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Fatigue in The Aviation: An Overview of The Measurements and Countermeasures

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Abstract

Fatigue is a crucial and cumulative factor for aviation safety causing human errors via decrease in the abilities to conduct tasks that require higher-order intellectual processing. Chronic form of fatigue is more insidious and subjective. Factors causing fatigue are lack of sleep, crew scheduling, a long duty period, Jet or shift lag, high workload, and lacking of physical or mental fitness. There are subjective and objective measurements to estimate fatigue levels. Subjective techniques are based on self-report of the sleep and tiredeness whereas objective interventions are built on the basis the physiological features of the subject (brain waves, eye gaze, facial feature recognition) or their physical manifestations (muscle tone, wrist inactivity, head orientation). Fatigue measurements aim to support and maintain alertness and performance during long or uneventful duty period. Fatigue contermeasures are mainly based on self-reported data and there is a need for "safety" factor for self-reports. The aim of this study was to evaluate the fatigue encountered in aviation and to review the methods used to prevent fatigue.

Keywords: Fatigue, Subjective, Objective, Measuruments, Countermeasures

1. Introduction

Fatigue is a crucial factor related to human errors causing a decrease in the abilities to conduct tasks that require higher-order intellectual processing [1]. Like stress, fatigue is cumulative and it could be either acute (short-term) or chronic (long-term). Acute fatigue is easily recognized and remedied by not flying and sufficient rest since it stems mainly from lack of sleep, hard physical or mental exertion, crew scheduling, a long duty period, Jet lag or shift lag [1,2].

Chronic fatigue, on the other hand, is more insidious and subjective which one pilot being able to tolerate more than the other before chronic fatigue emerges. High workload (mental and/or physical activity), financial or relational problems, lacking of physical or mental fitness are mainly causative factors in the development of the long-term fatigue [1,2].

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Symptoms of the fatigue vary with physical, mental and emotional manifestations including sleepiness, apathy difficulties in concentrating, decreased vigilance, attention lapses, increased reaction time, task fixation, slowing of higher-level mental functioning, miscommunication, lack of motivation, irritability, emotional sensitivity to increased errors while performing tasks especially during divergent processing (knowledge-based, innovative, creative problem solving) [2]. Causes, symptoms and consequences of fatigue were summarized in the Figure 1.

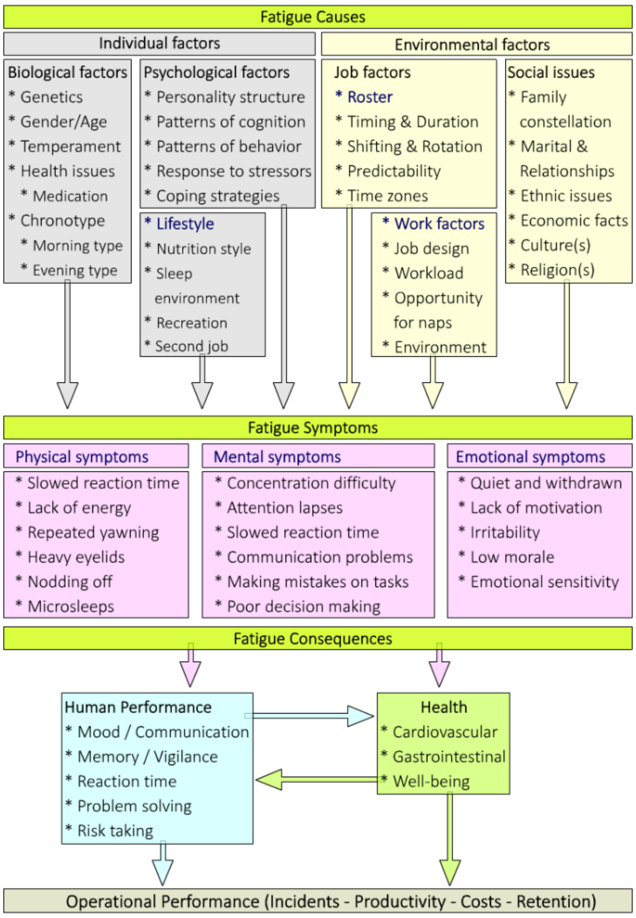

Figure 1. Causes, symptoms and consequences of fatigue (adapted from Australian Civil Aviation Safety Authority, Fatigue Management Strategies, reference [2])

Fatigue Measurement Methods

Techniques to estimate the level of fatigue in the aviation professionals are based on subjective (self-reported questionnaires) and objective (including polysomnography with EEG, electro-oculography, actigraphy) measurements [3].

