Physiology & Behavior 153 (2016) 91–96

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/phb

Brief communication

Effects of long and short simulated flights on the saccadic eye movement velocity of aviators

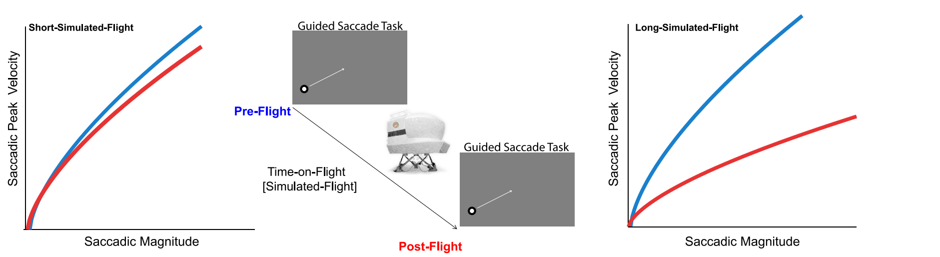
Leandro L. Di Stasi [a,b,c,1], Michael B. McCamy [a,1], Susana Martinez-Conde [a,d], Ellis Gayles [e], Chad Hoare [f], Michael Foster [f], Andrés Catena [b], Stephen L. Macknik [a,d,*]

[a] Barrow Neurological Institute, Phoenix, AZ, USA
[b] Mind, Brain, and Behavior Research Center (CIMCYC), University of Granada, Granada, Spain
[c] Joint Center University of Granada — Spanish Army Training and Doctrine Command, Granada, Spain
[d] Department of Ophthalmology, State University of New York, Downstate Medical Center, Brooklyn, NY, USA
[e] Aviation Survival Training Center Miramar, San Diego, CA, USA
[f] Marine Aircraft Group 39, 3rd Marine Aircraft Wing, Marine Corps Base, Camp Pendleton, CA, USA

HIGHLIGHTS

- Saccadic peak velocity varies with the simulated time-on-flight.
- Saccadic peak velocity decreases after long simulated flight >1 h.
- Saccadic peak velocity is a valid bio-marker of aviator fatigue.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 8 June 2015
Received in revised form 20 October 2015
Accepted 22 October 2015
Available online 24 October 2015

Keywords:
Saccades
Fatigue
Time-on-task
Main sequence
Neuroergonomics
Helicopter
USMC
Combat aviation
Flight simulation
Training

ABSTRACT

Aircrew fatigue is a major contributor to operational errors in civil and military aviation. Objective detection of pilot fatigue is thus critical to prevent aviation catastrophes. Previous work has linked fatigue to changes in oculomotor dynamics, but few studies have studied this relationship in critical safety environments. Here we measured the eye movements of US Marine Corps combat helicopter pilots before and after simulated flight missions of different durations. We found 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.

1. Introduction

Long duty hours and inadequate sleep are common in aviation, making aviator fatigue a significant problem [1] that can lead to catastrophic

* Corresponding author at: SUNY Downstate Medical Center, 450 Clarkson Ave., MSC 58, Brooklyn, NY 11203, USA.
E-mail address: macknik@neuralcorrelate.com (S.L. Macknik).
[1] These authors contributed equally.

http://dx.doi.org/10.1016/j.physbeh.2015.10.024
0031-9384/

outcomes in operational environments [2]. Military aviators must often perform long and continuous daytime/night-time operations to gain tactical advantage over the enemy. They therefore fly fatigued frequently [3], despite growing evidence that fatigue degrades neurobehavioral performance and fundamental piloting skills [4,5]. The development of non-invasive methods to monitor and detect fatigue in pilots is consequently an area of great military interest [6,7].

The standard practice to determine whether the pilot is fit to fly is for the commander to render a "go" or "no-go" decision while the aviator is still on the ground [8], based on the commander's personal assessment and experience, or on responses to subjective self-report measures. Subjective indices of fatigue are problematic, however—especially in the military [9,10]—because they lack sensitivity to small variations, and are moreover susceptible to biases arising from personal and motivational factors such as social acceptance [11,12]. Furthermore, subjective indices have rarely been validated on military air crews (see [13] for a recent review on this topic), thus their reliability is unknown.

Previous research has linked fatigue to decreased saccadic velocities, both in laboratory environments [14–16] and in simulated ecological scenarios (e.g. laparoscopic surgery [12], driving performance [17–19], and air traffic control operations [20]). Because saccadic velocity is not voluntarily controlled [21], it has the potential to provide an objective biomarker of aviator fatigue [22]. Yet, the effects of fatigue on saccadic velocity in military personnel—a population that is specifically trained to perform while fatigued—have not been investigated exhaustively [23–25]. Previous studies found a decrease in saccadic velocity in connection to sleepiness from sleep deprivation [26,27]. The results may not be generalizable to most operational scenarios, however, due to the long sleep deprivation periods (24 to 38 h) used. Moreover, there was the potential to conflate task-specific types of fatigue with sleep deprivation: a particular type of fatigue that may have specific effects on the oculomotor system. An additional obstacle to interpreting most prior military oculomotor studies on fatigue is their reliance on a commercial fatigue detector that is not fully validated [28–30], the PMI Fitness-for-Duty/Impairment Screener [FIT, Pulse Medical Instruments Inc., Rockville, MD, US; http://www.pmifit.co].

