International Journal of Aviation, Aeronautics, and Aerospace

Volume 5 | Issue 5 Article 6

2018

# Modeling Oculomotor Variability During Slow Cabin Decompression Using Infrared Technology

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## Introduction

Hypoxia remains a hazard in aviation (Temme, Still, & Acromite, 2010). The Federal Aviation Administration (FAA; 2013) warned that slow cabin decompression is notably perilous due to its gradual, generally imperceptible nature and absence of the environmental signs usually present during rapid and explosive decompression. Such slow decompression incidents are commonly associated with failures of the pressurization system on ascent and oxygen mask and supply systems onboard military trainer and fighter aircraft (Cable, 2003; Gradwell, 2006; Rayman & McNaughton, 1983). Given that more fatalities associated with cabin depressurization are slow compared to explosive models, it is prudent to better understand other physical impairments besides subjective sensations to help identify the insidious nature of slow-onset hypoxia. In this study, special attention is paid to using infrared technology to detect early changes in oculomotor behavior.

Without supplemental oxygen mitigation, increasing altitude can induce hypobaric hypoxia, in which decreasing atmospheric pressure lends to reduced oxygen partial pressure in the alveoli of the lungs. Physical, cognitive, psychomotor, and visual impairments, and loss of consciousness and life can eventually result (Petrassi, Hodkinson, & Gaydos, 2012). Given the high demands for oxygen imposed by the human retina and brain, the visual system can be an effective proxy for investigating the central nervous system's response to hypoxia (Cymerman, Muza, Friedlander, Fulco, & Rock, 2005). Further, gaze-related oculometrics have been shown to reflect visual attention allocation within an environment, and ultimately, flight performance (see Ziv, 2016, for a review) as the visual modality is heavily drawn upon in flight (Wickens, Goh, Helleberg, Horrey, & Talleur, 2003). For instance, experienced pilots fixate longer upon relevant instruments following a system malfunction (van de Merwe, van Dijk, & Zon, 2012; van Dijk, van de Merwe, & Zon, 2011), but after an unanticipated change in automation state, they tend to exhibit exploratory visual behavior as characterized by shorter fixations and more frequent saccades (Dehais, Peysakhovich, Scannella, Fongue, & Gateau, 2015).

Fixations stabilize the high-resolution fovea over an area of interest within the visual environment for information processing (Rolfs, 2009). Schleicher, Galley, Briest, and Galley (2008) described how the variability in fixation duration may reflect different cognitive processes and states. Generally, medium duration fixations (150 – 900 ms) are required for semantic processing (e.g., identifying stimuli in a visual scene, gathering information; Diez et al., 2001) especially in difficult tasks (Cornelissen, Bruin, & Kooijman, 2005). More specifically within this medium range, visually novel or rapidly changing scenes tend to necessitate greater sampling rates, thereby shortening fixations (Galley & Andrés, 1996), while decision-making and higher memory load can require longer fixations (Gould,

1973). Extremely short fixations (< 150 ms) are too brief for information processing but instead serve lower-level activity such as visuomotor reflexes and adjustment of gaze location (Galley & Andrés, 1996). Overlong fixations (> 900 ms) can indicate reduced alertness and impaired visual scanning.

Saccades are rapid eye movements, generally 10 – 100 ms in duration, that direct the fovea between fixations in accordance with both voluntary and reflexive motivations (Findlay, 2009; Rolfs, 2009). Microsaccades are small (< 1 degree of visual angle; see Martinez-Conde, Macknik, Troncosco, & Hubel, 2009) but high velocity involuntary movements that occur during fixations along with other small motions—intersaccadic drift and tremors. These three features assist in the acquisition and steadying of gaze during fixations, preventing visual image decay due to neural adaptation by continually repositioning the receptive fields over the fixated target (Rolfs, 2009) and may enhance acuity by improving spatial resolution during fixations (Martinez-Conde et al., 2009). Saccadic velocity has been proposed as a measure of cerebral activation (Galley, 1989) and cognitive arousal (DiStasi, Catena, Cañas, Macknik, & Martinez-Conde, 2013). Decelerated saccadic velocity may reflect deactivation more reliably than many other visual parameters (Galley, 1989); it is a signal of impaired cerebral states such as sleep deprivation and substance use (see Fransson et al., 2008; Merz et al., 2013) and has been suggested as a biomarker of aviator impaired state, namely fatigue (DiStasi et al., 2016).

Existing research on fixation metrics during hypoxia appears to be limited and somewhat variable. Kowalczuk et al. (2016) assessed pilots simultaneously exposed to both hypoxia and the Coriolis illusion and reported a non-significant increase in mean fixation time at 5000 m followed by a reduction at 6000 m, in addition to an increase in small or 'correctional' saccades, which was thought to reflect subjects' difficulty in executing effective fixations. Stepanek et al. (2014) tested non-pilot subjects on a rapidly paced reading task under reduced oxygen breathing and reported a marginal increase in mean fixation time.

