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The Impact of Cognitive Fatigue on Airline Pilots Performance

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Abstract

Purpose: Air transport is a highly regulated branch of aviation, but it continues to show occurrences where human error is present. Fatigue is now recognized as a hazard which degrades human performance and can put flight safety at risk. In this regard, the general objective of this study is to assess the impact of cognitive fatigue on airline pilots and how it can contribute to the occurrence of accidents and incidents.

Design/methodology: Three airline pilots participated in the case study. The participants' cognitive fatigue was monitored according to four methods, being two of them of a subjective nature – the sleep diary (SD) and the Samn-Perelli 7-Point Fatigue Scale (SPS), and the other two of an objective nature – the Psychomotor Vigilance Task (PVT) and the actigraphy (actiwatch ReadibandTM 5). During their flight duty periods (FDPs), the pilots' performance was also assessed according to the score delivered by a fatigue management software (FAID®).

Findings: The obtained results allowed to understand whether the pilots are aware of their alertness and to identify factors which affect their performance levels. Between the beginning and the end of each FDP, significant changes were observed concerning the assessment on the SPS scale, the reaction time (RT) and the fatigue score generated by the biomathematical models associated to the technique of the actigraphy and the software FAID®.

Originality/value: The risk of accident or serious error was classified according to the four methodologies used. Thus, it is possible to verify if there is a correspondence between the different scales or if there are scales more conservative (with a higher associated risk) than others.

Keywords: Cognitive Fatigue, Airline Pilots Performance, Flight Safety, Accidents and Incidents

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1. Introduction

Over the past several months, the aviation industry has been hit hard by the COVID-19 pandemic. However, it has previously managed to prove that it is able to resist to other external shocks, such as rising fuel prices and higher taxes associated with aircraft operations (Min & Joo, 2016), since, from 2003 to 2018, world air traffic doubled. Before the pandemic, Airbus forecasts stated that, in 2033, air traffic will double that of 2018 (Airbus, 2019). In this sense, flight safety is a major concern for air operators, so there is growing investment in measures to mitigate accidents and incidents.

In the early days of aviation, it was estimated that 80% of the accidents occurred due to some failure in aircraft equipments (Rankin, 2007). However, nowadays, most would agree that 60 to 80% of the accidents are caused by human error (pilots, air traffic controllers, engineers, mechanics, among others) (Shappell, Detwiler, Holcomb, Hackworth, Boquet & Wiegmann, 2007).

In Portuguese territory, over the last few years, the majority of accidents and incidents are in the field of general aviation (training, instruction, leisure). However, analyzing the documents of the investigations conducted by the *Gabinete de Prevenção e Investigação de Acidentes com Aeronaves e de Acidentes Ferroviários* (GPIAAF), there are also 22 final reports of occurrences with aircrafts in the air transport sector (GPIAAF, 2021). Human factors were involved in more than 70% of these episodes and there is even a record where pilots' fatigue is pointed out as the most probable cause of the accident (GPIAAF, 2019). Fatigue is a phenomenon that affects the alertness of airline pilots, increasing the risk of an incident, or even an accident, since it impairs their ability to operate the aircraft safely (Reis, Mestre & Canhão, 2013).

Thus, the general objective of this work is to investigate the relationship between cognitive fatigue and flight safety. Two specific objectives can be highlighted: the first is to compare, during the whole study (including FDPs), the risk inherent to the fatigue perceived by the pilots (self-assessment, using subjective measurements) with that associated with the data collected by the equipment used (which, through objective measurements, show the real deterioration of their alertness); the second is to assess, only during the FDPs, the risk associated with fatigue by two different biomathematical models, described in detail in 3.4. and 3.5.

2. Fatigue

The International Civil Aviation Organization (ICAO) defines fatigue as a "physiological state of reduced mental or physical performance capability resulting from sleep loss, extended wakefulness, circadian phase, and/or workload (mental and/or physical activity) that can impair a person's alertness and ability to adequately perform safety-related operational duties" (IATA, ICAO & IFALPA, 2015). In other words, fatigue is "the inability to function at the desired level due to incomplete recovery from the demands of prior work and other working activities" (Kandera, Škultéty & Mesárošová, 2019). In order to successfully restore the cognitive function, a restorative sleep is required, both in quantity and quality.

There are two main types of fatigue: physical and mental (the one being studied in this paper). Mental fatigue, also known as cognitive fatigue, concerns a general decrease of attention and ability to perform tasks, complex or simple, with the desired efficiency (Mizuno, Tanaka, Yamaguti, Kajimoto, Kuratsune & Watanabe, 2011). It often results from sleep loss or interruption of the normal sleep pattern. Therefore, is a major concern for airline pilots, who frequently need to work at night or early in the morning.

2.1. Fatigue Consequences

The effects of fatigue may vary depending on the person. However, there are common effects that are associated with tiredness: increased reaction times (RTs), decreased alertness, decreased situational awareness and inability to make decisions (FAA, 2012).

In regular air transport, the two most common types of flight are long-haul (L-H) and short-medium-haul (SM-H). L-H pilots usually attribute their fatigue to jet lag, caused by transmeridian flights, and SM-H pilots associate their fatigue to the high workload during the flight duty period (FDP), since they can conduct multiple take-offs and landings per duty period, the two most workload intensive stages of a flight (Reis, Mestre, Canhão, Gradwell & Paiva, 2016). However, in both group of pilots (L-H and SM-H), fatigue can manifest itself, for example, in the following situations (FAA, 2012): radio calls being missed, equipment malfunctions not being detected, routine tasks being performed inaccurately (or even forgotten), lining up with the wrong runway, landing without clearance and, in extreme cases, falling asleep in a FDP.