Subjective tools to evaluate fatigue are based on self-reporting of perceived feelings like "I'm tired" or person's sleep variables such as "extremely sleepy, fighting sleep". For assessing of the fatigue, there are validated scales including the Fatigue Assesment Instrument (FAI) [4], the World-Health-Organization-Quality of Life-Scale Energy and Fatigue subscale [5], the Visual Analogue Scales for fatigue (VAS-F) [6] and for sleepiness and alertness [7], the Chalder's Fatigue Scale (FS) [8], the Fatigue Severity Scale (FSS) [9] and The Crew Status Survey (also called as Samn-Perelli (SP) Fatigue Scale [10]. Self-report sleep evaluation includes sleep and wake times, how much and how well it is and the Stanford Sleepiness Scale (SSS) [11], the Karolinska Sleepiness Scale (KSS) [12] are commonly used tools. All subjective scales are easy to administer, either in paper-based or computer-based forms, provide data comparison but do not always reliably reflect objective performance measures since there may lack face validity because of relatively easy to misleading [3].

In addition to these self-report scales, biomathematical models are developed to predict an individual's alertness level or performance effectiveness prior a duty period to determine should the subject can maintain optimal performance throughout the work period [13]. In these models, self-reported amount and quality of sleep are formulated with subject's work schedule and hours of work. There are some models validated yet still needed to be improved their reliability including the Fatigue Avoidance Scheduling Tool (FAST), The Sleep, Activity, Fatigue and Task Effectiveness (SAFTE), and these combination as referred SAFTE/FAST, Fatigue Audit InterDyne (FAID), Fatigue Index Tool (FIT), and System for Aircrew Fatigue Evaluation (SAFE) models [14].

Objective tools to measure the fatigue in tha aviation subjects are mainly built on either circadian rhtyhms- (via temperature, biological tests), or sleep- (with the use of polysomnography (PSG), electroencephalography (EEG), actigraphy) or psychomotor performance- (simple mental tasks, complex behavior) based [3]. They aim to detect either the physiological features of the subject (brain waves, eye gaze, facial feature recognition, retinal functioning) or their physical manifestations (muscle tone, wrist inactivity, head position, percent eye closure) and support to maintain alertness and performance during long or uneventful duty period [13]. Objective techniques can also be applied in the real-time conditions with intrusive or non-intrusive ways.

Electroencephalography (EEG): The brain's electrical activities as known event-related potentials (ERPs) are valid and reliable method as "gold standard" for assessing of impaired alertness [15]. High mental workload reported with an increase in theta band and a decrease in alpha band in EEG as well as successive increase in theta, delta and alpha bands occurs during the transition between mental workload and mental fatigue [16]. Yet this method is intrusive and not be feasible due to the operational environment.

Polysomnography (PSG): The brain's event-related activities changes with increasing fatigue. PSG detects microsleep (alpha wave) and rolling eye movements via EEG, electrooculagraphy (EOG) and electromyography (EMG) combination. It is "gold standard" to measures sleep quantity and structure, sleep quality and alertness. It is intrusive and electrodes attached to the head/face and technicians are needed. It is useful to examine subsequent fatigue levels such as recovery from a series of duties (sleep in aircraft bunks on augmented flights or sleep at home on return from transmeridian flights) [3].

Actigraphy: Wrist-wrap actigraphy is used to monitor an individual's activity, and it indicates when the subject may be asleep, estimates the timing of periods of sleep and quality. It is non-intrusive and measures activity not sleep and it cannot distinguish between sleep and still wake and not easly affordable [3].

Non-intrusive eye-tracking measures: Fatigue and changes in the oculomotor functioning as decreased saccadic velocities are well-documented and suggest as a biomarker of aviator fatigue [17]. Other visual cues including eyelid movement, head orientation, line of gaze and facial expression are to be used for determining the state of alertness. Combination of these visual cues has been shown much more accurate than using a single cue for driver fatigue monitoring [18].

Critical flicker-fusion frequency (CFF) test: It is based on the frequency at which the retinal response is no longer modulated with a normal critical value of 25 hz-55 Hz [19] evaluates the efficiency of the visual response.

Psychomotor vigilance task (PVT): This test is used for evaluating psychomotor performance including the ability to sustain attention. Lapses in attention measured by PVT could occur as a result of lack of sleep and/or prolonged hours on the duty [20]. Task can be carried out in "noisy" surrounding, sensitive to changes in fatigue levels. It requires an equipment and at least 3 or 5 or standard 10 minutes without any disturbance [3, 21].

