AND PHOTOPLETHYSMOGRAM

PHOEBE ANN WANJIRU MAINA*, ZHANG SHAOJIE*

*College of Automation Engineering

Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Email: phoebemaina2020@outlook.com

Email: zhangsj@nuaa.edu.cn

Abstract

Fatigue plays a dangerous role in transport safety especially for the pilots since they work longest. About 68-91% of commercial Airline pilots have reported in-flight fatigue. Civil aircrew frequently experience loss or disturbance of sleep, trans-meridian flight, irregular work-rest cycles. In as much as aviation technology has exponentially evolved, the basic need for ample rest when it comes to the personnel still remains. Clear links are established between circadian rhythm and accidents that occur during the Window Of Circadian Low (WOCL), even after adjustment for traffic volume. In this paper, as per the title, the fatigue detection and measurement methods; speech analysis, photoplethysmography and electrocardiography will be analyzed. The in-depth step-by-step methodology and data analysis will also be discussed.

Keywords: fatigue, drowsiness, heart rate variability, psycho-physiological.

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I. Introduction

FATIGUE

Fatigue is the general term used to describe physical and/or mental weariness which extends beyond normal tiredness. It is associated with sleep loss and shift work for the most part. It often leads to reduced or total lack of attention, carelessness and ultimately inefficiency.

ICAO, defines fatigue as a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties.

Based on research, fatigue can be mainly classified as either physical or mental. Physical fatigue concerns the inability to exert force with one's muscles to the degree that would be expected while mental fatigue, which may include sleepiness, concerns a general decrease of attention and ability to perform complex, or even quite simple tasks with efficiency.

Civil aircrew frequently experience loss or disturbance of sleep, trans-meridian flight, irregular work–rest cycles. In as much as aviation technology has exponentially evolved, the basic need for ample rest when it comes to the personnel still remains. Fatigue could easily lead to problems such as reduction in operational ability, misjudgment, flight illusions, etc., and even cause serious flight accidents.

Types of Fatigue

Transient fatigue is acute fatigue brought on by extreme sleep restriction or extended hours awake within 1 or 2 days.

Cumulative fatigue is fatigue brought on by repeated mild sleep restriction or extended hours awake across a series of days.

Circadian fatigue refers to the reduced performance during nighttime hours, particularly during an individual's "window of circadian low" (WOCL) (typically between 2:00 a.m. and 05:59 a.m.).

The relationship between Fatigue and Mental Health.

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Research has proved time and again that human well-being and fatigue are directly related. The longer the work hours, the higher the fatigue which prompts poor well-being. This also affects the Mental Health of the personnel as elaborated below;

Pilot Fatigue

[1]Fatigue plays a dangerous role in transport safety especially for the pilots since they work longest.

About 68-91% of commercial Airline pilots have reported in-flight fatigue.

A study showed;

Carriers	**Approved Flying hours / duty day**
European-based	13 hours
U.S.-based	9 hours (two-pilot crew)
U.K.-based	13 hours
China-based	14 hours

O'Hagan AD, Issartel J, Nevill A, Warrington G. Flying Into Depression. Workplace Health Saf. 2017 Mar;65(3):109-117. doi: 10.1177/2165079916659506. Epub 2016 Sep 28. PMID: 27578874.

[2]A 13-hour work day can be exhausting and draining no matter your role.

Cumulative sleep deprivation, is one of the factors escalated by pilots crossing time zones. Clear links are established between circadian rhythm and accidents with peaks at 02.00, 06.00 and 16.00h, even after adjustment for traffic volume. Sleepiness, micro-sleeps, short-term memory impairment, reduced motivation and ineffective communication are some of the effects resulting from sleep deprivation, just to name a few. Continued sleep deprivation may eventually result to gastrointestinal issues among pilots.

II.OVERVIEW - FATIGUE DETECTION TECHNOLOGY

Many studies have focused on exploring effective methods and psycho-physiological indicators for detecting and monitoring fatigue. However, some fatigue indicators showed discrepancies among simulator

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and field studies, due to the vagueness and lack of specificity of fatigue, which hinders the development of fatigue monitoring devices.

Fatigue detection technologies are tools that can be effectively incorporated into overall safety management approaches. The table below shows contributors, expressions, and measurement method of fatigue.