The reported effects of hypoxia on saccadic velocity are also quite varied. Cymerman et al. (2003) did not observe any such changes in military personnel performing a visual reflex task in either a hypobaric chamber or during a 24-h mountaineering expedition. During a two-week version of the expedition, however, saccadic velocity was temporarily elevated from days 2 - 6, possibly due to sympathetic nervous system stimulation (Cymerman, Muza, Friedlander, Fulco, & Rock, 2005). Acclimatization was cited as the likely reason that Merz et al. (2013) did not observe changes in saccade metrics on a three-week mountaineering expedition. DiStasi et al. (2014) did not observe changes as a function of hypobaric hypoxia in a guided saccade task. In a visual reaction time test conducted under reduced oxygen breathing, van der Post et al. (2002) reported reduced peak saccadic velocity in larger saccades when blood oxygen saturation ($SpO_2$) decreased from

90% to 80%. Further, a non-significant increase was observed when progressing from normoxia to 90% $SpO_2$ and was attributed to possible compensatory-driven activation. However, post-hypoxia observations were not reported. Stepanek et al. (2014) also utilized the reduced oxygen breathing method but did not observe velocity changes during a fast-paced reading task. These prior investigations have employed several different means of inducing hypoxia under various settings and task demands and have used different populations of subjects. Research documenting the effect of slow-onset hypobaric hypoxia on saccadic velocity in the flight environment, however, is lacking.

Saccadic velocity is generally measured in one of two ways. *Peak* saccadic velocity is appropriate for large saccades (i.e., > 15 degrees) and is best recorded with high temporal resolution (e.g., 500 - 1000 Hz) techniques such as electrooculography (EOG). Alternatively, lower temporal resolution equipment can assess *mean* saccadic velocity, an adequate measure for smaller saccades, wherein the acceleration and deceleration phases of the velocity waveform are equivalent and symmetric across the duration of the saccade (Bahill, Clark, & Stark, 1975). Infrared camera-based eye-tracking is an example of a lower resolution technology that is generally more accessible, less expensive, and unobtrusive, particularly for use in vehicles for operator state monitoring (DiStasi et al., 2014; Stern, 1994). Hypoxia-driven changes in saccadic velocity as detected by lower resolution, infrared-based eye-tracking have not yet been reported, especially as measured within an applied aviation context. The objective of the current study was to assess the sensitivity of a lower resolution infrared-based eye-tracking system in modeling subtle changes in oculomotor biomarkers at progressive stages of slow decompression.

## Method

### Subjects

Subjects were 12 pilots (11 males, 1 female; mean age = 27.4 years, *SD* = 5.7) with a minimum of a commercial rating and 50 hours with the Garmin 1000 (G1000) avionics suite. Their mean total flight hours was 1473.8 (range: 340 - 3700). All subjects had a valid FAA medical certificate and were screened for disqualifying medical issues such respiratory and digestive concerns. Subjects were nonsmokers and dietary restrictions prior to participation were not imposed. Subjects were tested individually. To preclude possible diurnal effects, all subjects were tested between 1400 and 1600 hours local time. Subjects were informed that they would be experiencing decompression during simulated flight but were not kept aware of their current $SpO_2$ levels during the sessions.

### Materials

A flight simulator featuring a G1000 suite was housed inside a 10-ft. x 32-ft. Class D multi-lock hypobaric chamber maintained at 75˚ Fahrenheit with humidity between 45 and 50%, ambient chamber oxygen concentration below 21%,

and ambient chamber carbon dioxide below 0.1 mBar. Subjects' $SpO_2$ levels were monitored by chamber tenders via video display of readings from a finger-worn pulse oximeter. The subjects communicated with a simulated air traffic controller using a David Clark headset.

A head-mounted eye-tracker (Dikablis Professional by Ergoneers, Inc.) was used for oculomotor recording. It is comprised of a three-camera system featuring a scene camera that records a 90-degree, 1920 x 1080-pixel video of the subject's field of view and two infrared cameras, each recording an eye at 60 Hz. The D-Lab 3 software features a pupil detection algorithm with tracking accuracy within 0.05 deg. of visual angle with a pixels/deg. coefficient of 2.5.

**Design**

During each of seven possible $SpO_2$ conditions, oculomotor data was recorded and subjects were verbally queried regarding any symptoms of hypoxia. The sequence began with one pre-hypoxia normoxia baseline condition (sea-level equivalence), followed by gradually intensifying hypoxia conditions in which $SpO_2$ was reduced by approximately 5% (i.e., 95%, 90%, 85%, 80%, and 75%), and lastly, one post-hypoxia normoxia condition (sea-level equivalence). The average ascent rate was 1500 ft./min. The chamber was repressurized to sea-level equivalence and subjects donned an oxygen mask if their sustained $SpO_2$ fell below 70%, the simulated altitude exceeded 17,000 ft., or upon subjects' request, the latter of which did not occur at any point during the study.