The PMI FIT system records monocularly (at 750 Hz) four oculomotor variables: pupil diameter, pupil constriction, saccadic latency and velocity. Observers focus their dominant eye on a light in the center of the field of view, through an eye port, while resting their head against the system. Then, a trigger button initiates a 30 s test sequence [31]. During the test, the observer has to follow a green light, which moves on a horizontal path from left to right [23]. The PMI FIT system then calculates saccadic velocity as the average velocity of four horizontal ~28° of visual angle [°] saccades [32] [Note that published papers report contradicting information about this parameter (for example: 20° [23] vs. 26.8° [25])]. This system claims to provide an accurate measure of fatigue when saccadic velocity is compared with baseline data collected previously from either the same subject (or with baseline data based on a large population [28° horizontal movement, average saccadic velocity: 349°/sec (standard deviation: ±17)] [32]). The PMI FIT fatigue index indicates whether the current measure—compared to the baseline—is within the expected range. Indeed, the only study to investigate the effects of fatigue on saccadic eye movements—during regular duty periods [31]—required pilots to run the FIT test repeatedly (i.e. 10–44 times) to acquire sufficient data. This was possibly due to a failure of the device to capture eye movements, which could occur when the observers blinked too often or moved their heads, or failed to direct their gaze appropriately [25].

Here, we investigated how simulated time-on-flight [TOF] affects saccadic velocity in military aviators. TOF is a leading cause of pilot fatigue [5]; thus, here we posit (pilot) fatigue as the consequence of sustained attention to the flight over a period (i.e. long vs. short) of time [33] (note, despite the distinctions between fatigue and vigilance (decrement) [34], we will use these terms interchangeably [35]).

We tracked the eye movements of Cobra helicopter pilots before and after simulated missions of different durations, while they performed a short standardized guided saccade task [12]. Saccadic velocity decreased with TOF after long simulated flights (mean flight length: 109 ± 12 min), but not after short simulated flights (mean flight length: 54 ± 7 min).

This study might assist aviator medicine departments to develop reliable and noninvasive preflight tests of aviator fatigue. The availability of such biomarkers might further help to reduce fatigue-related accidents via the implementation of individualized fatigue assessment tools in regard to in-flight fitness-for-duty, based on scientific-based recommendations for flight regulations.

2. Methods

2.1. Ethical approval

We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki) [36]. The experimental protocol was approved by the Barrow Neurological Institute's Institutional Review Board (IRB approval number 10BN142) and the methods were carried out in accordance with the approved guidelines. Written informed consent was obtained from each pilot prior to the study.

2.2. Subjects

Participants attended the Marine Aviation Training System Site [MATSS] at Camp Pendleton (CA, USA) for aviation training. Most subjects were members of the Marine Light Attack Helicopter Training Squadron 303 (i.e. newly commissioned naval aviators). All volunteers were currently on flight status, with recent verification of good health [mean number of aircraft flight hours: 834 h (±798)]. Twenty-six male subjects [mean age: 29 yrs (±4.6)], all rotary wing aircraft pilots (qualified to fly the AH-1W Super Cobra helicopter), took part in the study. We created two subject groups according to the duration of the simulated flight missions: a Short-Simulated-Flight group ($n = 11$; mean flight length: 54 min [±7]; minimum: 45 min; maximum: 60 min) and a Long-Simulated-Flight group ($n = 15$; mean flight length: 109 min [±12]; minimum: 90 min; maximum: 120 min).

2.3. Experimental design

The study followed a quasi-experimental (Pre-/Post-Test) design. The simulated *flight length* (i.e.: TOF; two levels: Long-Simulated-Flight vs. Short-Simulated-Flight) was the between-subjects factor; the *measuring session* (2 levels: Pre-Flight vs. Post-Flight) was the within-subjects factor, and the saccadic main sequence relationships were the dependent variables (see Saccadic slope analysis section for more details on these metrics). Thus, we used the Pre-Flight data as a baseline measurement for each pilot. The simulated flights consisted of standard training sessions, and varied in length as a function of the instructor's determination of each pilot's training needs at that time of the session. Though the random assignment of the pilots to the two TOF groups was not possible, age and number of aircraft flight hours–both of which could affect simulated flight performance and saccadic metrics [37–40]—did not differ significantly between groups (p-values > 0.05).

2.4. Stimuli and instruments

The MATSS facility at the Marine Corps Air Station at Camp Pendleton houses several helicopter flight training simulator platforms, which provide general skills and tactical training for pilots. The training includes instruction on the use of the mission communications,