Fatigue Countermeasures

Advancement in understanding fatigue causes, symptoms and consequences has led to try to corporate evidence-based knowledge to aviation regulations and industry practices. There are some fatigue-mitigating strategies, developed mostly based on subjective fatigue reports and still more collective experience data is needed to develop standardized fatigue risk indicators [15]. Figure 2 shows in-flight and pre/post-flight contermeasures to combat fatigue.

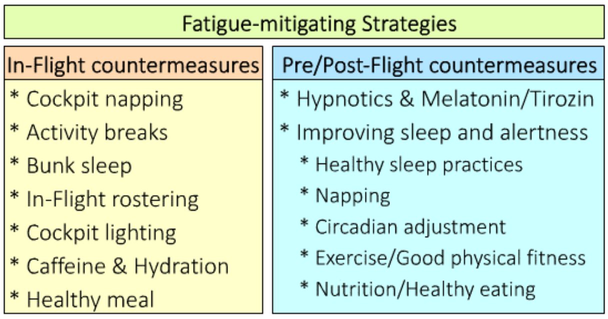

Figure 2. Fatigue mitigating strategies (adapted from Caldwell et al, 2009, reference [15])

2. Material and Methodology

In this article, the literature located in PUBMED and Google Scholar relating aviation, fatigue, surveys, subjective and objective measurements and countermeasures were reviewed and tools used in these studies, their superiorities, limitations were evaluated and lastly probable implication issues were pointed out.

3. Results

Subjective scales findings

The Fatigue Assesment Instrument (FAI) includes 29 items and evaluates fatigue with four subscales including Factor 1: The fatigue severity, Factor 2: The environment-spesific scale, Factor 3: The outcome scale and Factor 4: Sleep-evaluating scale [4]. In a study, Ma et al. (2014) evaluated twent-one-male aviators' subjective fatigue levels via FAI scale in pre- and post-flight simulations and there was no difference pre- and post-flight trials. Hovever, in this study, there was also an objective real-time assesment of CFF measurement which pointed out that the aviators had more fatigue levels in post-flight trial than that of pre-flight measurement [22].

The World-Health-Organization-Quality of Life-Scale Energy and Fatigue subscale (WHOQoL-EF) were frequently used in aviation fatigue studies as a part of a survey. It includes 4 items including 1) Do you have enough energy for everyday life? 2) How easily do you get tired? 3) How satisfied are you with the energy that you have? 4) How bothered are you by fatigue? [5]. Tvaryanas and Thompson (2006) evaluated the fatigue in 172 air force subjects with 4 different shift work (irregular, rotational, or fixed shifts). They used a composite fatigue survey including the fatigue scale, checklist individual strength concentration subscale, fatigue assesment scale, WHOQoL-energy and fatigue subscale, and Maslach burnout inventory-emotional exhaustion subscale. Shift workers were found equally fatigued whether at home base or deployed in current military operations, reinforcing the intrinsically fatiguing nature of shift work [23].

Visual analogue scales (VAS) is a 100-millimeter line with the end points labelled from "Not at all fatigued" to "Extremely fatigued". The person marks the line at the appropriate point and the distance along the line is measured and recorded. It is usually assigned a score between 0 and 100 [6].

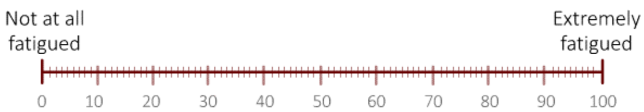

Figure 3. Visual analogue scale (VAS) for fatigue (reference [6])

There is VAS use for alertness and sleepiness which a 100-mm line, centered with "alert/able to concentrate," "anxious," "energetic," "feel confident," "irritable," "nervous", "sleepy," and "talkative" adjectives and labeled two ends with "not at all" and "extremely" [7]. The responder marks the point on the line that corresponded to how he/she felt along the specified continuum at the "right now". Wilson et al (2006) used this scale in 8 males and one female that sleep deprivation's effect on performance tests including psychomotor vigilance test (PVT), subjective scales of visual analog scales (VAS), and physiological measures of EEG, oculography, wrist activity monitors. They found that the subjective reports of alertness were significantly affected by the time of testing while not different from each other, being lower than the scores obtained at all other testing times [7]. Major drawback is that points along the line are not defined and the comparison with other studies is difficult [3].