Contributors to fatigue	Expressions of fatigue	Method of Measurement
• Sleep • Circadian disruption • Stress	• Eye • Brain • Heart • Blood vol. changes • Simple Cognition • Complex Cognition	• Actigraphy • Actigraphy • Ecological Momentary Assessment (EMA) • Saccadic velocity • Electroencephalography (EEG) • Electrocardiography (ECG) • Photoplethysmogram (PPG) • Psycho-motor Vigilance Task (PVT) • Flight Simulator

Independent research on Pilot Fatigue Measurement by the Netherlands Aerospace Centre

Pilot fatigue can be measured via:

1. Photoplethysmogram (PPG) data collection through aviation headsets[3]
2. Electrocardiogram signals[3]
3. Speech Analysis[4]

4. Eye metrics [5]
5. Brain Function/Activity [6]

In this paper, as per the title, the first three methods will be analyzed. [5]Eye metrics method is definitely worth mentioning since it's a huge contribution to technology when it comes to combating fatigue, but won't be discussed in depth.

Brief Overview of Method 1, Method 2 & Method 3

Method 1: Photoplethysmogram (PPG) data collection

[7]PPG, mainly used for heart rate monitoring, is an inexpensive, non-invasive but optical technique that reflects beat to beat relative blood volume changes in peripheral tissues usually on the forefinger or earlobe. Structure-wise, PPG contains an infrared emitter and a detector inside a probe which is responsible for the peripheral blood flow detection.

Theamount of infrared light reflected to the detector determines the amount of blood flowing to the tissue at any time. The brighter the infrared light the higher the blood volume and vice versa.

Method 2 - ECG Electrocardiogram

[7]ECG Method is used to assess one's ANS, Autonomic Nervous System, otherwise known as Reflect Psycho-physiological State.

The Reflect Psycho-physiological state changes upon a fluctuation in stress, fatigue and drowsiness.

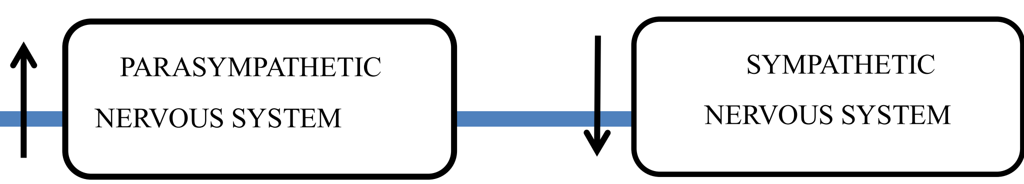
The two nervous systems are impacted as follows;

An increase in the *Parasympathetic Nervous System* and decrease in the Sympathetic Nervous System, indicate Stress/Fatigue/Drowsiness.

An increase in the *Sympathetic Nervous System* and decrease in the Parasympathetic Nervous System, indicate Wakefulness. ***(Furman et al., 2008; Michail et al., 2008; Vicente, Laguna, Bartra, & Bailon, 2011)***

Elaboration;

Stress, Fatigue & Drowsiness



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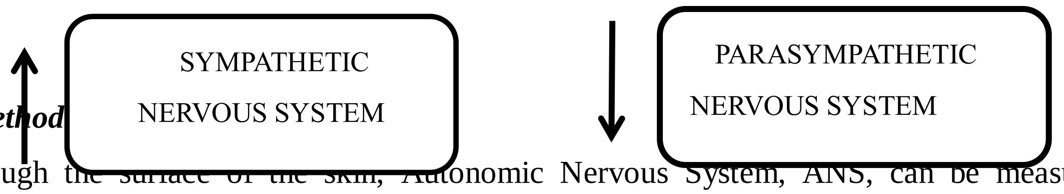
Wakefulness



Method

Through the surface of the skin, Autonomic Nervous System, ANS, can be measured by Heart Rate Variability, HRV, which is a non-invasive method to stipulate fatigue and/or drowsiness.

[8]The Mean Time Delay is calculated by dividing the sum of all values by the number of total values. Therefore;

$$[8]\text{Mean Time Delay} = \frac{\text{ECG. R wave} + \text{PPG foot to rest}}{n}$$

For thumb, ≥ 180 to $260 \leq$ (ms)

For earlobe, ≥ 125 to $155 \leq$ (ms)

For toe, ≥ 180 to $330 \leq$ (ms)

[9]The Median Time Delay between ECG Peak and PPG Peak, that is;

$$[9]\text{Pulse Arrival Time (PAT) peak at rest} =$$

For thumb, 436(ms)

For earlobe, 397(ms)

For toe, 515(ms)

Note: [7]As it will be further expatiated on in the Methodology, the Heart Rate Variability, HRV, results obtained by PPG and ECG are found to be correlated. Thus, ECG may be used in place of PPG and vice versa.

