Applied Ergonomics 113 (2023) 104079

Contents lists available at ScienceDirect

Applied Ergonomics

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

Hypoxia impairs reaction time but not response accuracy in a visual choice reaction task

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ARTICLE INFO

Keywords:
Hypoxia
Reaction time
Response accuracy
Glance time
Alertness
Visual contrast sensitivity
Visual field

ABSTRACT

We investigated the effect of hypoxia on the reaction time (RT) and response accuracy of pilots performing a visual choice reaction task that corresponded to the scanning of helmet mounted display (HMD) symbology. Eighteen male military pilots performed the task in a hypobaric chamber at two simulated altitudes (92 m and 4572 m) in a single-blinded repeated measures and counter-balanced design. The visual stimuli were displayed in low and high contrast and at a 30- and 50-degree field of view (FoV). We measured the pilots' RT and response accuracy. Using an eye tracker, we measured the pilot's glance time at each stimulus location. Finally, we collected subjective ratings of alertness. The results show that hypoxia increased the RT and glance time. Lowering the stimulus contrast and increasing the FoV further increased the RT, independent of hypoxia. These findings provide no evidence for hypoxia-induced changes in visual contrast sensitivity or visual field. Instead, hypoxia seemed to affect RT and glance time by reducing alertness. Despite the increased RT, the pilots maintained their accuracy on the visual task, suggesting that visual scanning of HMD symbology may be resistant to the effects of acute hypoxia.

1. Introduction

In military aviation, helicopter pilots increasingly rely on see-through helmet mounted displays (HMD) that superimpose flight, sensor, and weapon information (symbology) onto the real world view. HMDs help pilots maintain awareness of aircraft systems and the environment. The projected symbology is always in the pilot's field of view (FoV), irrespective of head position, so the pilot does not have to repeatedly look down at the cockpit instruments and can continuously scan the outside environment (Rash, 2009). Within the HMD, primary flight parameters such as air speed, altitude, heading, and engine torque are displayed at fixed positions. Other information, such as aircraft in the area, flight route, and target location relative to the helicopter, can be displayed anywhere on the HMD.

During flight, the HMD symbology changes frequently so pilots have to actively scan and focus their attention on the various symbols to perceive the information displayed. This requires good functioning of the visual system, which can be impaired by hypoxia when flying at altitude. Hypoxia is a state of oxygen deficiency in the blood and body tissue caused by the reduced atmospheric pressure (Gradwell and Rainford, 2016). It has been shown to decrease visual contrast sensitivity (Connolly and Hosking, 2008; Gekeler et al., 2019; Pescosolido et al., 2015; Phillips et al., 2015), which is the minimum contrast needed to discern an object from the background (Pescosolido et al., 2015). Hypoxia also narrows the visual field (Horng et al., 2008), which is the area that one can see when the eyes are fixed (Strasburger et al., 2004). These negative effects of hypoxia on the visual system may impair a pilot's visual perception. Hypoxia can also reduce alertness (Steinman et al., 2017, 2021), which can impair cognitive processing (Alhola and Polo-Kantola, 2007; Whitney and Hinson, 2010), and the perception of visual information, independent of the effect on visual contrast sensitivity and the visual field.

The aim of this study was to investigate how hypoxia affects a pilots' performance in a visual scanning task that corresponds to the scanning of symbology projected inside a HMD. Task performance was assessed by measuring reaction time (RT) and response accuracy. Hypoxia was induced by exposing participants to a simulated altitude of 4572 m (15,000 ft). We chose this altitude because it is the altitude at which the

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https://doi.org/10.1016/j.apergo.2023.104079
Received 8 March 2023; Received in revised form 21 June 2023; Accepted 22 June 2023
Available online 5 July 2023

helicopter pilots of the Royal Netherlands Air Force perform their hypoxia training. It is also an altitude where the effect of hypoxia has been demonstrated on RT (Dart et al., 2017), visual contrast sensitivity (Gekeler et al., 2019) and visual field (Kobrick, 1975).

The effect of hypoxia on visual contrast sensitivity and the visual field was determined by varying the contrast of the visual stimuli relative to the background, and their location in the peripheral visual field. We also analyzed gaze behavior by measuring the time pilots glanced at stimulus locations. Finally, we collected subjective ratings of alertness. Alertness can be defined as the quantification of the state of mind sensitive to incoming stimuli (van Schie et al., 2021). We measured alertness using the Stanford Sleepiness Scale (Hoddes et al., 1973) (SSS). The SSS is a subjective measure of sleepiness that is sensitive to a decrease in alertness and performance efficiency. A correlation has been found between the SSS score and the prediction of performance on tasks related to alertness (e.g. vigilance and choice reaction time) (Glenville et al., 1978; Hoddes et al., 1973).