The task, which was executed at each $SpO_2$ level, consisted of a simulated air traffic controller verbalizing a set of 15 periodic instructions in a randomized order pertaining to changes in heading, altitude, radio frequencies and transponder codes as well as queries regarding current flight parameters such as current heading or altitude (e.g., "Turn left heading 220", "Descend and maintain FL190", "State current altitude"). Subjects were instructed to program the autopilot or verbally respond accordingly. Each set of instructions required approximately 5 min. to complete.

**Data Analysis**

A gaze point was defined as one raw sample captured by the eye-tracker, which was recorded at a rate of 60 Hz for each dependent measure. Saccade and fixation durations were measured in milliseconds (ms). A fixation was defined as an alignment of the eyes upon a location lasting between 120 – 2000 ms. Saccade angle was measured in degrees (deg.). Mean saccadic velocity was measured in deg./sec. Saccade and fixation rates were measured in number per min. Pupil diameter was measured as width in pixels. Microsaccades were defined as saccades of an angle of < 1 deg. The dependent measures were aggregated for each subject over the duration of each $SpO_2$ level.

Data was analyzed using SPSS version 24. Descriptive statistics for each $SpO_2$ condition were calculated to show the progression of oculomotor changes

across stages of decompression. Due to individual differences in when subjects reached the predetermined safety limits, the 75% $SpO_2$ condition had data from five subjects, while the remaining seven subjects did not progress past the 80% $SpO_2$ condition; as such, 80% was the lowest $SpO_2$ level represented in the statistical analyses. Pupil diameter data was available on nine subjects due to a software failure.

## Results

### Subjective Symptoms and Heart Rate

Subjects self-reported the following symptoms during the hypoxia exposure: at 80% $SpO_2$, half of the participants reported experiencing lightheadedness, one third reported sensations of warmth, while other symptoms such as feeling slow or 'behind the aircraft', paresthesia, and euphoria were less common. Additionally, one participant reported more vivid color perception. At 75% $SpO_2$, two additional participants reported sensations of warmth as well as feeling slow or 'behind the aircraft', and one participant reported narrowed vision. One additional participant reported a lack of symptoms throughout the entire hypoxia exposure, including the 75% $SpO_2$ condition. All subjects reported resolution of the symptoms upon re-saturation.

The following mean equivalent simulated altitudes and heart rates (in beats/min.; BPM) recorded at each $SpO_2$ level are reported in Table 1. It was observed that heart rate increased concomitantly with simulated altitude and normalized in the post-hypoxia condition. All subjects' $SpO_2$ levels returned to their pre-hypoxia baseline levels in the post-hypoxia normoxia condition.

Table 1

*Mean Altitude and Physiological Response at Each $SpO_2$ Level*

| | BL Mean (SD) | 95% Mean (SD) | 90% Mean (SD) | 85% Mean (SD) | 80% Mean (SD) | 75% Mean (SD) | Post-Hypoxia Mean (SD) |
|---|---|---|---|---|---|---|---|
| Simulated Altitude (ft.) | -- | 6,597 (1,402) | 10,587 (1,770) | 13,590 (1,074) | 15,479 (1,240) | 16,514 (1,239) | -- |
| Heart Rate (BPM) | 91.1 (13.9) | 99.0 (14.4) | 101.0 (13.2) | 105.7 (12.6) | 108.6 (14.6) | 109.3 (16.5) | 90.3 (2.5) |

*Note.* BL = Baseline.

**Oculomotor Performance**

Oculomotor results indicated that as $SpO_2$ decreased, saccade angle, saccade rate, saccadic velocity, fixation duration, and pupil diameter decreased while saccade duration increased, and all metrics but saccade rate rebounded when the chamber was recompressed to sea-level equivalence in the post-hypoxia normoxia condition. Saccade rate continued to decrease upon recompression. Fixation rate was variable in its response to declining $SpO_2$. Table 2 indicates the descriptive statistics for the oculomotor variables at each level of $SpO_2$ condition, including the values from subjects' lowest attained $SpO_2$ levels as used in the rmANOVAs. Table 2 also indicates the mean percent change from pre-hypoxia baseline mean values (i.e., ΔBL) for each metric across subjects.

Table 3 presents the results of the rmANOVAs comparing mean values for each metric from the baseline, lowest attained $SpO_2$, and post-hypoxia normoxia conditions; the results of planned comparisons of 1) the baseline with the lowest attained $SpO_2$ to assess susceptibility to hypoxia and 2) the lowest attained $SpO_2$ with the post-hypoxia normoxia conditions to assess recovery upon re-saturation; and the results of polynomial contrasts to determine trends across decreasing $SpO_2$ levels (baseline through 80% $SpO_2$).