According to data from the European Cockpit Association (ECA), obtained through questionnaires applied to more than 6,000 European airline pilots, it is known not only that about 80% of them have to deal with fatigue in the cockpit, but also that a significant part of the pilots have already fallen asleep unexpectedly (i.e. without notifying the other pilot beforehand) during the course of a flight (ECA, 2012). Figure 1 presents, in more detail, the data for eight countries.

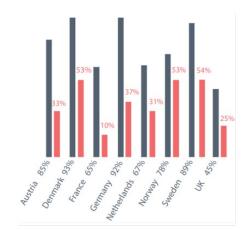


Figure 1. Percentage of pilots who have experienced fatigue (in grey) and have fallen asleep (in red) during a flight (ECA, 2012)

2.2. Cognitive Fatigue and Accidents

Dönmez and Uslu (2018) selected 50 official accident reports that occurred in several countries, according to the following main criteria:

- Investigation type: accident;
- Injury severity: fatal;
- Aircraft category: airplane;
- Operation: commercial air carrier;
- Flight type: passenger.

Subsequently, each of the reports was coded according to the four failure levels contemplated in the Human Factors Analysis and Classification System (HFACS) (Shappell & Wiegmann, 2000). More than 380 casual human factors were identified: 47% of them fit the unsafe acts (the only level of failure that is linked to active failures), but more than half (53%) is in the latent failures committed at the level of the preconditions for unsafe acts (31%), unsafe supervision (12%) and, finally, organizational influences (10%).

The second level of failure of the HFACS (preconditions for unsafe acts) is divided in two categories, being them the conditions of the operators and the practices of operators. In the first category, there are three subcategories: adverse mental state, adverse physiological state and physical/mental limitations (Shappell & Wiegmann, 2000). Dönmez and Uslu (2018) concluded that 35% of the preconditions for unsafe acts are related to the adverse mental state of the operators, to which the cognitive fatigue of airline pilots contributes significantly.

3. Materials and Methods

Airline pilots' cognitive fatigue was continuously monitored by two subjective measures (the sleep diary, SD, and the Samn-Perelli 7-Point Fatigue Scale, SPS) and two objective measures (the Psychomotor Vigilance Task, PVT, and the actigraphy) – all these methods were retired from (IATA et al., 2015) and (Millar, 2012). A fatigue management software was also used to evaluate the pilot's fatigue throughout their flight duty periods (FDPs), the FAID®, the one being used by a Portuguese airline in the process of managing the fatigue of its crew members.

Subjective tools are based on self-report of the sleep (e.g. "extremely sleep, fighting sleep") and tiredness (e.g. "I am tired"). On the other hand, objective tools are mainly built on the basis of the physiological features of the person or their physical manifestations (e.g. wrist inactivity) (Göker, 2018).

3.1. Sleep Diary (SD)

The SD is a useful tool when studying the quantity and quality of a person's sleep, especially if it is used in conjunction with other techniques, such as actigraphy, since, in this case, it becomes possible to make a comparison between the objective data of sleep and that perceived by the individual under study (IATA et al., 2015; Millar, 2012).

After a few days of filling the SD, it is possible to check if there are any patterns or practices (e.g. eating habits and the consumption of drinks with caffeine/alcohol) that are contributing or hindering the possibility of having a restorative sleep, so that, later, the necessary changes can be made to achieve this goal.

The diary used in this study is based on the one made by the National Sleep Foundation (National Sleep Foundation, 2021) and it contains two extra sections: the first one is dedicated to the assessment on the SPS scale, whereas the second one is dedicated to the results obtained on the PVT tests.

3.2. Samn-Perelli 7-Point Fatigue Scale (SPS)

Initially, the SPS was developed as a tool to subjectively assess pilots' fatigue, but nowadays it is widely used in several researches related to the issue of fatigue. The individual classifies his current status on a 7-point Likert scale (Greenberg, Aislinn & Kirsten, 2016), as can be seen in Table 1 (each one of the points is associated to a certain risk (IOGP & IPIECA, 2019)).

| Score | DescriptionState | Risk |
|-------|---|-----------|
| 1 | Fully alert, wide awake. | Low |
| 2 | Very lively, responsive, not at peak. | Low |
| 3 | Okay, somewhat fresh. | Low |
| 4 | A little tired. | Moderate |
| 5 | Moderately tired, let down. | Moderate |
| 6 | Moderately tired, very difficult to concentrate. | High |
| 7 | Completely exhausted, unable to function effectively. | Very high |

Table 1. SPS checklist and risk level associated to each score (IATA et al., 2015; IOGP & IPIECA, 2019)

It is important to highlight that it has been demonstrated in a laboratory, under controlled experimental conditions, that the SPS is sensitive to the effects of sleep loss and the circadian body clock cycle (IATA et al., 2015).

3.3. Psychomotor Vigilance Task (PVT)

The PVT is a task of permanent attention that aims to measure the time with which the individual responds to a visual stimulus (Millar, 2012). Developed in the 1980s, it is the most popular validated reaction time (RT) test (Brunet, Dagenais, Therrien, Gartenberg & Forest, 2016).

The PVT-192 is the original device designed to measure a person's RT. However, besides its high cost, it is too big for some research protocols that require a pocket device, such as a smartphone (Brunet et al., 2016). Recently, taking into account this need, efforts have been made to create more accessible and portable tools, such as the application used in this study, the sleep-2-Peak (s2P), available both for iOS (App Store) and Android (Google Play).