Method 3: Speech Analysis

[4]Audio recording analyses provided objective measures of the temporal organization of speech, such as hesitations, silent pauses, prolongation of final syllables and syllable articulation rate.

A backdated study of the communication between an air traffic control tower and a pilot just before a deadly mishap was used as the case study. The main aim as to verify whether there were any variations in the phonatory aspects and speech of the 45-year-old Brazilian pilot, with no prior history of pre-existing illness, who complained of fatigue and sleepiness just before the accident. As a result of technical error, the aircraft tilted down with no time to recover, just minutes before landing. Beware that this was a fully functional aircraft which had been cleared before take-off, as per the regulations.

The in-depth accident analysis performed by the Center for Investigation and Prevention of Aeronautical Accidents, CENIPA, indicated that sleepiness and fatigue most likely contributed to the accident. The audio recordings provided for analysis contained the dialogues of the pilot:

1) off-days (private);
2) 35 hours prior to the crash
3) in-flight.

The speech samples that were analyzed and compared were from the;

1) data recorded 35hours before the air crash
2) data collected about 1hours before and during the accident

The method of analysis used and the exact steps will be discussed in a later chapter.

II. Research Objective

The noise and vibration of the cabin, air pressure changes, long-haul flights, high-load work, circadian rhythm disturbance, and lack of sleep lead pilots to often be in a state of fatigue. Therefore, how to identify the real-time fatigue state of pilots quickly and accurately has become a scientific problem that needs to be addressed urgently hence aiding in aviation safety. Identifying, let alone accurately measuring pilot fatigue is highly theoretical and warrants more research.

This paper will review pre-existing detection technologies, the methodology used in their development, functionality, usability, and limitations (if any).

III. Methodology

This chapter involves an in-depth step-by-step analysis of the three methods introduced above; PPG, ECG and Speech Analysis.

A. PPG & ECG

*Data:*Heart Rate collected through the chest and earlobe for the ECG and PPG three-lead measurement respectively, was analyzed to determine feasibility of the sensor placement within the physiological confines of a general aviation headset.

The purpose was to examine variability of predicting drowsiness and/or fatigue using aviation headset sourced cardiac signal in flight.

Data Collection

BIOPAC is the proprietary digital teaching device introduced to replace chart reorders and oscilloscopes.

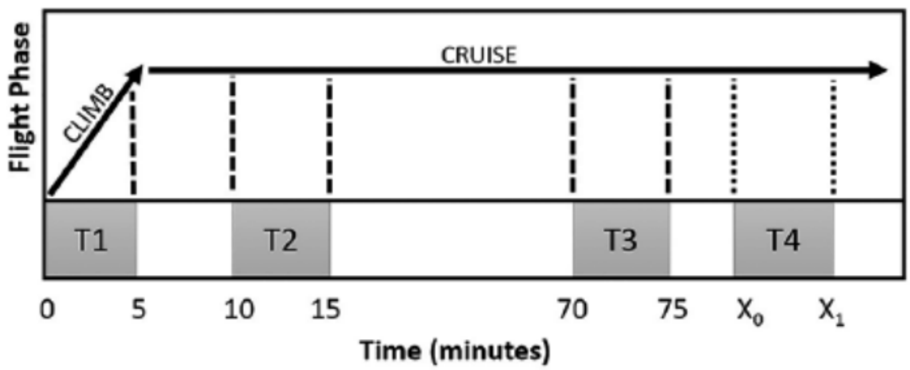
It is used to study cardiovascular systems, muscles, pulmonary function, Autonomic Nervous System (ANS) and the brain. BIOPAC records, analyses, and reports data in a much more efficient way.

In this case, data was collected from 18 FAA certified commercial pilots during WOCL, Window Of Circadian Low between 2:00am and 5:59am. The experiment was conducted in a Piper Seminole fixed base flight simulator for two hours.

Procedure

[3]2 hours of data acquisition with two phases after take-off; phase 1 - climb and phase 2 - cruise.

[3]At phase 2, the pilots were instructed to use autopilot, both vertical and lateral control. This was mainly to maximize the time-frame of the workload; hence increased time-frame with the least amount of workload.