Table 2

*Descriptive Statistics for Each Metric by $SpO_2$ Level and Mean Percent Change from Baseline*

| Metric | BL Mean (SD) | 95% Mean (SD) ΔBL | 90% Mean (SD) ΔBL | 85% Mean (SD) ΔBL | 80% Mean (SD) ΔBL | 75% Mean (SD) ΔBL | Lowest Mean (SD) ΔBL | Post-Hyp. Mean (SD) ΔBL |
|---|---|---|---|---|---|---|---|---|
| Saccade Angle (deg.) | 5.47 (0.88) | 5.17 (0.73) -4.21% | 5.21 (0.95) -3.93% | 5.28 (0.77) -2.59% | 4.98 (0.94) -8.13% | 5.52 (0.52) -1.75% | 4.91 (0.88) -9.27% | 5.49 (0.96) -2.08% |
| Saccade Duration (ms) | 36.88 (7.91) | 37.08 (4.36) +2.75% | 37.28 (4.63) +3.78% | 40.33 (8.56) +12.14% | 40.46 (10.50) +10.76% | 44.33 (12.83) +18.3% | 42.44 (12.83) +15.3% | 36.36 (5.48) +0.80% |
| Saccade Rate (per min.) | 58.50 (17.6) | 56.45 (18.84) -4.11% | 51.23 (18.25) -13.3% | 54.05 (17.67) -7.44% | 56.05 (20.22) -5.50% | 63.05 (10.49) -4.22% | 55.36 (18.71) -5.75% | 49.18 (8.09) -11.85% |
| Saccadic Velocity (deg/sec) | 168.08 (32.0) | 154.83 (19.01) -6.28% | 157.08 (17.65) -4.82% | 149.55 (24.64) -9.20% | 150.86 (23.47) -8.70% | 142.48 (39.69) -12.69% | 144.97 (25.55) -12.85% | 164.10 (27.47) -1.21% |
| Fixation Duration (ms) | 954.80 (263) | 965.26 (324.05) +0.32% | 995.19 (321.05) +3.82% | 902.57 (264.97) -5.20% | 854.23 (287.66) -11.74% | 762.33 (288.69) -9.59% | 868.03 (284.71) -9.84% | 1002.72 (196.34) +10.15% |
| Fixation Rate (per min.) | 63.10 (18.8) | 63.45 (21.38) +0.001% | 60.59 (20.08) -4.24% | 64.24 (17.76) +2.61% | 68.83 (22.66) +8.22% | 69.04 (23.35) -1.50% | 64.70 (22.00) +2.60% | 56.59 (9.52) -6.43% |
| Pupil Diameter (pixels) | 28.03 (3.36) | 27.54 (3.30) -1.67% | 26.93 (3.48) -3.98% | 26.86 (3.34) -4.18% | 26.09 (3.39) -6.87% | 25.60 (2.15) -4.03% | 27.35 (5.03) -6.78% | 28.94 (5.03) +0.21% |

*Notes.* BL = Baseline. ΔBL = mean percent change from BL.

Table 3

*Statistical Analyses Comparing Changes in Metrics Across $SpO_2$ Levels*

| Metric | rmANOVA (BL, Lowest, Post) | BL vs. Lowest | Lowest vs. Post | Polynomial Contrast (BL through 80%) |
|---|---|---|---|---|
| Saccade Angle | $F(2, 22) = 3.089$, $p = .091$, $\eta_p^2 = .255$ | $F(1, 11) = 4.054$, $p = .069$, $\eta_p^2 = .269$ | $F(1, 11) = 13.823$, $p = .003$, $\eta_p^2 = .557$ | Linear (not sig.); $F(1, 11) = 2.951$, $p = .114$, $\eta_p^2 = .212$ |
| Saccade Duration | $F(2, 22) = 2.746$, $p = .086$, $\eta_p^2 = .200$ | $F(1, 11) = 3.527$, $p = .087$, $\eta_p^2 = .243$ | $F(1, 11) = 2.993$, $p = .112$, $\eta_p^2 = .214$ | Linear (not sig.); $F(1, 11) = 2.736$, $p = .126$, $\eta_p^2 = .199$ |
| Saccade Rate | $F(2, 22) = 3.511$, $p = .048$, $\eta_p^2 = .242$ | $F(1, 11) = 1.504$, $p = .246$, $\eta_p^2 = .120$ | $F(1, 11) = 2.335$, $p = .155$, $\eta_p^2 = .175$ | Quadratic; $F(1, 11) = 5.474$, $p = .039$, $\eta_p^2 = .332$ |
| Saccadic Velocity | $F(2, 22) = 6.413$, $p = .006$, $\eta_p^2 = .368$ | $F(1, 11) = 9.421$, $p = .011$, $\eta_p^2 = .461$ | $F(1, 11) = 7.250$, $p = .021$, $\eta_p^2 = .397$ | Linear; $F(1, 11) = 5.498$, $p = .039$, $\eta_p^2 = .187$ |
| Fixation Duration | $F(2, 22) = 3.703$, $p = .041$, $\eta_p^2 = .252$ | $F(1, 11) = 11.792$, $p = .006$, $\eta_p^2 = .517$ | $F(1, 11) = 4.929$, $p = .048$, $\eta_p^2 = .309$ | Linear; $F(1, 11) = 27.334$, $p = .0003$, $\eta_p^2 = .713$ |
| Fixation Rate | $F(2, 22) = 2.334$, $p = .120$, $\eta_p^2 = .175$ | $F(1, 11) = 0.261$, $p = .620$, $\eta_p^2 = .023$ | $F(1, 11) = 3.163$, $p = .103$, $\eta_p^2 = .223$ | Linear*; $F(1, 11) = 16.249$, $p = .002$, $\eta_p^2 = .596$ |
| Pupil Diameter | $F(2, 16) = 4.031$, $p = .038$, $\eta_p^2 = .335$ | $F(1, 9) = 20.698$, $p = .002$, $\eta_p^2 = .721$ | $F(1, 9) = 4.443$, $p = .068$, $\eta_p^2 = .357$ | Linear; $F(1, 8) = 34.161$, $p < .0005$, $\eta_p^2 = .810$ |