When opening the application, the individual has the possibility to introduce the time he went to sleep the previous night, the time he woke up, and if, at the time he intends to perform the test, he is under the effect of some substance, such as sleeping pills, alcohol or caffeine (first image of Figure 2). To start the test, which lasts three minutes, the person press "Do test" and then "Start test" (second image of Figure 2). The task involves tapping on the smartphone screen (with the dominant index finger) as quickly as possible when the visual stimulus, a representation of the Sun, appears (third image of Figure 2) (Brunet et al., 2016). When finished, the individual has immediate access to all his reaction times (RTs), as well as their average value (fourth image of Figure 2).

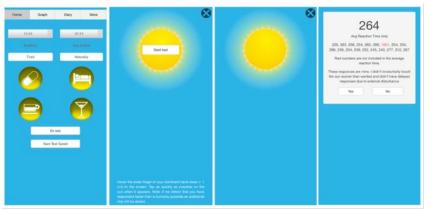


Figure 2. Use of the s2P in the iOS operating system(Based on App Store, 2021)

The application presented is validated by a study conducted by Brunet et al. (2016) which "showed that a 3-min version of s2P, a PVT-type test designed for smartphones, is a valid tool for differentiating alert from sleepy states in the same individual and is as sensitive as the gold-standard PVT for tracking fatigue-related changes during an extended wakefulness and sleep loss condition".

3.4. Actigraphy

Polysomnography (PSG), being the most reliable technique in sleep measurement studies, requires the use of multiple physiological recording devices to assess the quantity and quality of sleep. However, since it requires medical supervision, this technique is mainly intended for research and treatment of sleep disorders (Fatigue Science, 2017).

Since PSG is an impractical tool for daily fatigue management (Fatigue Science, 2017), actigraphy appears as an alternative and less invasive option. The device used in this technique (actiwatch) contains an accelerometer that

tracks the frequency of wrist movements. These are then processed by algorithms that provide information regarding the sleep/wake cycle (Russel et al., 2016).

The actiwatch used in this study was the Readiband[™] 5 (Figure 3), from Fatigue Science. This device is validated by Russel et al. (2016), who concluded that "The Fatigue Science actigraph was 93% accurate in determining sleep scoring when contrasted to results derived from sleep scoring using gold-standard polysomnography".



Figure 3. Actiwatch Readiband[™] 5 (Fatigue Science, 2017)

The data recorded by the actiwacth is exposed in a graph from midnight to midnight, like the one presented below (Figure 4) (Fatigue Science, 2013). In this graph:

• The black vertical lines represent motion/activity;

• The blue zones refer to sleep periods (the greater the movement captured in this zone, the lower is the quantity and quality of sleep). For most adults, the recommended sleep quantity is between 7 and 9 hours (IATA et al., 2015). In terms of quality, a value above 0.68, resulting from the division between the number of times the person woke up during the night and the number of sleep hours, is an indicator of poor sleep quality (a good value is under 0.37) (Fatigue Science, 2021);

• The grey areas refer to the periods when the individual is awake.

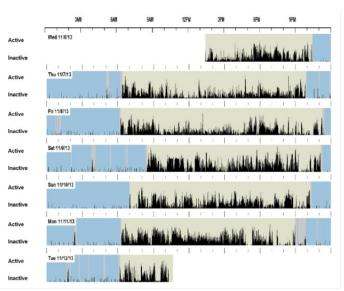


Figure 4. Actigraphy record with sleep and activity periods (Fatigue Science, 2013)

Information like the one presented in the Figure 4 is absolutely essential for the subsequent application of the SAFTETM (Sleep, Activity, Fatigue and Task Effectiveness) fatigue model. This biomathematical model is one of the most used in researches carried out in the area of fatigue and human performance, having been tested and validated by several entities, such as the US Army, the US Department of Transportation and the Federal Aviation Administration (FAA) (Fatigue Science, 2017).

The SAFTETM model, after the person has used ReadibandTM 5 for three consecutive nights, analyzes all the information collected and then provides a score (from 0 to 100%), known as SAFTETM Alertness Score (Fatigue Science, 2017), which can be seen in Figure 5. Note that, for a score of 70% (cognitive performance reduced by 30%), fatigue affects performance in the same way as a blood alcohol concentration of 0.08%.

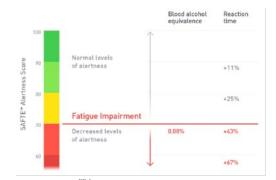


Figure 5. SAFTETM Alertness Score (Fatigue Science, 2017)

Table 2 shows the risk of accident or serious error associated with each score (from the SAFTETM Alertness Score) and the increase in RT.

| SAFTE [™] Alertness Score [%] | Increased RT [%] | Risk |
|---|------------------|-----------|
| [90;100] | [0;11] | Very Low |
| [80;90[|]11;25] | Low |
| [70;80[|]25;43] | Elevated |
| [60;70[|]43;67] | High |
| [0;60[|]67;100] | Very high |

Table 2. Risk of accident or serious error associated with the SAFTETM Alertness Score and the increase of RT (Fatigue Science, 2017, 2021)

3.5. FAID®

FAID® (Fatigue Assessment Tool by InterDynamics) is an analytical tool which can support the management of hours of work within an organization's fatigue risk management guidelines (InterDynamics, 2014a). Based on formulas tested and validated at the Centre for Sleep Research, in University of South Australia, this program was created with the objective of assessing the level of fatigue to which a worker is exposed during a shift. The algorithm takes into consideration, fundamentally, factors such as the time and duration of shifts, break times, previous periods of service and the opportunity to sleep between different working hours (InterDynamics, 2014a; McCulloh, Baker, Ferguson, Fletcher, Dawson, Marcil et al., 2007).