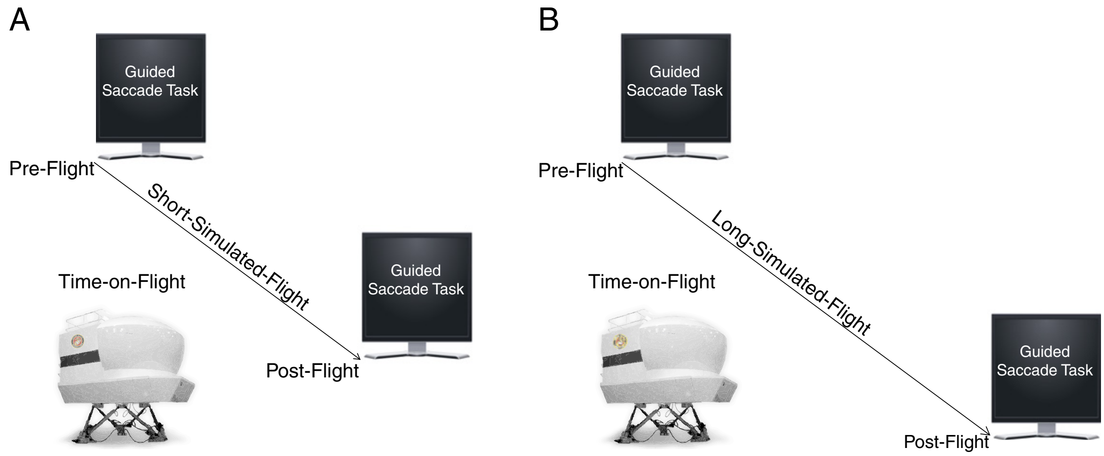


Fig. 1. Experimental timeline. A) Short-Simulated-Flight group (mean flight length: 54 ± 7 min) and B) Long-Simulated-Flight group (mean flight length: 109 ± 12 min). A & B) Pilots performed the guided saccade task outside the Bell AH-l Whiskey Weapon System full-motion cockpit training simulator. For both groups, the experiment began (Pre-Flight) and finished (Post-Flight) with the guided-saccade task. Pilots carried out their regular simulated training mission between the Pre-Flight and Post-Flight sessions.

navigation and weapons systems. Here, pilots flew the Bell AH-l Whiskey (Super Cobra) Weapons Systems full-motion cockpit training simulator.

Before and after the simulated flight (Fig. 1), we assessed the pilot's oculomotor dynamics via a standard guided-saccade task [12], while he was sitting on a comfortable chair in a dark room. To improve the accuracy of eye movement recordings [41] by reducing the influence of head movements on saccadic detection—noting that the head moves more often when subjects become fatigued [42]—we supported their heads with a chinrest (Richmond Products, USA).

We displayed visual stimuli on a 19-in screen (864 × 1152 pixels, refresh rate: 100 Hz) located ~57 cm in front of the subject. The computer screen spanned 37° of visual angle horizontally and 29° vertically. The fixation target was a 0.5° white dot centered on a 2° black disk. Pilots made saccades as follows. Saccades always started at one (randomly selected) of the four corners of an invisible square (22.5° side length), centered on the middle of the monitor. Subsequent saccadic target locations were presented at one of 7 random distances (7.5°, 10°, 12.5°, 15°, 17.5°, 20°, or 22.5°) and one of three random directions (vertical, horizontal, or diagonal). Thus, there were $84 = 4 * 7 * 3$ possible stimulus trajectories for guided saccades, from which 310 trials were generated randomly per session per subject.

2.5. Eye movement recordings and analyses

We sampled eye movements binocularly at 500 Hz using the Eyelink II helmet-mounted eye tracking system (SR Research, Ontario, Canada), which had a resolution of 0.01° of visual angle, RMS. We identified and removed blink periods as portions of the Eyelink II raw data where pupil information was missing. We also removed portions of data where very fast decreases and increases in pupil area occurred (>50 units/sample; such periods were potentially partial-blinks that failed to fully occlude the pupil) [43,44]. We removed the 200 ms epochs before and after each blink/partial-blink from analysis to eliminate the potential for eye position measurements made while the pupil was still partially occluded [43,44]. Saccades were identified with a modified version of the algorithm developed by Engbert and Kliegl [45] with $\lambda = 6$ (threshold used for saccade detection) and a minimum saccadic duration of 6 ms. To reduce the amount of potential noise, we considered only binocular saccades, that is, saccades with a minimum overlap of one data sample in both eyes [45].We imposed a minimum intersaccadic interval of 20 ms so that potential overshoot corrections might not be categorized as new saccades [46].

2.6. Saccadic slope analysis

Saccadic velocity (both measured at the peak and as a mean across each entire saccade) and saccadic duration increased with saccadic magnitude through a relationship known as the *main sequence*, which is affected by fatigue [47,48]. Because changes in pilots' scanning strategies (e.g. change in saccadic magnitudes)—due to the flight maneuver for example—will also affect saccadic velocity, here to investigate the effects of TOF on saccadic metrics, we analyzed the slope of the saccadic

Table 1
Effects of simulated time-on-flight and measuring session on the saccadic mean main sequences relationships and on other saccadic parameters.

	Long-Simulated-Flight		Short-Simulated-Flight	
	$n = 15$		$n = 11$	
	Pre-Flight	Post-Flight	Pre-Flight	Post-Flight
Slope [peak velocity–magnitude]$^{+}$	0.62 ± 0.04	0.60 ± 0.04	0.58 ± 0.04	0.58 ± 0.04
Slope [mean velocity–magnitude]*	0.55 ± 0.03	0.53 ± 0.04	0.52 ± 0.02	0.52 ± 0.03
Slope [duration–magnitude]	0.47 ± 0.04	0.49 ± 0.04	0.50 ± 0.03	0.50 ± 0.03
Peak velocity [°/s]$^{*,\wedge}$	295.68 ± 31.85	269.09 ± 38.10	256.71 ± 58.64	239.17 ± 44.65
Mean velocity [°/s]$^{*,\wedge}$	164.00 ± 11.44	157.98 ± 18.26	152.98 ± 29.50	143.62 ± 21.04
Magnitude [°]*	8.20 ± 0.59	7.47 ± 0.85	7.78 ± 1.09	7.55 ± 0.83
Duration [ms]	38.83 ± 3.99	38.25 ± 5.15	40.44 ± 2.91	40.46 ± 3.21