*Notes.* BL = Baseline. *Quadratic trend also significant, $F(1, 11) = 6.004$, $p = .032$, $\eta_p^2 = .353$.

**Microsaccades.** The relative frequencies of microsaccades across decreasing levels of $SpO_2$ (baseline through 80%, including the post-hypoxia condition) were analyzed. A chi-square test of independence was significant, $X^2(5) = 25.465$, $p = .0001$, Cramer's $V = .05$. An analysis of the standardized residuals indicated significantly fewer microsaccades in the baseline condition (std. residual = -2.86; $p < .01$) and significantly more microsaccades in the 80% $SpO_2$ condition (std. residual = 3.40, $p < .001$).

In the baseline condition, the mean microsaccade duration was 41.40 ms ($SD$ = 44.86), with a mean angle of 0.62 deg. ($SD$ = 0.24) and a mean velocity of

0.028 deg./sec. In the 80% $SpO_2$ condition, the mean duration increased to 68.66 ms (*SD* = 67.11), with a mean angle of 0.55 deg. (*SD* = 0.26), and mean velocity decreased to 0.017 deg./sec. (*SD* = 0.016). In the post-hypoxia condition, the mean duration decreased to 42.31 ms (*SD* = 38.50), with a mean angle of 0.51 deg. (*SD* = 0.26), and mean velocity increased to 0.020 deg./sec. (*SD* = 0.016).

**Fixation duration.** To further evaluate changes in fixation duration, we assessed the occurrences of specific categories that are thought to reflect different cognitive states (see Schleicher et al., 2008): short (< 150 ms, indicating visuomotor reflexes), medium (150 – 900 ms, indicating semantic processing), and overlong (> 900 ms, indicating reduced alertness). A chi-square test of independence assessing the relative proportions of these fixation durations across $SpO_2$ levels (baseline through the 80% condition, including the post-hypoxia condition) was significant, $X^2(10) = 40.55$, $p < .0001$, Cramer's $V = .04$. Figure 1 shows the pattern of standardized residuals of each duration category by $SpO_2$ condition; positive residual values indicate a higher occurrence and negative residual values indicate a lower occurrence.

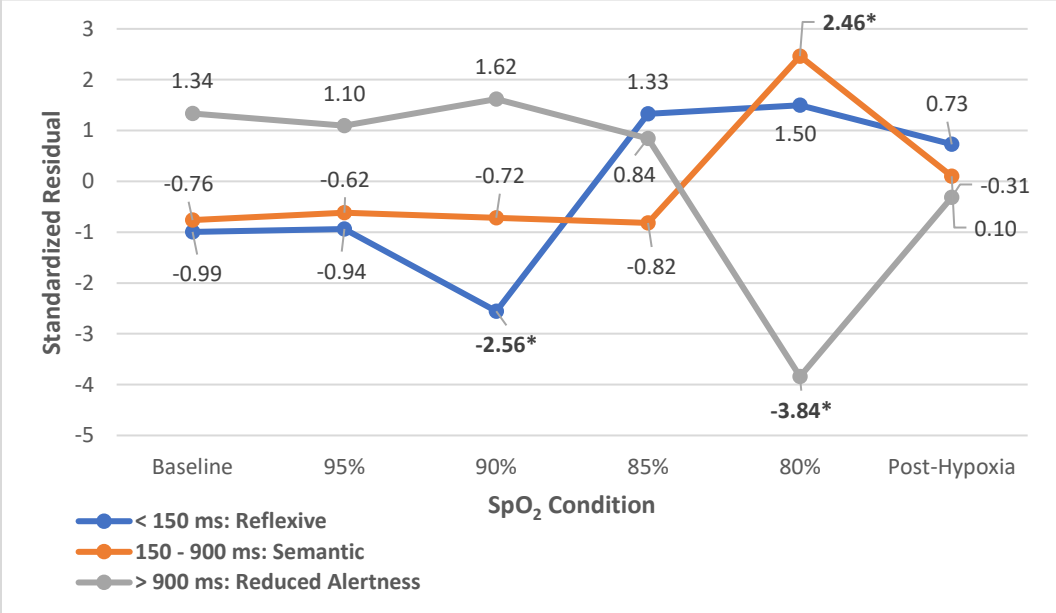


*Figure 1.* Standardized residuals of fixation duration categories.
*Note.* * indicates significant at the .05 level.