In the aviation industry, flight crews, especially those operating L-H flights, have to deal with multiple time zones, resulting in a higher level of fatigue. In this sense, a specialized version of FAID® has been developed, based on the FAID® Time Zone model (InterDynamics, 2014b). It is a biomathematical model that, besides the factors mentioned in the previous paragraph, considers the number of time zones crossed and the direction of flight (East – West or West – East) (InterDynamics, 2014c).

The software provides a score (FAID[®] Score) that should be interpreted as an indication of the likelihood of performance impairment associated with fatigue (InterDynamics, 2014a). These scores range from 0 to 150, and the higher the value, the greater the risk associated with fatigue (euroAtlantic Airways, 2020a). As previously shown in Table 2, the SAFTE[™] Alertness Score's values range from 0 to 100%, but a higher value corresponds

to a lower risk of accident or serious error. Thus, and in order to make the comparison between these two scales more intuitive, it was decided to compress and invert the FAID® scale, as can be seen in the second and third columns of Table 3, respectively (all the values regarding FAID® Score presented in section 4. are in accordance with the third column of this table). The risk scale presented in Table 3 is the one used by the airline of the pilots under study.

| FAID® Score | New scale [%] | Inverted new scale [%] | Risk |
|-------------|---------------|------------------------|----------|
| [120;150] | [80;100] | [0;20] | Extreme |
| [90;120[| [60;80[|]20;40] | High |
| [70;90[| [46,67;60] |]40;53,33] | Moderate |
| [0;70[| [0;46,67[|]53,33;100] | Low |

Table 3. Risk of accident or serious error associated with the FAID® Score (euroAtlantic Airways, 2020a)

3.6. Daily Procedure Followed by the Pilots

The collection of data from the three pilots was carried out in July and August 2020. All flights reviewed were conducted under the "EASA temporary exemptions under Article 71(1) of Regulation (EU) 2018/1139" (EASA, 2020) and with the respective endorsement of the National Civil Aviation Authority (ANAC).

During the entire data collection period, the day started with the filling of the SD, in the section "Fill in the morning, after waking up". To complete this task, in addition to providing information such as the time they went to bed and got up, pilots were required to rate their status when waking up, according to the SPS scale, and to do a PVT test on the s2P application.

On flight days, pilots were asked to complete a document providing relevant information about the FDP, namely: the date, so that performance during the flight(s) could be related to the sleep periods considered relevant; the time zone difference between the place of departure and the final destination; the take-off hours, in Universal Coordinated Time (UTC); the flight time of each sector. Before the first sector, pilots classified their current status (SPS) and performed a PVT test (s2P). This information was updated after each sector.

Finally, and again during the whole data collection period, the day ended with the filling of the SD, in the section "Fill at night, before going to bed". As was the case in the morning, pilots rated their status at bedtime (SPS) and did a new PVT test (s2P), besides providing information such as nap periods, caffeine and alcohol intake or the ingestion of heavy meals.

The pilots kept the actiwatch ReadibandTM 5 on their wrist throughout the whole study period, removing it only for activities that could put it in direct contact with water (they all started using the device at least three days before their first FDP). FAID® Score values were directly provided by the airline, through fatigue reports from the pilots involved.

It is important to note that none of the three pilots was tracked for less than 15 days (pilot 1 - 16 days; pilot 2 - 18 days; pilot 3 - 15 days). All the pilots started wearing the actiwatch ReadibandTM 5 at least three days before their FDP, otherwise the SAFTETM Alertness Score would not be available during the flights. In addition, if the data collection period were too short, it might not have been possible to find relationships between the results from the subjective methods and those from the objective ones.

4. Results

| Country (City) | IATA Code | ICAO Code |
|-----------------------|-----------|-----------|
| Portugal (Lisbon) | LIS | LPPT |
| Nigeria (Lagos) | LOS | DNMM |
| São Tomé and Príncipe | TMS | FPST |
| (São Tomé) | | |
| United Arab Emirates | DWC | OMDW |
| (Dubai) | | |
| Afghanistan (Kabul) | KBL | OAKB |

Table 4 presents the location and the codes of the airports involved in the analyzed flight sectors.

Table 4. Airports' location and codes (Great Circle Mapper, 2021)

4.1. Airline Pilot 1

Pilot 1 is a 43-year-old man with 7,000 flight hours. He used the actiwatch ReadibandTM 5 for 16 days and slept an average of 7.2 hours per night, recording 0.62 awakenings per hour of sleep. The average value of SAFTETM Alertness Score was 92.90%, being in the category of very low risk of accident or serious error. His assessment on the SPS scale had average values of 3.81, after waking up, and 5.00, before going to bed. In terms of RTs, he recorded average values of 487.60 and 514.25 ms, after waking up and before going to bed, respectively (among all the results of the PVT tests, his best RT was 413 ms, which was assumed to be the fastest RT of this pilot).

According to the SD records, pilot 1, during the data collection period, did not take naps and did not consume drinks with caffeine or alcohol. Regarding eating habits, the pilot ingested a heavy meal (in the hours before he went to bed) on days 1 and 2.

From Figure 6, it is possible to compare, for pilot 1, the objective data resulting from the PVT tests and the subjective data coming from the SPS scale, both in the morning and at night.