Means and standard deviations (±) were calculated from the mean values of each subject. All p-values < 0.05.
$^{+}$ Statistical significance for the interaction between flight length and measuring sessions.
* Statistical significance between measuring sessions (Pre-/Post-Simulated-Flight).
$^{\wedge}$ Statistical significance between subject groups.

peak velocity–magnitude relationship (and the other main sequence relationships; see Table 1) [48] [22]. This type of analysis is useful to ascertain whether one factor (e.g. TOF) moderates the association between two other variables (e.g. amplitude and velocity) [49]. Specifically, we assumed a power–law between saccadic magnitude and peak/mean velocity, such that peak/mean velocity $= e^b(\text{magnitude})^m$, where b is the y-intercept and m is the slope. We performed a linear regression on $\ln(\text{peak/mean velocity}) = m \ln(\text{magnitude}) + b$, using the robust function in MATLAB (The MathWorks, Natick, MA) [20,50]. The assumption of a power–law relationship was supported by the goodness of fit (measured by mean r^2); r^2 was higher for the linear fits of the log-transformed data ($r^2 = 0.95$) compared to linear fits of the raw data ($r^2 = 0.86$).

2.7. Statistical analyses

We analyzed the saccadic eye movement metrics following a 2 × 2 mixed repeated measures ANOVA with the *measuring session* (Pre-Flight vs. Post-Flight) as the within-subjects factor and the *flight length* (i.e. TOF: Short-Simulated-Flight vs. Long-Simulated-Flight) as the between-subjects factor. Thus, *measuring session* data were analyzed by contrasting the data from each pilot (independently from the *flight length*), from before the simulated flight, against the data from the same pilot acquired after the simulated flight. We used Bonferroni correction to control for multiple comparisons. Furthermore, we used two separate paired t-tests to describe the slope changes between sessions in both groups. Finally, to explore the relationship between flight