**Individual differences in oculomotor response.** Individual differences in oculomotor responses to changes in oxygen saturation were noted. Figure 2 below provides a one-minute sample of the sequence of time spent in fixations (red), saccades (blue), and blinks (white) for three of the subjects during the pre-hypoxia baseline, 80% $SpO_2$, and post-hypoxia normoxia. It can be generally observed that

spans of fixations were longer during normoxia conditions. Conversely, saccades and blinks were more pronounced during hypoxia. These timelines demonstrate the individual variability in response to hypoxia, with Subject A (top graph) exhibiting a mild degree of change in response to hypoxia, Subject B (middle graph) exhibiting a moderate degree of change, and Subject C (bottom graph) exhibiting what appears to be the greatest susceptibility. The timelines also show that oculomotor behavior reverted to pre-hypoxia patterns in the post-hypoxia conditions.

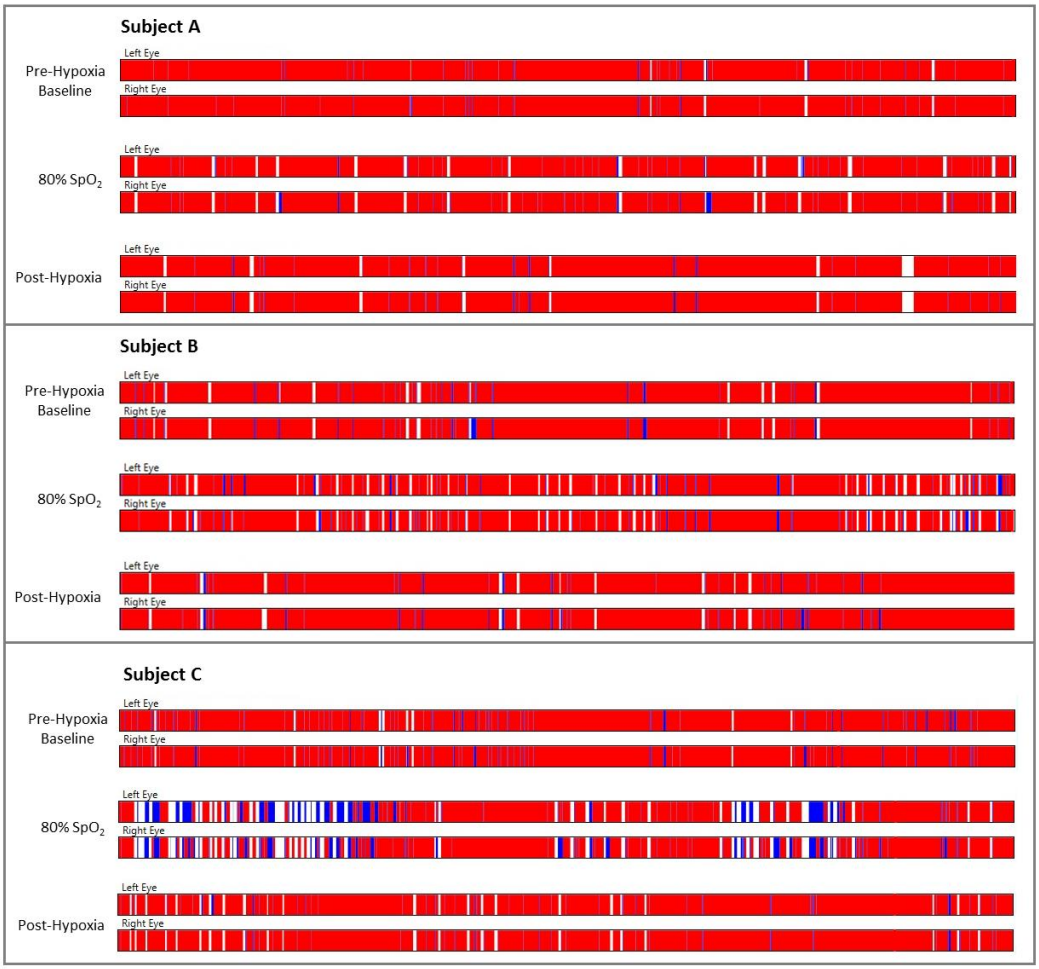


*Figure 2*. One-minute timeline samples showing varying degrees of oculomotor response to altered oxygen saturation in three different subjects. Red sections indicate fixations, blue sections indicate saccades, and white sections indicate blinks. Individualized responses are shown by changes in the distribution patterns of these oculometrics between the pre-hypoxia baseline, 80% $SpO_2$, and post-

hypoxia recompression, ranging from minimal response (top; Subject A) to considerable response (bottom; Subject C).