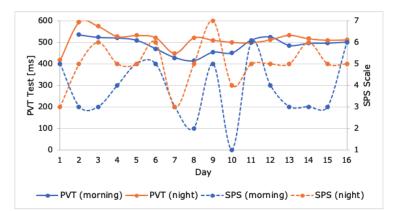


Figure 6. SPS and PVT in the morning (after waking up) and at night (at bedtime) - Pilot 1

As can be seen, on most days (days 2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 14, 15 and 16), it was possible to observe an increase in the RT between the morning and night periods, and this increase was often followed by an increase in the level chosen on the SPS scale, which shows that the pilot was aware of the deterioration in his alertness. There was a decrease in the RT only on days 11 and 12. In the first case, the RT at night (498 ms) was 2.35% lower than in the morning (510 ms), with this slight decrease corresponding to a decrease from 6 (high risk) to 5 (moderate risk) on the SPS scale. In the second case, the result of the PVT test performed at night (512 ms) was

2.48% lower than the value recorded after waking up (525 ms). Despite this decrease in the RT, the pilot rated his condition at bedtime with level 5 of the SPS scale, higher than the 4 (moderate risk) recorded in the morning.

It was also found that the morning of day 10 was the only one in which the pilot rated his status with the lowest level of the SPS scale (level 1, low risk). However, it was not on this day that he recorded the best RT after the sleep period. Something similar happened on the night of day 9, in which, although the pilot classified his condition at bedtime with the highest level of the SPS scale (level 7, very high risk), the worst result of the PVT tests performed at night was not obtained. This occurred in the night of day 2, after the ingestion of a heavy meal, having a value of 594 ms, which corresponds to an increase of 43.83% over the fastest RT (the risk of accident or serious error was high, since the increase in RT exceeded the limit of 43%) and 15.51% over the average value of the PVT tests' results performed at night.

Flight Duty Period 1

On day 4, pilot 1 performed two sectors, LIS – LOS and LOS – LIS. On the night immediately before this FDP (night 4), the pilot slept 5.8 h and recorded 0.52 awakenings per hour of sleep, which means that both quantity and quality of sleep were outside the recommended values. After waking up, the pilot classified his condition with level 4 (moderate risk) of the SPS scale and obtained, in the PVT test, a result of 520 ms, this being 25.91 and 6.64% higher than 413 and 487.60 ms, respectively.

When starting the first sector (LIS – LOS), the pilot felt more tired than when waking up, since he classified his status, according to the SPS scale, with level 5, a value associated to a moderate risk for human error. In fact, there was a slight increase in the RT to 533 ms, which corresponds to an increase of 2.50% over the value recorded in the morning and 29.06% over his fastest RT. After this sector, the pilot classified his status with level 6 (high risk) of the SPS scale and the RT had again a small increase, being now 541 ms, only 1.50% higher than that recorded before the flight, but 30.99% higher than 413 ms. As can be understood from the results of the PVT tests, the pilot started and ended this sector with an elevated risk of accident or serious error, since the increase in RT exceeded the limit of 25%.

After the second sector (LOS – LIS), the fatigue perceived by the pilot remained unchanged, as it continued to be classified with level 6 of the SPS scale. However, there was an improvement in the RT to 522 ms, i.e. 2.06 and 3.51% lower than the results obtained before and after the first sector, respectively. However, being 26.39% higher than 413 ms, the risk of accident or serious error remained elevated.

Regarding the SAFTETM model, before the beginning of the LIS – LOS flight, the score produced was 92.7%, i.e. the risk for accident or serious error was very low. However, after this sector, the score decreased to 89.7%, which means that there was an increase in risk, which became low. At the end of the LOS – LIS segment, the SAFTETM Alertness Score did not register a remarkable change (the risk remained low). According to this biomathematical model, the reduction in cognitive performance of the pilot, throughout the operation, was 4.3%.

Finally, according to FAID®, the risk associated with fatigue, both at the end of the first sector and at the end of the second, was low. However, FAID® Score decreased from 94.17 to 83.35%.

Table 5 shows the results obtained by pilot 1 during the two flight sectors.

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| | LIS-LOS | | LOS-LIS |
|-------------------------|--------------|--------------|--------------|
| Hour (UTC) | 09:10 h | | 17:50 h |
| Flight Time | 05:10 h | | 04:55 h |
| SPS Scale | Before: 5 | After: 6 | After: 6 |
| PVT Test [ms] | Before: 533 | After: 541 | After: 522 |
| SAFTE TM [%] | Before: 92.7 | After: 89.7 | After: 88.4 |
| FAID® [%] | | After: 94.17 | After: 83.35 |

Table 5. Pilot 1 performance: sectors LIS - LOS and LOS - LIS

4.2. Airline Pilot 2

Pilot 2 is a 45-year-old man with 450 flight hours. He used the actiwatch ReadibandTM 5 for 18 days and slept an average of 5.2 hours per night, recording 1.19 awakenings per hour of sleep. The average value of SAFTETM Alertness Score was 76.56%, being in the category of elevated risk of accident or serious error. His assessment on the SPS scale had average values of 3.11, after waking up, and 3.33, before going to bed. In terms of RTs, he recorded average values of 191.22 and 179.56 ms, after waking up and before going to bed, respectively (among all the results of the PVT tests, his best RT was 157 ms, which was assumed to be the fastest RT of this pilot).

According to the SD records, pilot 2, during the data collection period, took naps and consumed drinks with caffeine (average of 0.94 beverages per day). The intake of drinks with alcohol and the ingestion of heavy meals (in the hours before going to bed) were not considered relevant.

From Figure 7, it is possible to compare, for pilot 2, the objective data resulting from the PVT tests and the subjective data coming from the SPS scale, both in the morning and at night.