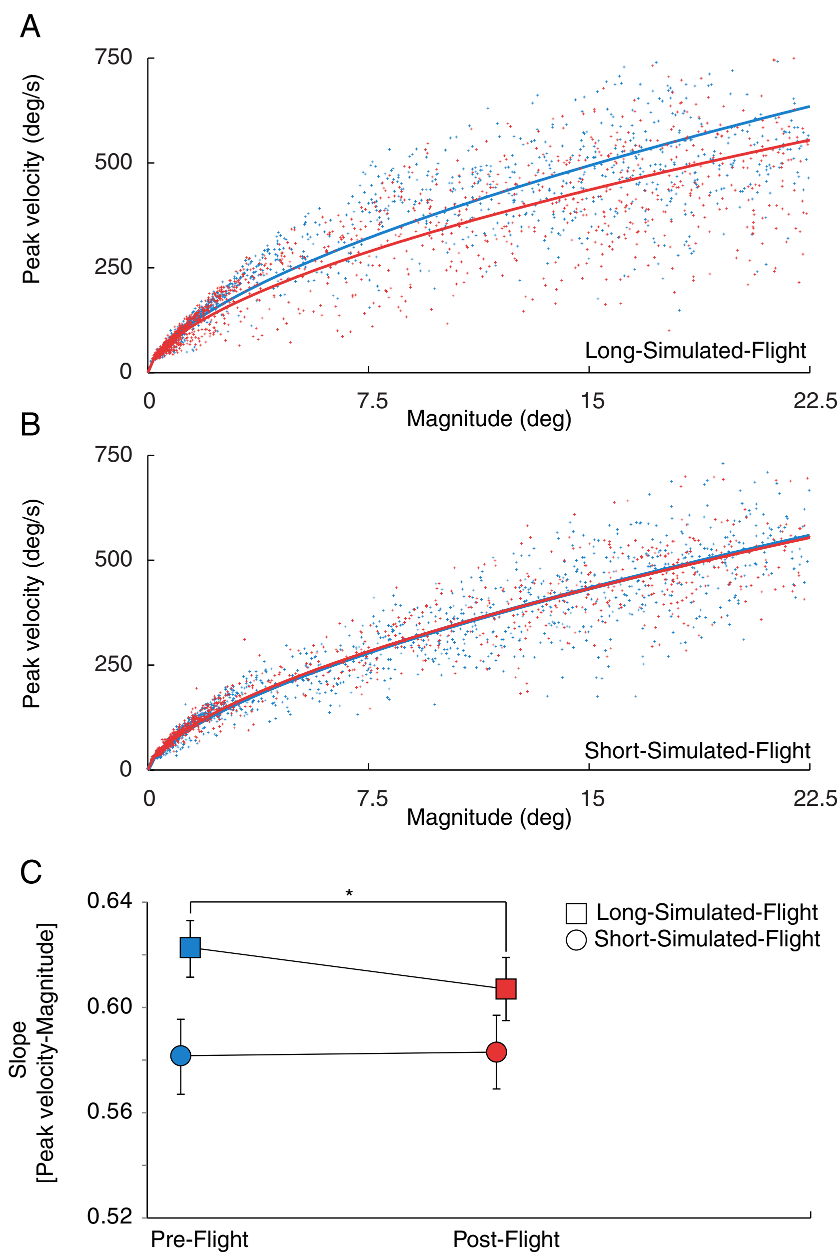


Fig. 2. Effects of simulated time-on-flight and measuring session on the saccadic peak velocity–magnitude relationship. A, B) Saccadic peak velocity–magnitude relationships for two pilots: Long-Simulated-Flight (A) and Short-Simulated-Flight (B), each of them at two different measuring sessions: Pre-Flight (blue) and Post-Flight (red). Each dot represents one saccade. There are ~300 saccades per measuring session (per pilot). In panels A and B, the curves are the power–law fits to the data from a pilot showing typical performance for each condition (#329 for Long-Simulated-Flight: #323 for Short-Simulated-Flight). C) The graph indicates the average slopes across all participants for each measuring session and group ($n = 15$ [Long-Simulated-Flight group] and $n = 11$ [Short-Simulated-Flight group]). Striped bars indicate the Long-Simulated-Flight group. Slopes decreased from the Pre-Flight to the Post-Flight session only for the Long-Simulated-Flight group. Error bars represent the SEM across subjects for each group. The symbol "*" denotes statistical significance between measuring sessions (Pre-/Post-Simulated-Flight). Note that the slope difference, between the two groups of pilots at the Pre-Flight session, may be due to inter-subject variability.

expertise (i.e. number of aircraft flight hours) and TOF, we correlated the difference between the Pre-Flight and Post-Flight slopes values with the number of aircraft flight hours in both groups.

3. Results

3.1. Saccadic main sequence relationships

The slope of the saccadic peak velocity–magnitude relationship (Fig. 2 and Table 1) decreased from the Pre-Flight to the Post-Flight session for the Long-Simulated-Flight group (corrected p-value < 0.05), but not for the Short-Simulated-Flight group (interaction between *measuring session* and *flight length* [$F(1, 24) = 4.91$, $p = 0.036$], *measuring session* [$F(1, 24) = 4.1$, $p = 0.053$], and *flight length* [$F(1, 24) = 3.57$, $p = 0.070$]). Even though the differences between Long/Short-Simulated-Flight were small, slope decrements from Pre-Flight to Post-Flight were on average 37% larger in the Long-Simulated-Flight than in the Short-Simulated-Flight, with 13 pilots (out 15) showing the same tendency. Furthermore, a paired t-test showed that slope decrements in the Long-Simulated-Flights were significantly different from 0 ($t(14) = 3.03$, $p = 0.007$). Slope decrements in the Short-Simulated Flight did not, however, differ from 0 ($t(10) = -0.14$, $p = 0.894$), indicating that Short-Simulated-Flights had no measurable effect on the main sequence slope. Finally, there was no effect of pilot expertise on the slopes in either Long- or Short-Simulated-Flight were not mediated by flight expertise ($r_{(\text{Long-Simulated-Flight})} = 0.30$ and $r_{(\text{Short-Simulated-Flight})} = 0.20$; all p-values > 0.05).

The slope of the saccadic mean velocity–magnitude relationship decreased between measuring session for both groups [$F(1, 24) = 4.43$, $p = 0.046$] (see Table 1).

The slope of the saccadic duration–magnitude relationship was not affected by the *measuring session* or *flight length* (all p-values > 0.05) (see Table 1). The lack of *measuring session* and *flight length* modulation on saccadic duration–magnitude relationships is consistent with the results from our recent work [12] where the effect of surgical fatigue (after 24 hour shift) was not apparent in this main sequence relationship.

Overall these results are consistent with previous reports indicating a link between increased time-on-task and decreased saccadic peak velocity [18,20,22]. See Table 1 for additional details about the effects of *measuring session* and *flight length* on other saccadic parameters.

4. Discussion

We examined the effects of simulated TOF on saccadic metrics within similar temporal windows to the durations of simulated light attack squadron missions during actual aviator training sessions, where the maximum TOF is ~2 h (i.e. the approximate maximal time of a helicopter mission when carrying ordnance, as limited by fuel capacity).

We found evidence of a relationship between simulated TOF and the saccadic metrics of naval aviators. Simulated TOF modulated the saccadic peak velocity–magnitude main sequence relationship in a manner consistent with previous observations conducted in the laboratory and in non-safety critical time-on-task scenarios [17,18,51]. This difference was significant for long simulated flights only, indicating that fatigue associated with sessions of more than one hour was demonstrable. Because pilots simulated air-combat maneuvers and emergency checklist procedures, it is highly improbable that they felt bored during the simulated flight [52]. Therefore, the decrease in saccadic velocities observed here is most parsimoniously explained by TOF, rather than boredom.

Previous studies [18,53] found that short (<1 h) simulated driving sessions did not affect the saccadic peak velocity–magnitude relationship, but that long driving sessions (~2 h) did. This dissociation might be explained by variations in sympathetic nervous system activation; that is, by variations in the pilot's arousal level [22]. Several saccade generation models [54–58] have assumed the presence of an excitatory connection from hypothetical arousal neurons to omnipause neurons [OPNs], which are critical to encoding saccadic velocity [59], in the brainstem. OPNs stop firing during sleep [60], and their inactivation produces slower saccades [61–63]. Decreased activation of hypothetical arousal neurons results in saccadic metrics “similar to those observed in case of fatigue state” [56]. Thus, variations in arousal, mediated by hypothetical arousal neurons projecting onto OPNs, might lead to changes in saccadic velocity with increased time-on-task.