## Discussion

An increase in heart rate was observed as blood oxygen saturation decreased, an effect consistent with prior research (e.g., Nesthus, Rush, & Wreggit, 1997; Truszczynski, Wojtkowiak, Biernacki & Kowalczuk, 2009; and see Richard & Koehle, 2012 for a review). Acute high-altitude exposure increases both heart rate and blood pressure, an effect that is attributable to the autonomic nervous system response to the reduced partial pressure of oxygen at altitude (Bernardi et al., 1998; Hainsworth et al., 2007). This result has been documented in normobaric setting as well (see Botek, Krejcí, De Smet, Gába, & McKune, 2015) though it has been suggested that the response is more pronounced in a hypobaric environment (see Netzer et al., 2017). There is a very close association between heart rate and oxygen saturation during exposure to high altitude. This relationship can be considered continuous wherein as the oxygen saturation decreases, there is a corresponding increase in heart rate so reliable that a cardio-pulmonary index can be derived (Katari, 2016). Furthermore, once the subject dons the oxygen mask, this relationship is preserved during re-saturation.

As to be expected, there was a lack of self-reported symptoms at lower altitudes, as healthy individuals under minimal physical exertion are unlikely to experience symptoms under 10,000 ft. (Gradwell, 2006). Upon attaining higher simulated altitudes, however, subjects reported lightheadedness, paresthesia, and warm flushing—symptoms attributable to the hypoxic ventilatory response which results in hyperventilation and hypocapnia. Such symptoms mirrored those documented by Cable (2003), who reviewed incidents involving slow decompression among military aviators, wherein most symptoms occurred between 10,000 – 20,000 ft. Additionally, subjects in the present study commonly reported the performance-related symptom of 'feeling behind the aircraft', akin to the prevalent 'cognitive impairment' documented in Cable's (2003) sample. Though one subject did not report any symptoms at any point during the decompression in the present study, it is possible that symptoms may have been present but not recognized. Previous investigations have also illustrated instances of decompression incidents in which symptoms were not detected, and that it may be easier to observe symptoms in a fellow crewmember than in oneself (Cable, 2003; Smith, 2005).

Because specific symptoms and their onset times vary across individuals, high altitude chamber training is an effective means of self-familiarization with one's own signature response pattern. Such traditional hypobaric chamber training frequently involves removing a mask providing 100% oxygen while the trainee is at altitude; this sudden desaturation is more representative of the rapid

decompression typically associated with transport aviation incidents (Cable, 2003). Training for slow decompression scenarios, as more commonly experienced via failure of the oxygen mask, oxygen supply equipment, and pressurization equipment on ascent, however, is also valuable.

Oculomotor responses indicated a systematic, linear decrease in mean saccadic velocity as $SpO_2$ decreased, with a significant rebound once subjects were re-saturated to sea-level equivalence. Changes in saccadic velocity were driven by patterns of concomitantly increasing saccade duration and decreasing saccade angle, both of which normalized to near baseline levels in the post-hypoxia condition. Greater percent changes in mean saccadic velocity relative to the baseline were observed as $SpO_2$ decreased.

The observed saccadic velocity deceleration contradicts other previous findings which have shown either acceleration under hypoxia or no significant changes at all (e.g., Cymerman et al., 2003, 2005; DiStasi et al., 2014; Merz et al., 2013; Stepanek et al., 2014). A possible factor is the varying task demands in these studies, with previous investigations employing fast-paced reading, tracking, or reaction time-based demands and the present slower-paced flight task permitting more free-viewing behavior. Though we did not observe the temporary acceleration in early hypoxia as reported by van der Post et al. (2002), both sets of results indicated eventual deceleration, with van der Post et al. specifically showing decreased peak velocity in larger saccades of 15 deg. in amplitude in a standard neuropsychological visuomotor task and our results showing decreased mean velocity in saccades that were considerably smaller on average, as would be consistent with the finer gaze movements required for systematic searches conducted among instruments and their components on the G1000 interface. Further, the present results indicated a post-hypoxia recovery. This observed relationship between saccadic velocity and $SpO_2$ provides evidence that it may be susceptible to hypoxia in flight.