The Chalder's Fatigue Scale (FS) is a 14-item with two dimensions (physical fatigue, first 8 items and mental fatigue, 6 items). Likert system (0=better than usual, 1=no more than usual, 2=worse than usual and 3=much worse than usual) of scoring was adopted. The total score ranges from 0-33 [8]. Chaturvedula et al (2011) reported that 53 civil pilots were evaluated with the NEO-FFI questionnaire for personality trait and the Chalder's fatigue scale for fatigue evaluation and they found that positive correlation between openness and physical fatigue, and negative correlation between conscientiousness and mental fatigue [24].

The Fatigue Severity Scale (FSS) is a self-report tool evaluating the past week with a nine-item scale and scored from 1=disagree to 7=agree [9]. In a study, conducted by Reis et al. (2013), medium/short haul flying pilots were found to be more fatigued (in total and mental fatigue scores) based on Fatigue Severity Scale (FSS) than that of long-haul flying [25]. Another study, via FSS scale use, among 328 commercial airlines pilots in the Gulf Cooperation Council (GCC) pointed out that 68.3% pilots had an FSS score ≥ 36 indicating severe fatigue and 67.4% of them reported making mistakes in the cockpit because of fatigue which regular assessment by aviation authorities is needed to detect and treat these medical problems [26].

The Crew Status Survey (Samn-Perelli (SP) Fatigue Scale) is a seven-point ranging from 1-fully alert, wide awake" to "7-completely exhausted, unable to function" with the reading 6-7 scores as severe fatigue [10]. Powell et al (2007) reported fatigue levels of 1370 pilots via SP scale and revealed that length of duty, number of sectors, time of day, and departure airport affect fatigue levels in short-haul operations, with most deteriorating factors were the number of sectors and duty length [27]. Petrilli et al (2006) measured 19 international airline pilots' fatigue levels and factors that have effects on. Wrist actigraphy, 5 min PalmPilot-based psychomotor vigilance task (PVT) and self-rated their level of fatigue using the Samn-Perelli Fatigue Checklist were used. The stage of flight and flight sectors had more effect on fatigue. Sleep in the prior 24 h was found a significant predictor of self-rated fatigue and mean response speed after the international flight sectors [28]. Gander et al (2015) studied with 237 pilots' (with 730 out-and-back flights between 13 city pairs and 1-3-day layovers). Their sleep variable was monitored with wrist actigraphy, and sleep diaries) before, during and after trips. On duty days, sleepiness was evalauted via the KSS scale, fatigue was scored with the SP scale and mean response speed were measured via 10-minutes PVT at the pre-flight phase and at the top of the descent (TOD). More sleep in the 24 h prior to duty was associated with lower pre-flight sleepiness and fatigue and faster response speed. At the top of the descent, pilots felt less sleepy and fatigued after more in-flight sleep and less time awake [29]. Similar to this, Gander et al (2014) reported crew fatigue and related factors from 133 landing crewmembers on 2 long-range and 3 ultra-long-range trips (4-person crews, 3 airlines, 220 flights). Sleep was evaluated as total sleep in the prior 24 h and time awake at duty start and at TOD (actigraphy); subjective sleepiness (the KSS) and fatigue (the SP scale); and psychomotor vigilance task (PVT) performance [30].

The Stanford Sleepiness Scale (SSS) is a seven-point scale expressing from "1=feeling active and vital, alert, wide awake" to "7=almost in a reverie, sleep onset soon, lost struggle to remain awake" [10]. Kamimori et al (2005) reported the caffeine effect comparted to the placebo on alertness via 10-min the Psychomotor Vigilance Test (PVT) and the SSS and caffeine was found to be effective on the SSS scores with increasing over time concluding that bi-hourly administration of 200 mg of caffeine supplies vigilance performance across a single night without sleep [31].

Objective Measurements Findings

Studies with the brain's event-related potentials (ERPs) in fatigue consistently points out that the pattern of brain activity changes with increasing fatigue as an increase in EEG's theta band and a decrease in alpha band which suggest a high mental workload [16]. The polysomnography detecs microsleeps (alpha waves) and rolling eye movements. It measures sleep quantity and structure, sleep quality and waking alertness via EEG, EOG and EMG combination. Attachment of electrodes to head/face and technicians are needed. It is gold standard method and useful to examine subsequent fatigue levels including recovery from a series of duties (sleep in aircraft bunks on augmented flights, sleep at home on return from transmeridian flights) [3].

Wrist actigraphy measures sleep on the basis of monitoring activity and indicates when an individual may be asleep, estimates the timing of periods of sleep and quality. It measures activity not sleep and cannot be able to distinguish between sleep and still wake [3]. Its validation for aviation fatigue was proven in the studies [28, 32, 33].