Note that fatigue levels, as indicated by saccadic metrics, differed between physically fit US Marine Aviators who ran simulator missions that varied in duration by 60 min or less. The effect size is, not surprisingly modest (~17%). To ensure the sensitivity of our biomarker, when used in practical applications, we suggest the creation of a database containing baseline scores for each individual pilot (i.e. data obtained when the pilot is rested — across a long time frame), using a pre-/post-test comparison in the analysis, so as to control for inter-subject variability and maximize sensitivity. This would reduce false-positive results potentially caused by the high intra-individual variability that characterizes saccadic metrics ([39,48]).

5. Conclusions

Fatigue is one of the most cited factors contributing to flight accidents. It has cost—within the US in the last two decades—both human lives as well as hundreds of millions of dollars in equipment loss [64]. Our findings have shown that saccadic velocity decreases with increased simulated time-on-flight, suggesting that saccadic metrics could serve as a biomarker of aviator fatigue. A saccadic-based index of aviator fatigue advances a potential biomarker for in-flight fitness-for-duty standards that if implemented into a pre-flight testing system could reduce fatigue-related accidents providing scientific-based recommendations for new flight regulations and individualized fatigue assessment tools. Furthermore, in the future, our findings might offer medical aviation departments a tool that may assist the development of screening and training programs.

Author contributions

SLM, LLDS, SMC, MBM, EG, CH, and MF designed the experiment. LLDS completed all experimental work at the 3rd Marine Aircraft Wing Corp Base (Camp Pendleton, CA, USA). MBM, LLDS, SLM, SMC and AC analyzed and interpreted the data. LLDS, SMC, and SLM wrote the article.

Acknowledgments

We thank Max Dorfman for administrative and technical assistance and the Cubic Corporation staff for their help during the data collection. This study was supported by a challenge grant from Research to Prevent Blindness Inc. to the Department of Ophthalmology at SUNY Downstate, the New York State Empire Innovation Program (Awards to SMC and SLM), the Barrow Neurological Foundation (Awards to SMC and SLM), the National Science Foundation (Award 1439189 to SLM and Award 1153786 to SMC), the Spanish Ministry of Economy and Finance (project PSI2012-39292 to AC), the Fellowship programs MEC-Fulbright and Talentia-Postdoc (Grants PS-2010-0667 and 267226 to LLDS), the CEMIX UGR-MADOC and the Spanish Department of Transportation (Projects PINS201416 and SPIP20141426 respectively, to LLDS). The authors have no conflicts of interest to declare.

References

[1] J.A. Caldwell, M.M. Mallis, J.L. Caldwell, M.A. Paul, J.C. Miller, D.F. Neri, Fatigue countermeasures in aviation, Aviat. Space Environ. Med. 80 (2009) 29–59.
[2] K.E. Friedl, S.J. Grate, S.P. Proctor, J.W. Ness, B.J. Lukey, R.L. Kane, Army research needs for automated neuropsychological tests: monitoring soldier health and performance status, Arch. Clin. Neuropsychol. 22 (2007) S7–S14.