Wilson N, Guragain B, Verma A, Archer L, Tavakolian K. Blending Human and Machine: Feasibility of Measuring Fatigue Through the Aviation Headset. Hum Factors. 2020 Jun;62(4):553-564. doi: 10.1177/0018720819849783. Epub 2019 Jun 10. PMID: 31180741.

[3]The simulation time was as follows:

T1 = 0 - 5 minutes

T2 = 10 - 15 minutes

T3 = 70 - 75 minutes

T4 = x0 - x1, this being the EOG data of each participant.

This is the uniquely defined data produced by Electrooculography.

Note: The simulated scenario did not allow the participants to reach their intended destination.

Data collection was concluded;

1) Within 2.5 hours of flight time, N = 0.

1) When pilot was awakened twice from a 5+ minute sleep more than once.

1) When pilot elected to discontinue.

ECG Data - single channel using Lead 11 Einthoven's Triangle.

PPG Data - single channel PPG sensor on earlobe with the sampling rate of 500Hz using BIOPAC.

T1, T2, T3 and T4 were the periods applied were,

T1 - baseline period (essentially take-off and climb)

T2 - relaxed period (early cruise / activating autopilot)

T3 - hypothesized fatigue period

At this point, the participants were to begin witnessing noteworthy drive for sleep and accumulated sleep deprivation stemming from the day before.

T4 - drowsy period of indisputable levels of fatigue

Long sleep events of each participant were based on EOG Analysis accounting for eye-blink while filtering the periods of blinking. The no eye-blink was signified by;

- Eyes closed
- Eyes partially open but without movement
- Eyes fully open

These 3 signals suggested drowsiness.

The criteria applied in choosing the participants was as follows;

- Age;

  21.8 years $\pm$ 2.6

  22 years $\pm$ 2.5
- 2 females and 16 males.
- The pilots were to take no naps and no caffeinated or energy drinks.
- 18 to 20 hours of awakeness.

Data was collected by the American Psychological Association (APA) Code of Ethics.

Data Processing

[3]*ECG*

QRS Complex is the main spike screen on an ECG.

Q wave - downward deflection following a decline in the P-wave

R wave - upward deflection

S wave - any downward deflection after an R- wave

In Heart Rate Variability Analysis, HRV, from ECG;

Step 1: detect R

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Step 2: determine RRI, RR Intervals

RRI is the duration between two adjacent R peaks in the QRS Complex.

Step 3: calculate HR using RRI

RRI is used to calculate Heart Rate, HR.

Mean HR = Reciprocal of Mean RRI within duration x

that is;

$$[3]\mathrm{Avg.HR} \quad = \frac{60 \ \ \mathrm{beats}}{\mathrm{Avg.RRI} \ \ (s)} \ \ \mathrm{beats/min}$$

PPG

Step 1: determine PAT

Step 2: detect P peak

Step 3: determine PPI, Pulse-to-Pulse Intervals

Step 4: calculate HR using PPI

Statistical Analysis

Step 1: Shapiro-Wilk Test was conducted.

This test is used to determine data normality to ascertain the method of data distribution; that is: parametric or non-parametric.

The findings showed mixed behavior due to limited sample size.

Step 2: As a result, Kruskal-Wallis Test was then applied which is a non-parametric approach used to compare the three or more groups of dependent variables, measured at least on a ordinal level.

Step 3: Bonferroni Correction was applied to test the consequential difference at $\alpha = .05$

The 3 steps were all conducted on *MATLAB.*

B. Speech Analysis

Acoustic speech analysis is the study of the acoustical characteristics of both normal and abnormal speech, involving the physical aspects of spoken language. The most widely used software is known is PRAAT, which aided in syllable identification carried out via Linguistic classification whereas the syllabic division was applied to the phonetic identification.

The established parameters were as follows;

Note: Speech Disfluency is the involuntary disruption in one's speech, such as; repetitions and prolongations.

1) TAT - Total Articulation Time (no disfluencies)
2) TPT - Total Pause Time (includes non-silent disfluencies, such as; silent pauses)
3) TDT - Total Disfluency Time
4) ET - Elocution Time (speech duration)

$$[4]\mathrm{ET} = \mathrm{TAT} + \mathrm{TPT}$$

5) NP - No. of Pauses
6) Average Pause Duration
7) NS - No. of Syllables
8) ER - Elocution Rate

$$[4]\mathrm{ER} = {}^{\mathrm{NS}}/_{\mathrm{ET}}$$

9) AR - Articulation Rate

$$[4]\mathrm{AR} = {}^{\mathrm{NS}}/_{\mathrm{TAT}}$$

10) ND - No. of Disfluencies
11) PD - % Disfluency

$$[4]\mathrm{PD} = \left({}^{\mathrm{ND}}/_{\mathrm{NS}}\right) \times 100$$

Note:

Prolongation (Disfluency) - Normal Syllabic Production = Unreliable TAT

[4]**Examples of acoustic speech measures as analyzed by PRAAT are shown below.**

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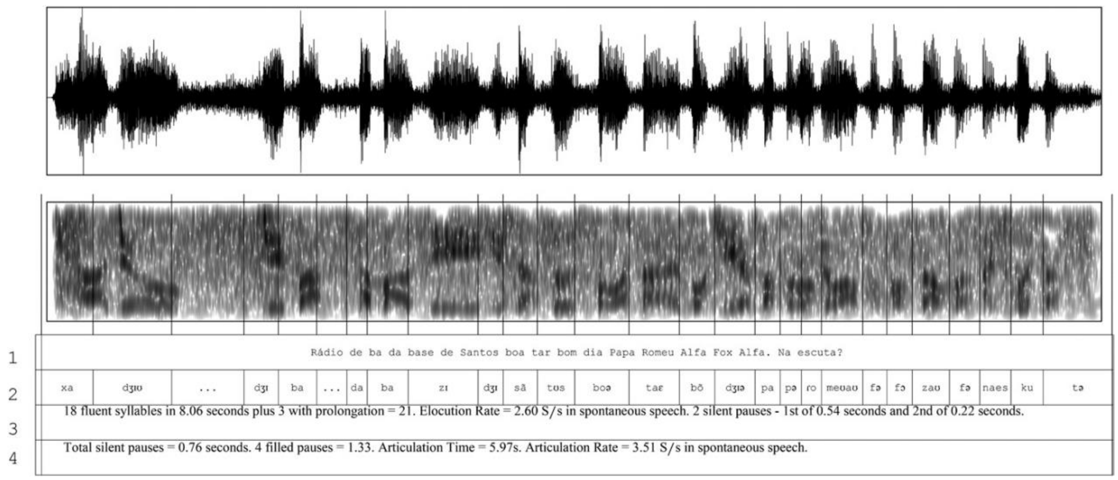

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Step 1 - Syllabic Segmentation

Step 2 - Typology of pauses, including; hesitations, repetitions and unfinished words.

Step 3 - Calculating Percentage of Disfluency

$$PD = (ND/NS) \times 100$$

Step 4 - Normality testing through Kolmogorov-Smirnov normality test

Note: This test produces test statistics which are used to test for normality, as the name suggests. It allows for a degree of freedom parameter.

In this step, dependence was assumed since the speech was from the same speaker.

Step 5 - Correlation Measurements using;

$|r|$ - parametric distribution

$|x|$ - non-parametric distribution

IV. RESULTS

This chapter presents the results obtained from all the 3 methods discussed above, as well as future developments that will enhance the field of fatigue detection objectively.

A. PPG & ECG

To prove correlation, the Person Correlation Coefficient was applied.

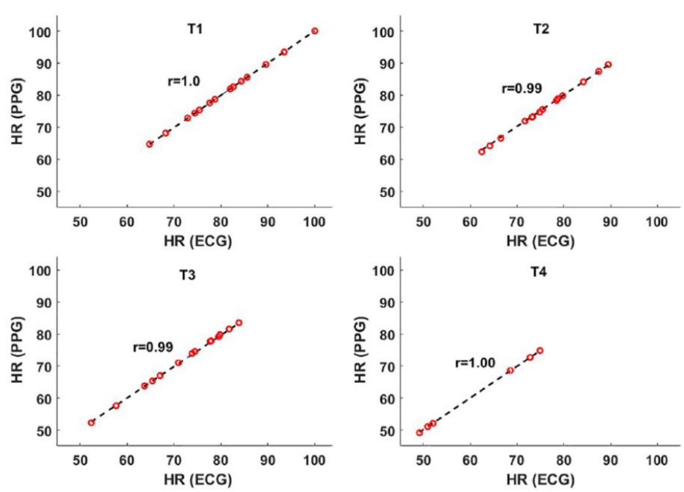
After eliminating the data that did not fit the criteria mentioned in the methodology, the final data set included 14 participants.

Within T1, T2, T3 and T4, change in HR was noted both in ECG and PPG results.

These T periods were applied to test reliability of PPG and ECG in the shift between Alertness and Drowsiness and Fatigue.