One of the non-intrusive eye-tracking measures, saccadic velocities point fatigue in affected subjects. Di Staci et al. (2016) showed that a decrease in saccadic velocities after long simulated flights compared to short simulated flights. These results suggest that saccadic velocity could serve as a biomarker of aviator fatigue [17].

An-intrusive ocular function, the Critical flicker-fusion frequency (CFF) test evaluates the efficiency of the visual response. A decrease in the CFF frequencies points out the fatigue as Ma et al. (2014) reported that workload influences fatigue and this could be detected via CFF method in the pilots [22].

The Psychomotor vigilance task (PVT), a performance task, is based on simple reaction time (RT) and evaluates the ability to sustain attention and respond in a timely manner to salient signals [21]. This task measures mean response speed via responding to a visual timer bull's-eye stimulus on a display, and is expressed as the mean reciprocal response time multiplied by 1000, as per standard methodology. Lower scores point out reduced sustained attention and great level of impairment [28]. It runs for 3-minutes [21], or 5-minutes [28] or PVT 10-minutes [30]. The device records reaction time and the number of missed responses. It has been validated as a function of sleep loss and circadian influences [7]. In a study, Wilson et al (2006) showed that The simple reaction time task, PVT, exhibited the longest reaction times with the most variability and the most response lapses at the next-to-the-last test session (at the 0740 hr), after approximately 25 hours of continuous wakefulness [7]. Kamimori et al (2005) reported the effect of multiple doses of caffeine on the sleep deprivation during early morning operations [30]. Six 10-minutes of the Psychomotor Vigilance Test (PVT) were completed during each 2-hour test block. Lapses on the PVT were categorized as response times greater than 1, 3, or 5 seconds. Caffeine significantly decreased lapses in all categories compared to the placebo and reduced the number of lapses in a dose-related manner, concluding that performance was maintained at baseline levels for the entire sleep loss period with multiple doses of 200 mg caffeine.

Subjective versus Objective: The consistency

In terms of sleep and fatigue measurements, there are studies consistent with subjective and objective measures as well as that are not. In evaluating sleep measurements, in a study, conducted by van Dongen et al. (2003), sleep restriction was found more harmful than that of the subjects perception of fatigue, evaluated by polysomnography versus sleep scales of self-report [34]. Similar to this, Ma et al. (2014) measured fatigue levels of the 21-male aviators with subjective FAI scale and objective real-time CFF test. Although CFF pointed out that there was a significant decrease in CFF measures compared to pre- and post-flight trials there was no difference between trials in terms of FAI scores [22]. On the other hand, Wilson et al. [7] reported consistency with subjective reports of alertness with visual analog scale and objective EEG, and 10-minutes PVT measurements.

Fatigue Countermeasures Findings

In-Flight Countermeasures

Cockpit napping: Sallinen et al (2017) studied with 86 pilots (operating lang-haul, short-haul and both) and evaluated sleep (via actigraphy) and on-duty alertness (the KSS scale). The results point out that the pilots use on-duty alertness management strategies to combat the fatigue and sleepiness, including strategic naps [35].

Bunk sleep: Zaslona et al (2018) reported of 291 pilots with long-range and ultra-long range trips, that in-flight sleep as the primary fatigue mitigation on long-haul flights [36]. Rosekind et al. (2000) reported with 1404 pilots operating long-haul flights of their sleep quality, quantity with bunk sleep. Two-thirds of pilots reported that sleeping in the bunk improved their subsequent flight deck alertness and performance [37].

In-flight rostering: It involves number of pilot assigned to the flight and is determined in advance during the scheduling process. Eriksen et al. (2006) revealed that performance level of two-pilot operations at the TOD were significantly lower than that of three-pilot flyings, on the basis of wrist actigrapy measures [32]. Reduction of crew size by one pilot seems to be related with moderately increased levels of sleepiness, pointing out that in-two pilot operations there is aneed for improvement of sleepiness conditions.

Cockpit lighting: This is another mitigating strategy to improve alertness levels in the cockpit at night [38]. Light supresses the melatonin secretion resulting in phase shifting and alertness. Short-wavelength light pulses (especially 420 nm) has been found to be effective on subjective alertness, measured with 9-point VAS scale [39].

Caffeine: Kamimori et al [2005) revealed that 200 mg caffeine with multiple doses improves the early morning flight operations [30].