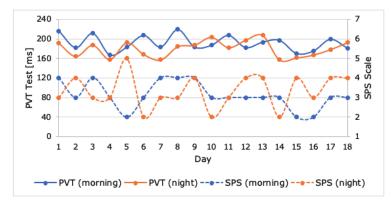


Figure 7. SPS and PVT in the morning (after waking up) and at night (at bedtime) - Pilot 2

As can be seen, and unlike to what happened with pilot 1, it was possible to observe, on most days (days 1, 2, 3, 4, 6, 7, 8, 11, 14, 15, 16 and 17), a decrease in the RT between the morning and night periods. However, this improvement was only followed by a decrease in the level chosen on the SPS scale on half of these days (days 1, 3, 6, 7, 8 and 14), which may indicate that the pilot is not the best judge of his alertness. For example, on day 15, although the result of the PVT test performed after waking up (170 ms) had been 5.6% higher than that achieved at night (161 ms), the pilot increased the rating of his level of fatigue on the SPS scale from 2 (low risk) to 4 (moderate risk).

It was possible to verify that, despite this improvement not only happening in these days, the pilot's RT decreased whenever he reported, in the SD, that he took a nap, namely:

- Day 3 \rightarrow 30 minutes nap \rightarrow RT at night (187 ms) was 11.37% lower than in the morning (211 ms);
- Day 7 \rightarrow 50 minutes nap \rightarrow RT at night (157 ms) was 14.21% lower than in the morning (183 ms);

- Day $11 \rightarrow 50$ minutes nap \rightarrow RT at night (182 ms) was 12.08% lower than in the morning (207 ms);
- Day $17 \rightarrow 35$ minutes nap \rightarrow RT at night (178 ms) was 10.55% lower than in the morning (199 ms).

It is important to highlight that the fastest RT of this pilot (157 ms), besides being reached on the night of day 7, was also obtained on the night of day 14, which corresponds to the only day that the pilot had consumed two drinks with caffeine (on the remaining days, this consumption was always lower). On this day there was the greatest improvement between the RTs registered in the morning (197 ms) and at night, in a total decrease of 20.30%. Thus, it is very likely that caffeine played a relevant role in improving the cognitive performance of the pilot.

Regarding the days when there was an increase in the RT, one of the most significant differences occurred on day 12, with an increase of 8.24% in the RT between the morning (182 ms) and night (197 ms).

4.2.1. Flight Duty Period 2

Pilot 2 participated in an operation that started on day 6 and ended on day 7, which was composed of four flight sectors: LIS – DWC, DWC – KBL, KBL – DWC and DWC – LIS. However, the pilot only operated in the sectors DWC – KBL and KBL – DWC.

On the night immediately before this FDP (night 6), the pilot slept only 3.1 h and recorded 1.94 awakenings per hour of sleep, which means that both quantity and quality of sleep were outside the recommended values. After waking up, the pilot considered that his condition fitted the level 3 of the SPS scale, a level that is associated with a low risk for the occurrence of human error, and obtained a RT of 207 ms, this being 31.85 and 8.25% higher than 157 and 191.22 ms, respectively.

Before the start of the DWC - KBL flight, the pilot continued to classify his status with level 3 of the SPS scale. However, there was a significant improvement of 14.01% in the PVT test result, which decreased from 207 to 178 ms, being 13.38% higher than his fastest RT. After the flight, the fatigue perceived by the pilot remained unchanged again. His RT was, as in the morning, 207 ms, which corresponds to an increase of 16.29% over the result of the test performed before the flight. Thus, evaluating the results of the PVT tests, the pilot started this sector with a low risk of accident or serious error, since the increase in RT exceeded the limit of 11%, but ended it with an elevated risk, since the limit of 25% was exceeded.

After the second sector (KBL – DWC), the pilot classified his status with level 5 (moderate risk) of the SPS scale. However, despite the greater feeling of fatigue, a slight improvement was observed in the RT, which decreased to 197 ms, i.e. 10.67% higher than the result recorded before the first sector and 4.83% lower than the result obtained after it. However, being 25.48% higher than 157 ms, the risk of accident or serious error remained elevated.

Regarding the SAFTETM model, before the start of the DWC – KBL flight, the score produced was 81.4%, i.e. the risk for accident or serious error was low. After this sector, this score barely changed (the risk remained low). However, at the end of the KBL – DWC segment, the SAFTETM Alertness Score registered a major change, decreasing to 50.8%, which means that the risk became very high. According to this biomathematical model, the reduction in cognitive performance of the pilot, throughout the operation, was 30.6%.

Finally, according to FAID®, the risk associated with fatigue, both at the beginning and the end of the first sector, was low. However, at the end of the second sector, FAID® Score decreased considerably to 50.85%, a score that is associated with a moderate risk.

Table 6 shows the results obtained by pilot 2 during the two flight sectors.

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| | DWS-KBL | | KBL-DWC |
|-------------------------|---------------|--------------|--------------|
| Hour (UTC) | 16:50 h | | 00:00 h |
| Flight Time | 05:10 h | | 03:15 h |
| SPS Scale | Before: 3 | After: 3 | After: 5 |
| PVT Test [ms] | Before: 178 | After: 207 | After: 197 |
| SAFTE TM [%] | Before: 81.4 | After: 81.7 | After: 50.8 |
| FAID® [%] | Before: 78.11 | After: 72.65 | After: 50.85 |

Table 6. Pilot 2 performance: sectors DWC - KBL and KBL - DWC

4.3. Airline Pilot 3

Pilot 3 is a 53-year-old man with 1,050 flight hours. He used the actiwatch ReadibandTM 5 for 15 days and slept an average of 7.3 hours per night, recording 0.35 awakenings per hour. The average value of SAFTETM Alertness Score was 91.15%, being in the category of very low risk of accident or serious error. His assessment on the SPS scale had average values of 2.33, after waking up, and 3.80, before going to bed. In terms of RTs, he recorded average values of 187.80 and 190.15 ms, after waking up and before going to bed, respectively (among all the results of the PVT tests, his best RT was 160 ms, which was assumed to be the fastest RT of this pilot).