HR at all 4 periods was found to have high correlation for both PPG & ECG.

[3]Illustrated below is the Pearson correlation coefficient of HR between ECG and PPG for a representative participant. HR = heart rate; ECG = electrocardiogram; PPG = Photoplethysmogram.



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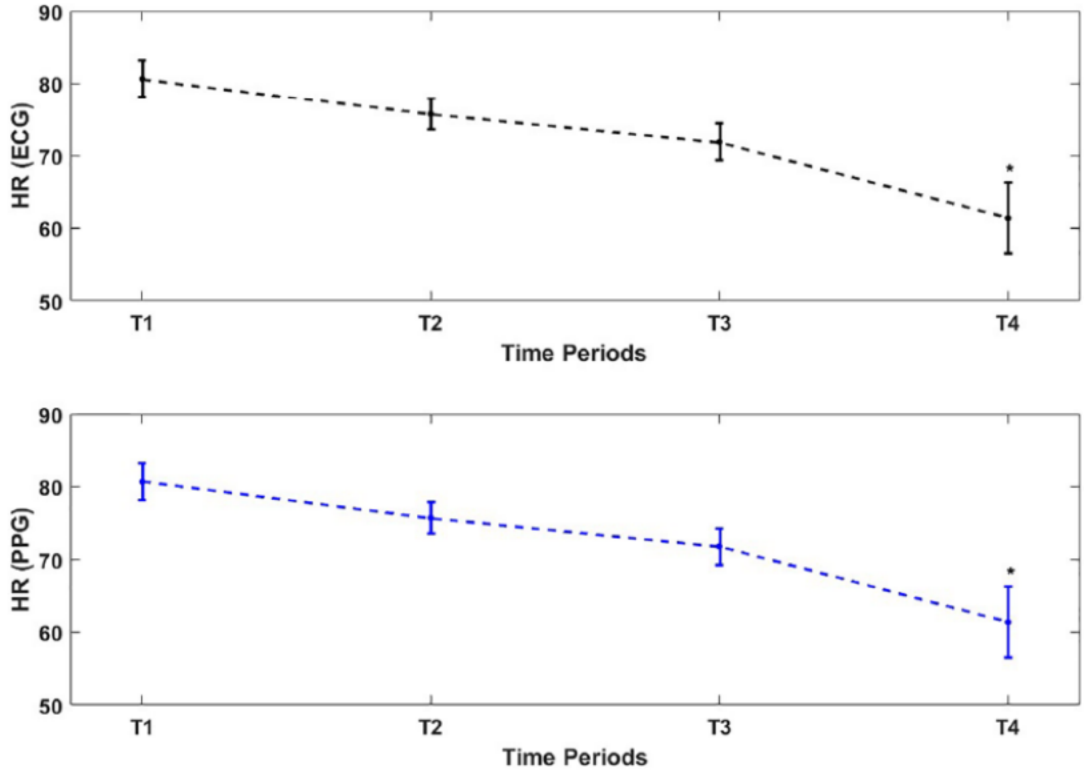
Mean ± SE (HR Trend) show;



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$p < .05$ at T4 compared to T1

Note: there's an insignificant decline between T1 to T2 and T1 to T3.

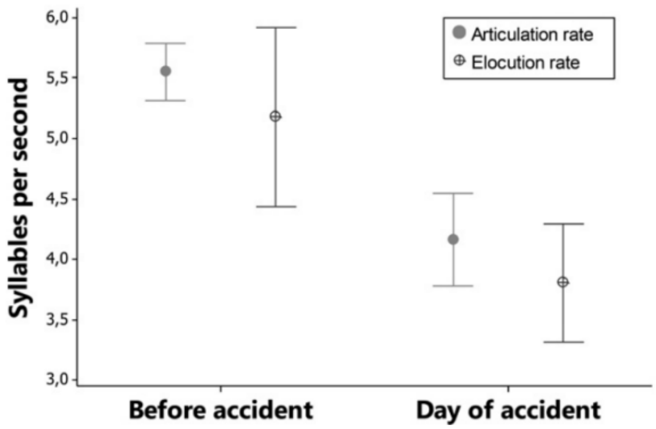
Discussion

Results show high correlation between the ECG and PPG results, therefore suggesting that one can be usec in place of the other.

Correlation of PPG data through the earlobe is feasible and hence an alternative of highly invasive and more complex forms of psycho-physiological data collection.