[3] J.A. Caldwell, J.L. Caldwell, J.S. Crowley, Sustaining female helicopter pilot performance with dexedrine during sleep deprivation, Int. J. Aviat. Psychol. 7 (1997) 15–36.
[4] F.H. Previc, N. Lopez, W.R. Ercoline, C.M. Daluz, A.J. Workman, R.H. Evans, et al., The effects of sleep deprivation on flight performance, instrument scanning, and physiological arousal in pilots, Int. J. Aviat. Psychol. 19 (2009) 326–346.
[5] J.A. Caldwell, Crew schedules, sleep deprivation, and aviation performance, Curr. Dir. Psychol. Sci. 21 (2012) 85–89.
[6] M.N. Tennison, J.D. Moreno, Neuroscience, Ethics, and National Security: The State of the Art, PLoS Biol. 10 (2012) e1001289.
[7] I. Tracey, R. Flower, The warrior in the machine: neuroscience goes to war, Nat. Rev. Neurosci. 15 (2014) 825–834.
[8] J.A. Caldwell, C.F. Kelly, K.A. Roberts, H.D. Jones, J.A. Lewis, W. Larry, et al., A Comparison of EEG and Evoked Response Data Collected in a UH-1 Helicopter to Data Collected in a Standard Laboratory Environment, DTIC Document, U.S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama, 1997.
[9] T.L. Signal, J. Gale, P.H. Gander, Sleep measurement in flight crew: comparing actigraphic and subjective estimates to polysomnography, Aviat. Space Environ. Med. 76 (2005) 1058–1063.
[10] R.K. Gore, T.S. Webb, E.D.A. Hermes, Fatigue and stimulant use in military fighter aircrew during combat operations, Aviat. Space Environ. Med. 81 (2010) 719–727.
[11] L.L. Di Stasi, A. Antolí, J.J. Cañas, Evaluating mental workload while interacting with computer-generated artificial environments, Entertain. Comput. 4 (2013) 63–69.
[12] L.L. Di Stasi, M.B. McCamy, S.L. Macknik, J.A. Mankin, N. Hooft, A. Catena, et al., Saccadic eye movement metrics reflect surgical residents' fatigue, Ann. Surg. 259 (2014) 824–829.
[13] W.M. Troxel, R.A. Shih, E.R. Pedersen, L. Geyer, M.P. Fisher, B.A. Griffin, et al., Sleep in the Military: Promoting Healthy Sleep Among U.S. Servicemembers, RAND Corporation-RR739, Santa Monica, CA, 2015.
[14] R. Dodge, The laws of relative fatigue, Psychol. Rev. 24 (1917) 89–113.
[15] M. Prsa, P.W. Dicke, P. Thier, The absence of eye muscle fatigue indicates that the nervous system compensates for non-motor disturbances of oculomotor function, J. Neurosci. 30 (2010) 15834–15842.
[16] D. Schmidt, L.A. Abel, L.F. DellOsso, R.B. Daroff, Saccadic velocity characteristics — intrinsic variability and fatigue, Aviat. Space Environ. Med. 50 (1979) 393–395.
[17] C. Ahlstrom, M. Nyström, K. Holmqvist, C. Fors, D. Sandberg, A. Anund, et al., Fit-for-duty test for estimation of drivers' sleepiness level: eye movements improve the sleep/wake predictor, Transp. Res. Part C Emerg. Technol. 26 (2013) 20–32.
[18] L.L. Di Stasi, R. Renner, A. Catena, J.J. Cañas, B.M. Velichkovsky, S. Pannasch, Towards a driver fatigue test based on the saccadic main sequence: a partial validation by subjective report data, Transp. Res. Part C Emerg. Technol. 21 (2012) 122–133.
[19] L.L. Di Stasi, M.B. McCamy, S. Pannasch, R. Renner, A. Catena, J.J. Cañas, et al., Effects of driving time on microsaccadic dynamics, Exp. Brain Res. 1–7 (2015).
[20] L.L. Di Stasi, M.B. McCamy, A. Catena, S.L. Macknik, J.J. Cañas, S. Martinez-Conde, Microsaccade and drift dynamics reflect mental fatigue, Eur. J. Neurosci. 38 (2013) 2389–2398.
[21] R.J. Leigh, D.S. Zee, The Neurology of Eye Movements, Oxford Univ Press, 2015.
[22] L.L. Di Stasi, A. Catena, J.J. Cañas, S.L. Macknik, S. Martinez-Conde, Saccadic velocity as an arousal index in naturalistic tasks, Neurosci. Biobehav. Rev. 37 (2013) 968–975.
[23] K. Hirvonen, S. Puttonen, K. Gould, J. Korpela, V.F. Koefoed, K. Müller, Improving the saccade peak velocity measurement for detecting fatigue, J. Neurosci. Methods 187 (2010) 199–206.
[24] L. McIntire, R. Andy, J. McIntire, C. Goodyear, J. Nelson, Eye metrics: an alternative vigilance detector for military operators, Mil. Psychol. 25 (2013) 502–513.
[25] Y. Morad, Y. Barkana, D. Zadok, M. Hartstein, E. Pras, Y. Bar-Dayan, Ocular parameters as an objective tool for the assessment of truck drivers fatigue, Accid. Anal. Prev. 41 (2009) 856–860.
[26] J. Tong, J. Maruta, K.J. Heaton, A.L. Maule, J. Ghajar, Adaptation of visual tracking synchronization after one night of sleep deprivation, Exp. Brain Res. 232 (2014) 121–131.
[27] H.P. Van Dongen, J.A. Caldwell, J.L. Caldwell, Investigating systematic individual differences in sleep-deprived performance on a high-fidelity flight simulator, Behav. Res. Methods 38 (2006) 333–343.
[28] D. Dawson, A.K. Searle, J.L. Paterson, Look before you (s)leep: evaluating the use of fatigue detection technologies within a fatigue risk management system for the road transport industry, Sleep Med. Rev. 18 (2014) 141–152.
[29] C.A. Portman-Tiller, The Fitness Impairment Test (FIT): A First Look, DTIC Document, 1998.
[30] A. Watson, L. Miller, M. Dawkins, C. Lorenz, N.S. Latman, Evaluation of validity of the PMI FIT 2000-3 Fitness-for-Duty/Impairment Screener, J. Clin. Eng. 31 (2006) 206–212.
[31] P.A. LeDuc, J.L. Greig, S.L. Dumond, Involuntary eye responses as measures of fatigue in U.S. Army Apache Aviators, Aviat. Space Environ. Med. 76 (2005) C86–C91.