According to the SD records, pilot 3, during the data collection period, consumed drinks with caffeine (average of 2.27 beverages per day) and alcohol (average of 1.33 drinks per day). Naps were not considered relevant, as well as heavy meals before bedtime.

From Figure 8, it is possible to compare, for pilot 3, the objective data resulting from the PVT tests and the subjective data coming from the SPS scale, both in the morning and at night.

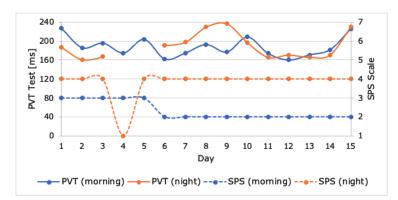


Figure 8. SPS and PVT in the morning (after waking up) and at night (at bedtime) - Pilot 3

As can be seen, and in contrast to what was observed with pilots 1 and 2, who registered, respectively, a generalized increase and decrease of the RT between the morning and night periods, in the case of this pilot, this variation was very balanced: on days 1, 2, 3, 10, 11, 13 and 14, the RT decreased; on days 6, 7, 8, 9, 12 and 15, the RT increased. However, although there was an improvement in the RT on the days mentioned, the pilot rated his status at bedtime with level 4 (moderate risk) of the SPS scale, a level that reflects a higher degree of fatigue than the levels with which the pilot self-assessed himself in the morning (levels 2 and 3, low risk). This may indicate that the pilot is not the best judge of his own alertness.

The intake of three drinks with caffeine (the maximum the pilot consumed per day) occurred on days 1, 2, 3, 11, 12, 13 and 14. On six of these seven days, as mentioned in the previous paragraph, the RTs recorded at night were lower than those recorded in the morning, suggesting that this quantity of caffeine helped the pilot in the improvement of his cognitive performance. The greatest decrease occurred on day 1, when the result of the PVT test performed at night (187 ms) was 17.62% lower than that achieved in the morning (227 ms).

Regarding the days when there was an increase in the RT, the most significant difference occurred on day 9, with an increase of 33.90% in the RT between the morning (177 ms) and night (237 ms). This result of 237 ms was the worst of all the PVT tests performed at night and corresponds to an increase of 48.13% over the fastest RT (the risk of accident or serious error was high, since the increase in RT exceeded the limit of 43%) and 24.64% over the average value of the PVT tests' results performed at night. On this day, the pilot consumed four alcoholic drinks (well above the daily average of 1.33), so it is extremely likely that the alcohol contributed to the degradation of his alertness.

4.3.1. Flight Duty Period 3

On day 15, pilot 3 performed two sectors, LIS – TMS and TMS – LIS. On the night immediately before this FDP (night 15), the pilot slept 7.9 h and recorded 0.38 awakenings per hour of sleep (a value very close to 0.37, but, being superior, the sleep period cannot be considered of good quality). After waking up, the pilot rated his status with level 2 (low risk) of the SPS scale and obtained, in the PVT test, a result of 226 ms, this being 41.25 and 20.34% higher than 160 and 187.80 ms, respectively.

When starting the first sector (LIS – TMS), the pilot classified his perception of fatigue again with level 2 of the SPS scale and his RT remained at 226 ms, which means that, evaluating only by this result of the PVT test, the pilot started this sector with an elevated risk of accident or serious error, since the increase in RT exceeded the limit of 25%. After this sector, the fatigue felt by the pilot slightly increased, fitting the level 3 (low risk) of the SPS scale, but it was not possible to verify if the RT would also have increased, since the pilot did not do a new PVT test (for operational reasons).

After the second sector (TMS – LIS), the fatigue perceived by the pilot increased again, being classified with level 4 (moderate risk) of the SPS scale. In fact, a small increase was observed in the RT, which, being 230 ms, is only 1.77% higher than the result obtained before the first sector. However, being 43.75% higher than 160 ms, the risk of accident or serious error became high, since the increase in RT exceeded the limit of 43%.

Regarding the SAFTETM model, before the start of the LIS – TMS flight, the score produced was 82.7%, i.e. the risk for accident or serious error was low. After the first and second sector, this score was 89.3 and 88.9% respectively, but, despite this increase, the risk remained low. Thus, according to this biomathematical model, the cognitive performance of the pilot, throughout the operation, did not undergo a major change.

Finally, according to FAID®, the risk associated with fatigue, both at the end of the first sector and at the end of the second, was low. However, FAID® Score decreased from 90.53 to 81.41%.

| | LIS-TMS | | TMS-LIS |
|-------------------------|--------------|--------------|--------------|
| Hour (UTC) | 4:55 h | | 13:55 h |
| Flight Time | 05:50 h | | 05:55 h |
| SPS Scale | Before: 2 | After: 3 | After: 4 |
| PVT Test [ms] | Before: 226 | After: | After: 230 |
| SAFTE TM [%] | Before: 82.7 | After: 89.3 | After: 88.9 |
| FAID® [%] | | After: 90.53 | After: 81.41 |

Table 7 shows the results obtained by pilot 3 during the two flight sectors.

Table 7. Pilot 3 performance: sectors LIS - TMS and TMS - LIS

5. Discussion

The data collected by the actiwatches showed that, on average, only pilots 1 and 3 reached the quantity of sleep recommended for most adults, recording values above 7 h. In terms of sleep quality, pilot 3 was the only one

who recorded an average value of awakenings per hour of sleep that reflected the good quality of it. Pilots 1 and 2 recorded values over 0.37 awakenings per hour of sleep, which indicates that their sleep was too fragmented. Pilot 2 mentioned that the temperatures recorded during the data collection period impaired the possibility of having a restorative sleep. In fact, the ideal bedroom temperature is between 18 and 20 °C (IATA et al., 2015), so, taking into account that the study was conducted in the Summer months, this factor may have influenced the sleep pattern of the pilot.