Healthy meal: In another survey study, Avers et al (2009) evaluated 9,180 of flight attendants from 30 operators with seven domain: work background, workload and duty time, sleep, health, fatigue, work environment and general demographics, concluding that scheduling and providing healthy meal are crucially recommended factors to improve sleep and fatigue scores [40].

Pre/Post-Flight Countermeasures

For improving sleep and alertness as pre- and post-flight countermeasures, resting and limiting day-time duties are one of the issues. Medium/short haul flying (less than 6 hour duration with several segments in one duty period), for instance, were reported as more causative for fatigue compared to the long-haul flights (flights with 6 or more hours, usually one or two sectors minimum) [25], and duty length were shown as an important fatigue cause in pilots with short-haul operations [27], pointing out that because of diminished resting period for these pilots [41].

Napping: This is another well-documented factors to mitigate fatigue. In a study, conducted by Petrie et al. (2011) with 253 pilots operating international flights showed that daytime napping prior to overnight duties revealed significantly lower fatigue levels, based on short-form health survey (SF-36) use [42]. Hartzler (2014) reported that the strategic naps are considered an efficacious means of maintaining performance while also reducing the individual's sleep debt. These types of naps have been advocated for pilots in particular, as opportunities to sleep either in the designated rest facilities or on the flight deck may be beneficial in reducing both the performance and alertness impairments associated with fatigue, as well as the subjective feelings of sleepiness. Evidence suggests that strategic naps can reduce subjective feelings of fatigue and improve performance and alertness [43].

Circadian adjustment: Jet lag is an undeniable factor for long haul pilots. It affects the ability to stay alerted and awake. Dai et al (2018) reported that a fatigue questionnaire for Chinese civil aviation pilots. 74 (all males) civil aviation pilots. Some international flight pilots, who had taken medications as a sleep aid, had worse sleep quality than those had not. The long-endurance flight across time zones caused significant differences in circadian rhythm [44].

Shift lag is another circadian rhythm disruption via work in shifts at night. Wright et al (2013) reported that shift-work schedules negatively influence worker physiology, health, and safety disrupting circadian sleep and alerting cycles with disturbed daytime sleep and excessive sleepiness during the work shift. Management strategies include approaches to promote sleep, wakefulness, and adaptation of the circadian clock to the imposed work schedule [45]. Tvaryanas and Thompson (2006) reported that 172 USAF personnel which shift work (irregular, rotational, fixed shifts). Self-reported average daily sleep and sleep quality did not correlate with fatigue. Crewmembers and maintenance personnel reported equal levels of fatigue, suggesting crewmember work/rest guidelines may not be useful for mitigating fatigue associated with shift work. Shift workers were equally fatigued whether at home base or deployed in current military operations, reinforcing the intrinsically fatiguing nature of shift work [23]. In a study, two-pilot operations were examined for fatigue since there is little opportunity for in-flight rest. Powell et al. (2008) examined this issue in pilots flying 3-12 hours with the SP scale evaluating fatigue at the TOD. The window of circadian low (WOCL, 0200-0600) had the highest level of fatigue in terms of the starting of the duty and two-sector duty's fatigue scores were higher than that of single-sector duty, implying that limiting daytime duties [46]. Kelley et al (2018) reported with a-125-item questionnaire of 214 U.S. Army aviators. The majority of subjects sleep less than the recommended 8 h per night and nearly half of them report sleeping less than their own preferred amount of sleep. Approximately 40% of the sample indicated that they believed fatigue to be a widespread problem in the U.S. Army aviation community. Inconsistent shiftwork, less than optimal levels of rest, and poor sleep quality in the field were identified [47].

Excercise: Exercise helps to change in the phase of sleep-wake cycles via delaying in the sleep-wake cycle resulting in alertness. Barger et al (2004) reported that daily exercise of 18-fit males with strictly controlled very dim light caused a phase delay of melatonin onset, meaning that westbound traveller could benefit from exercise [48].

4. Conclusions and Implications

Fatigue effects are cumulative and could cause impaired performance. The degree of deterioration seems to be related to the numbers of hours awake, less than optimal levels of rest, inconsistent shiftwork, duty-long, and poor sleep quality in the field were identified, and the "engagement" value of the task.

Simple, subjective assesment tools including KSS, SP, as well as FAI and non-intrusive objective techniques, such as the PVT or actigraphy, are promising to evaluate fatigue yet needs to be more complex and more engaging tasks such as eye-tracking measures to be measured and implied.

5. Symbols

Hz: Hertz (as one cycle per second)

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