[32] M. Rothberg, T.N. Cornsweet, R.D. Marc, Fitness impairment tester, Patent number: US 542269 A, 1995.
[33] C.D. Wickens, J.S. McCarley, Applied Attention Theory, CRC Press, Boca Raton, 2007.
[34] B.S. Oken, M.C. Salinsky, S.M. Elsas, Vigilance, alertness, or sustained attention: physiological basis and measurement, Clin. Neurophysiol. Off. J. Int. Fed. Clin. Neurophysiol. 117 (2006) 1885–1901.
[35] J. Roca-Dorda, J. Roca-González, F. Martínez-Gonzalez, A. Guillamón-Frutos, Fatigue, Wiley Encycl. Biomed. Eng. John Wiley & Sons, Inc., 2006.
[36] WMA, Human experimentation: code of Ethics of W.M.A. Br. Med. J. 2 (1964) 177.
[37] Q. Kennedy, J.L. Taylor, G. Reade, J.A. Yesavage, Age and expertise effects in aviation decision making and flight control in a flight simulator, Aviat. Space Environ. Med. 81 (2010) 489–497.
[38] J.L. Taylor, Q. Kennedy, A. Noda, J.A. Yesavage, Pilot age and expertise predict flight simulator performance, Neurology 68 (2007) 648–654.
[39] A.T. Bahill, A. Brockenbrough, B.T. Troost, Variability and development of a normative data base for saccadic eye movements, Invest. Ophthalmol. Vis. Sci. 21 (1981) 116–125.
[40] L.A. Abel, B.T. Troost, L.F. Dell'osso, The effects of age on normal saccadic characteristics and their variability, Vis. Res. 23 (1983) 33–37.
[41] D.P. Morasso, E. Bizzi, D.J. Dichgans, Adjustment of saccade characteristics during head movements, Exp. Brain Res. 16 (1973) 492–500.
[42] E. Vural, M. Cetin, A. Ercil, G. Littlewort, M. Bartlett, J. Movellan, Drowsy Driver detection through facial movement analysis, in: M. Lew, N. Sebe, T.S. Huang, E.M. Bakker (Eds.), Human–Computer Interact, Springer, Berlin Heidelberg 2007, pp. 6–18.
[43] M.B. McCamy, J. Otero-Millan, S.L. Macknik, Y. Yang, X.G. Troncoso, S.M. Baer, et al., Microsaccadic efficacy and contribution to foveal and peripheral vision, J. Neurosci. 32 (2012) 9194–9204.
[44] X.G. Troncoso, S.L. Macknik, S. Martinez-Conde, Microsaccades counteract perceptual filling-in, J. Vis. 8 (2008) 1–9.
[45] R. Engbert, K. Mergenthaler, Microsaccades are triggered by low retinal image slip, Proc. Natl. Acad. Sci. 103 (2006) 7192–7197.
[46] F. Møller, M. Laursen, J. Tygesen, A. Sjølie, Binocular quantification and characterization of microsaccades, Graefes Arch. Clin. Exp. Ophthalmol. 240 (2002) 765–770.
[47] A.T. Bahill, M.R. Clark, L. Stark, The main sequence, a tool for studying human eye movements, Math. Biosci. 24 (1975) 191–204.
[48] A.T. Bahill, L. Stark, Overlapping saccades and glissades are produced by fatigue in the saccadic eye movement system, Exp. Neurol. 48 (1975) 95–106.
[49] L. Aiken, S. West, Multiple Regression: Testing and Interpreting Interactions, SAGE Publications, Inc., Newbury Park, Calif., 1991.
[50] L.L. Di Stasi, R. Cabestrero, M.B. McCamy, F. Ríos, A. Catena, P. Quirós, et al., Intersaccadic drift velocity is sensitive to short-term hypobaric hypoxia, Eur. J. Neurosci. 39 (2014) 1384–1390.
[51] L.L. Di Stasi, A. Antolí, J.J. Cañas, Main sequence: an index for detecting mental workload variation in complex tasks, Appl. Ergon. 42 (2011) 807–813.
[52] L.L. Di Stasi, C. Diaz-Piedra, J. Suárez, M.B. McCamy, S. Martinez-Conde, J. Roca-Dorda, et al., Task complexity modulates pilot electroencephalographic activity during real flights, Psychophysiology 52 (2015) 951–956.
[53] L.L. Di Stasi, R. Renner, P. Staehr, J.R. Helmert, B.M. Velichkovsky, J.J. Canas, et al., Saccadic peak velocity sensitivity to variations in mental workload, Aviat. Space Environ. Med. 81 (2010) 413–417.
[54] G. Gancarz, S. Grossberg, A neural model of the saccade generator in the reticular formation, Neural Netw. 11 (1998) 1159–1174.
[55] B. Girard, A. Berthoz, From brainstem to cortex: computational models of saccade generation circuitry, Prog. Neurobiol. 77 (2005) 215–251.
[56] S. Grossberg, M. Kuperstein, Neural Dynamics of Adaptive Sensory-motor Control: Ballistic Eye Movements(North Holland) 1986.
[57] A.K. Moschovakis, Neural network simulations of the primate oculomotor system, Biol. Cybern. 70 (1994) 291–302.
[58] A. Rahafrooz, A. Fallah, A.H. Jafari, F. Bakouie, S. Zendehrouh, S. Gharibzadeh, Saccadic and smooth pursuit eye movements: computational modeling of a common inhibitory mechanism in brainstem, Neurosci. Lett. 448 (2008) 84–89.
[59] D.L. Sparks, The brainstem control of saccadic eye movements, Nat. Rev. Neurosci. 3 (2002) 952–964.
[60] V. Henn, R.W. Baloh, K. Hepp, The sleep–wake transition in the oculomotor system, Exp. Brain Res. Exp. Hirnforsch. Expérimentation Cérébrale 54 (1984) 166–176.
[61] C.R. Kaneko, Effect of ibotenic acid lesions of the omnipause neurons on saccadic eye movements in rhesus macaques, J. Neurophysiol. 75 (1996) 2229–2242.
[62] K. Miura, L. Optican, Membrane channel properties of premotor excitatory burst neurons may underlie saccade slowing after lesions of omnipause neurons, J. Comput. Neurosci. 20 (2006) 25–41.
[63] R. Soetedjo, C.R.S. Kaneko, A.F. Fuchs, Evidence that the superior colliculus participates in the feedback control of saccadic eye movements, J. Neurophysiol. 87 (2002) 679–695.
[64] A. Nunes, P. Cabon, The fatigue conundrum, Am. Sci. 103 (2015) 218–223.