When asked about the factors that negatively affect his alertness, pilot 1 mentioned that the previous sleep period is the only parameter that has an impact on it. However, the data collected suggest that his eating habits also have a role on his alertness, since his worst RT was achieved in a PVT test that succeeded the intake of a heavy meal. Pilot 3 also said that, besides the previous sleep period, also alcohol intake and eating habits influence his performance. The data confirmed that alcohol impaired the cognitive performance of the pilot, since the greatest increase in his RT, between the morning and night periods, occurred on a day in which the pilot had consumed four alcoholic drinks.

Pilots were also questioned about the measures they adopt to mitigate the adverse effects coming from fatigue. Pilot 1 did not take any measure, but pilots 2 and 3 referred that they take a nap in order to recover from those effects. It was possible to confirm that this measure is very effective in improving the performance of pilot 2, since there was a decrease in RTs on all days when naps were reported. The data collected also suggests that the caffeine intake is useful in improving the performance of these two pilots: in the case of pilot 2, the best RT was achieved at the end of the day during which he ingested the highest number of drinks with caffeine (two); in the case of pilot 3, his RT time improved significantly after the intake (throughout the day) of three drinks with caffeine.

Throughout the analyzed FDPs, the workload to which the pilots were subjected contributed to a progressive increase in the fatigue perceived by them, which resulted in an increase of the level chosen on the SPS scale. In FDPs 2 and 3, it was also possible to observe an increase in the RT between the beginning of the FDP and the end of the last sector. However, there was a decrease of the RT in the segments LOS - LIS (pilot 1) and KBL – DWC (pilot 2), and, to these improvements, may have contributed the several procedures that pilots have to follow in the final approach and landing phases. These procedures require pilots' maximum attention and therefore help to restore their alertness (euroAtlantic Airways, 2020b).

As can be verified by the results obtained by the three pilots, the risk of accident or serious error associated with the results of the PVT tests (RTs) tends to be higher than the risk associated with the values provided by the SAFTETM biomathematical model. Thus, in several analyzed flight sectors, it was not possible to verify the correspondence between the SAFTETM Alertness Score and the increase of the RT, previously illustrated in Table 2. It is in this context that the differences between the laboratory data used in the development of the SAFTETM model and the methods used in this work may be more relevant, namely: the PVT tests in this study lasted three minutes, while the tests for the development of the model lasted ten minutes (Roma et al., 2012); the devices used to measure the pilots' RTs (smartphones) were not the same as those used in the development of the model, due to their high cost and big dimensions (Brunet et al., 2016). Other factors that may have affected the results of the PVT tests made in the cockpit of the aircraft are the noise and light conditions, which are considerably different from those present outside the working environment.

At the end of the analyzed flight sectors, it was possible to obtain three of the five levels of accident or serious error risk contemplated by the SAFTETM model, from the lowest to the highest (very low risk, low risk, very high risk). However, with the FAID® Time Zone model, only the two lowest risk levels (low risk, moderate risk) were obtained. The fact that FAID® does not consider the actual sleep time obtained by the pilots (InterDynamics, 2014c), unlike the SAFTETM model, may have contributed to underestimate their actual levels of fatigue. One of the assumptions of FAID® is that "recovery from work-related fatigue by sleeping can be obtained at any time an individual is not working" (InterDynamics, 2014c), but this assumption may not be verified. It is still important to highlight that neither of these two biomathematical models takes into account personal factors

related to food and caffeine/alcohol intake (Independent Transport Safety Regulator, 2010), which can easily impair the performance of the pilots.

The highest levels of accident or serious error risk occurred, both in the SAFTETM model and in the FAID® Time Zone, after the flight KBL – DWC (pilot 2). In the case of the first model, the risk was very high, which would have been expected considering that, after the flight, almost 24 hours had passed since the pilot's last night of sleep. In the case of the second model, the risk was moderate and FAID® Score was the lowest of all those registered (50.85%).

6. Conclusions

The case study involved the participation of three airline pilots, and, through the experimental work, it was found that pilots 1 and 3 were the only ones to achieve, on average, the amount of sleep recommended, but that only pilot 3 had a good quality sleep. Besides sleep, which all pilots consider playing a key role in their alertness, it was possible to find, based on records in the SD, other factors that seem to affect the performance of the pilots, namely: the intake of caffeine and alcohol, the eating habits and, finally, taking naps.

Six flight sectors were analyzed, in a total of three FDPs. Throughout these FDPs, the pilots' perception of fatigue gradually increased, and there were even records of the second highest level of fatigue on the SPS scale, level 6, associated with a high risk for human error. In some of the analyzed segments, the pilots' RT also increased between the beginning and the end of the flights and, classifying the risk based on the results of the PVT tests, certain sectors ended up with an elevated or high risk of accident or serious error.

Considering the duration of some of the FDPs, it was possible to observe changes in the fatigue scores produced by SAFTETM and FAID® Time Zone models. However, a greater variation in risk was observed when the assessment was made by the first model. There was even a flight that started with a low risk of accident or serious error but ended with a very high risk.

Although the small sample size may be a limitation of the study, the results obtained showed that the three airline pilots felt the effects of cognitive fatigue during the flight sectors. Therefore, the next steps in the investigation should look deeper into the relationship between cognitive fatigue and flight safety, and its consequences not only for the pilots, but also for their companies and their clients, the passengers.

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