B. *Speech Analysis*

[4]The key results related to the temporal organization of speech are presented below;



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The day of the accident compared to the 35hours pre-flight, show a decrease in ER and AR. The obtained results were also compared to the Normality patters of spontaneous speech in males of the same dialect (Minas Gerais State, Brazil) which also indicated a decrease.

An increase in %PD ($\%PD = (ND/NS) \times 100$) was noted on the day of the accident. Moreover, an increase in both TPT and NP was also noted.

Correlation Analysis Results

Using the Person's Correlation Coefficient, to determine ER and TDT, the result then was as follows;

$$0.7 \leq |r| < 0.9$$

The correlation was negative.

r = -0.73

P = < 0.001

Note: (r^2) is the coefficient of determination. It is a measure of the proportion of variability in one variable that is explained by the variability of the other.

$r^2 = 0.54$

which means;

$$0.54 \times 100 = 54\%$$

The 54% of ER was explained by TDT.

ER may also have been affected by the other 46% where AR was a parameter, determined to be lower on the day of the air-crash.

NP & NS Results

$$0.3 \leq |x| < 0.5$$

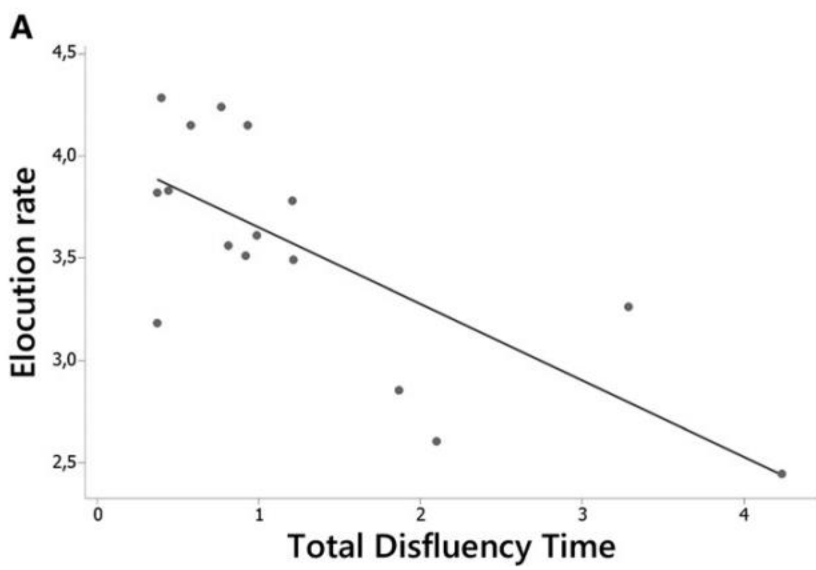
whereby;

$$x = 0.47$$

This shows that the increase in NS was in direct relation to the increase in NP.

As a result, it was concluded that the increase in both NP and NS, lead to an increase in %PD which was consequence by fatigue and sleepiness of the 45-year-old Pilot.

A) Representation of the correlation between the variables Elocution Rate vs. Total Disfluency Time



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B) Representation of the correlation between the variables Number of Pauses vs. Number of Syllables.

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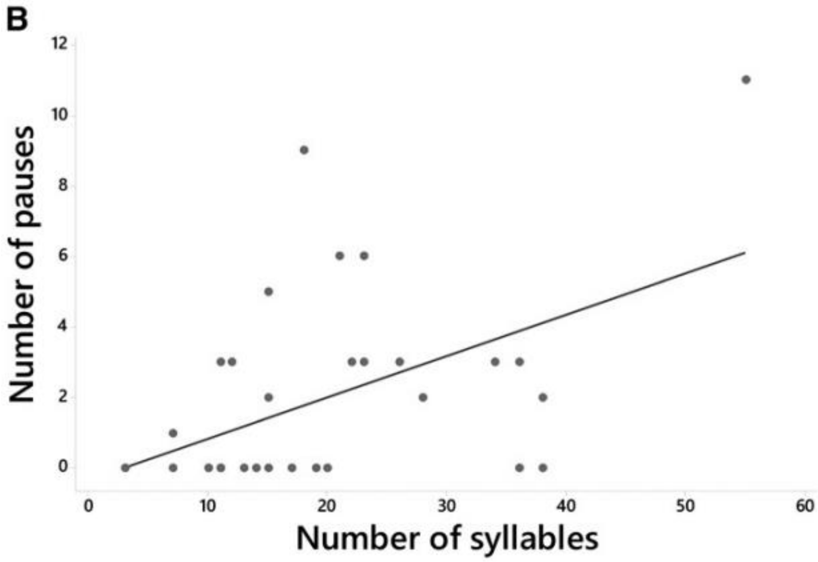

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Lombard Reflex Results

The instinctive tendency of speakers to increase their vocal effort when speaking in loud noise to enhance their audibility is known as the Lombard Effect or Reflex as defined on Wikipedia. This includes; loudness, pitch, rate and duration of syllables to maintain Auditory signal-to-noise of the speaker's spoken words.