Mean fixation duration fluctuated directly with $SpO_2$, with the greatest reductions occurring at the lowest saturation levels, followed by recovery upon return to normoxia. Further inspection showed that early, mild hypoxia was characterized by fewer short duration fixations which are considered lower-level, non-cognitive visuomotor reflexes as they are too short to accommodate thorough visual information processing (Galley & Andrés, 1996; Schleicher et al., 2008). As such, these ‘express fixations’ are thought to be inhibited when the subject is interested in the visual environment (Schleicher, Galley, Briest, & Galley, 2008). The pattern began to reverse thereafter; at 80% $SpO_2$, there was an increase in medium duration fixations, which are cognitive in nature, and fewer overlong fixations, which are linked to reduced alertness. This pattern suggests that moderate hypoxia was generally associated with increased sematic processing. A possible explanation is that subjects may have engaged in self-activation (i.e., increased

effort) to preserve task performance (see Hockey, 1997) in combating what would normally be deactivating conditions. Further, fatigue is characterized by diminished medium duration fixations and increased short and overlong fixations, a pattern that signals disinterest in one's environment (Schleicher et al., 2008); the patterns observed under hypoxia thus did not match that which is associated with fatigue, but instead appear to reflect greater engagement in the environment.

The higher microsaccade rate observed during hypoxia may provide support for a recently proposed theory that hypoxia destabilizes eye movements. Because microsaccades are not large enough to move the pilot's gaze between instruments (Kowalczuk et al., 2016), but rather, along with tremor and intersaccadic drift, assist in the maintenance of fixations (Martinez-Conde et al., 2009; Rolfs, 2009), their increased prevalence under hypoxia could signal difficulty in acquiring or maintaining fixations. Microsaccades have also been linked to working memory, increased covert attentional demand, and production of *transients*, or abrupt changes in the visual information stream that serve as a unique form of cognitive stimulation (see Martinez-Conde et al., 2009; Rolfs, 2009). In previous studies, hypoxia has been associated with increased drift velocity (DiStasi et al., 2014) and increased correctional (i.e., small) saccades when combined with spatial disorientation (Kowalczuk et al., 2016); such outcomes are possible reflections of the visual system's compensation for destabilized fixations. Our results indicated higher cognitive fixation and microsaccade rates under moderate hypoxia, in addition to normalization of a previously diminished short duration fixation rate below 90% $SpO_2$, which altogether may indicate increased need for gaze adjustment. This visual instability may also require the subject to compensate with more cognitive processing and may thus be linked with overall increased cognitive effort and/or demand.

A significant linear trend indicated that pupil diameter varied directly with $SpO_2$, with the greatest reduction at the 80% $SpO_2$ condition followed by recovery upon return to normoxia. This result confirms findings from prior high-altitude research (e.g., Cymerman et al., 2003; Stepanek et al., 2014) and may be attributable to increased parasympathetic activity or paradoxical sympathetic mediated inhibition.

**Practical Implications**

Of importance is the finding that fixation and saccade behavior are early indicators of hypoxia exposure and occur before the first subjective symptom is recognized by the pilot. This finding supports objective evidence that eye behavior changes may serve as a useful tool for early hypoxia detection. The present results show that after only a 5% decrement in $SpO_2$, which was associated with an approximate average of 6,600 ft. in simulated altitude, the human eye responds differentially and these changes are detectable by lower resolution infrared devices. Further, this infrared technology shows evidence of being an effective research tool

in the detection of subtle oculomotor changes and may thus be a more accessible alternative to relatively expensive and invasive devices such as EOG.

The human visual system is motion-based (Martinez-Conde et al., 2009; Rolfs, 2009). When head and body movements are reduced, as may be the case during some aspects of piloting an aircraft, drift and microsaccades provide an important degree of retinal image slip for foveal registry (Rolfs, 2009). Increased microsaccades under hypoxia may signal compensation for altered fixations and scanning behavior, which may have implications for divided attention and system monitoring (Sarter & Woods, 1994; Wickens et al., 2003). Although continued investigation is necessary, the increased number of cognitive fixations observed could reflect higher mental workload.

While our study simulated the cruise phase of flight, it is also of interest to investigate the impact of hypoxia during other phases and if there are differences in one- vs. two-pilot operations, wherein task demands would differ considerably. Also worthy of further study is the extent to which oculomotor performance, notably microsaccade and fixation metrics, varies as a function of region of interest (e.g., out the window vs. instrument panel). Finally, though beyond the scope of the present investigation, other adverse states that have been linked to oculomotor changes (e.g., fatigue; see Schleicher et al., 2008) could likewise be screened with infrared cameras.

## Conclusion

Some of the current results, as derived from simulated flight tasks, differed from those of prior related studies, many of which involved basic and standard oculomotor tests. Further, the current results suggest differential, system-specific effects of hypoxia upon human performance; the decreased saccadic velocity and pupil diameter suggest central depressive effects, whereas increased cognitive fixations may suggest compensatory activation efforts. It may be speculated that the present outcomes are specific to flight-related tasks during a slow decompression event. There is a battery of oculomotor signs which, especially when detected together, could serve as biomarkers for hypoxia, as even mild and early exposure can yield observable eye movement changes that precede subjective symptoms.

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