The vocal fry and creaky voice happen in low subglottic pressure, while the Lombard effect can only be witnessed in high subglottic pressure.

The changes in temporal speech, hence slowed speech, is an outcome of muscular contraction and the alteration of patterns in neurological speech commands.

In this case, the results show that the change in temporal speech organisation, the increase in %PD and voicing aspects are confirmation that the pilot was indeed experiencing Fatigue and Sleepiness.

C. *DIFFICULTIES ENCOUNTERED*

Data set could be enhanced simply by increasing the number of participants.

Collecting Data during normal wakeful and rest hours of each participant may aid in providing a separate baseline in ECG and PPG Data Collection.

During the experiment. The PPG sensor on the earlobe, required extra adhesive tape to refine connection to the skin as well as decrease involuntary participant movement otherwise known as motion artifact. This may have resulted from low pressure due to the structure of the aviation headset.

Another reason may have been the change in blood volume during each ventricular hypopolarisation at the earlobe. This may result to the reduction in amplitude of the PPG pulsating wave peaks, which in turn cause signal distortions and false HRV results using PPI (due to affected peak detection).

To counter this effect, a slight adjustment in the placement of the PPG sensor should be considered. For example, since the blood rate from the maxillary artery is more reliable, placing the sensor on the upper maxilla could be considered.

Speech analysis though quite reliable in fatigue and drowsiness detection, it is applicable ONLY when verbal communication between the crew and Air Traffic Controllers occurs.

D. *FUTURE DEVELOPMENTS*

Examining feasibility of using a mounted PPG sensor for stress measurement.

[3]Use of ECG combined with advanced HR Signal processing techniques may open up a window of research into the user's psychological state.

[3]According to the results acquired, PPG & ECG can be used interchangeably and yield similar findings. Hence, a properly mounted sensor placed on the earlobe or on the upper maxilla, reliable data indicating fatigue and drowsiness will be obtained.

With additional research to provide the specifics or any other predictions, the overall flight safety is pushed forward by this research.

The significance and consequences of workload on fatigue still warrants further research. There is a knowledge gap when it comes to fatigue detection and management in aviation across different demographics and operations.

Though EASA is already at the forefront of the groundwork on fatigue implications resulting from night duties, the analysis on the effectiveness and proper implementation of the regulations is lacking to say the least.

[5]Psychological based methods as it relates to assessing [6]electrical brain activity and eye movement are indirect, highly invasive, quite difficult to carry out and on some cases less feasible.

[4], [10]Speech analysis for fatigue and drowsiness detection on the other hand, has yielded promising results. The research and analysis conducted in this area can be used to assess pilots before and during flights. This alleviates accidents risks, boosting general aviation safety.

In this area of speech analysis, a few suggestions include;

- Full scale validation studies to determine whether the results can be replicated in other languages.
- Adapting speech recognition techniques to measure Articulation Rate (AR) and Elocution Rate (ER).
- Use of a [10]Voice Activity Detector to detect the pauses and patterns in a speech.
- Automatic Analysis of Elocution Rate (ER), Articulation Rate (AR) and the no. of pauses in a speech can be done in real time.

In conclusion, as per voice quality associated parameters, for example; vocal fry or the Lombard effect, a more in-depth analysis is necessary.

V. CONCLUSION

There is still plenty of room left for research when it comes to Pilot Fatigue Analysis. The already researched and developed techniques such as Speech Analysis via PRAAT, Photoplethysmography and Electrocardiography to monitor the heart-rate through aviation headsets, are a huge victory in the aviation sector and therefore worthy of celebration. Other methods such as Eye metrics have also played a huge role in propelling the industry forward.

As discussed above in future developments, some of the improvements and perhaps other solutions could be discovered later.

ACKNOWLEDGEMENT

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To my amazing family, a big thank you for being the best cheer-leading squad ever. Thank you.

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