We addressed the following research questions: 1. Does RT differ between baseline and hypoxia, especially when the visual stimuli have a low contrast relative to the background and are presented further in the visual periphery? 2. Does glance time differ between baseline and hypoxia? 3. Does response accuracy differ between baseline and hypoxia 4. Does alertness differ between baseline and hypoxia?

Based on the described effects of hypoxia, we expected that hypoxia would increase the RT to visual stimuli. We also expected that this effect would be exacerbated for stimuli with a low contrast relative to the background and that are presented further in the visual periphery. Additionally, we expected that glance time at the stimuli locations would be longer under hypoxia, and that glance time would be positively correlated with RT. Finally, we also expected response accuracy to be reduced under hypoxic conditions, presumably because of reduced alertness.

2. Materials and methods

2.1. Participants

Eighteen military pilots (mean age, 37 ± 7.7 years and mean total flight hours, 1337 ± 1114) of the Royal Netherlands Air Force (RNLAF) volunteered for the experiment. The pilots were recruited following a presentation about the study at the squadron. After the presentation, an invitation email describing additional study information was sent and a reminder email was sent two weeks after the initial email. To be eligible for inclusion, pilots needed to have passed their mandatory yearly medical examination and be declared "fit to fly". Pilots were excluded if they had been consecutively staying at altitudes higher than 2438 m (8000 ft) for longer than a week three months before the study started. All participating pilots had previous experience in the hypobaric chamber and were familiar with hypoxia symptoms. On test day, the researcher explained the experimental procedure to all participants and answered any questions about the study. The pilots then voluntarily signed the informed consent form. The study protocol was approved in advance by the Medical Ethical Committee of the Amsterdam Academic Medical Center (2020_311#B2021132).

To determine the *a priori* sample size we used the software G*Power (Version 3.1.9.7; Berlin, Germany). Effect size was calculated using data reported by Dart et al. (2017), who evaluated the effects of exposure to hypoxia compared to baseline on the performance of choice reaction task. They found a mean RT of 449.0 ms (±32.7 standard deviation) at baseline condition, and a mean RT of 466.4 (±37.7) in the hypoxia condition 4572 m (15.000 ft). Considering a standard α of 0.05, a β of 0.80, and an effect size of 0.49 this resulted in a sample size of 20 participants (power sample: 0.81).

2.2. Design

This study had a single-blinded, repeated measures, counterbalanced design. The altitudes and visual conditions were counterbalanced to minimize potential order effects. Hypobaric hypoxia was induced in a hypobaric chamber. In the baseline condition, the simulated altitude was 92 m (300 ft) and in the hypoxia condition, the simulated altitude was 4572 m (15,000 ft). Both altitudes and the sequence of the visual stimuli were randomly assigned using an online randomization software program (www.randomizer.com). Only the researcher present on test day was aware of the exact order of altitudes.

2.3. Visual task

The visual task was a choice reaction task. It corresponded with the visual scanning of HMD symbology that pilots perform during flight. The pilots were instructed to scan and recognize four targets, presented around a central fixation point. The central fixation point and the four targets had a "T" character that could be presented in two ways: upside-down or right side up. The fixation "T" was displayed at the center of the screen. Each of the four target "T″s was presented at a corner of a virtual square around the fixation "T" (Fig. 1). The target "T″s were presented at a FoV of 30 and 50°, defined as the distance between two diagonally opposite targets – 32.14 cm for the 30-degree FoV and 55.96 cm for the 50-degree FoV. The size of all "T″s was 5.2 × 5.2 mm (0.5 × 0.5°), which corresponds with the symbology size projected in current HMDs. The pilots rested their heads on a chin rest positioned 60 cm from the screen, making sure that their eyes were at the same level as the fixation "T". All "T″s were green and the background was grey. There were two levels of stimulus luminance – low (0.66 cd m^{-2}) and high (1.19 cd m^{-2}) – and the background luminance was 0.59 cd m^{-2}. Ambient illumination was 94 lux. A stimulus-background luminance contrast of 10% (low) is sufficient to discriminate symbology from a uniform background and a contrast of 100% (high) is sufficient to discriminate symbology from a busy background (Harding et al., 2005).

There were four visual conditions:

1) 30-degree FoV with high contrast between stimuli and background (30H);
2) 30-degree FoV with low contrast between stimuli and background (30L),

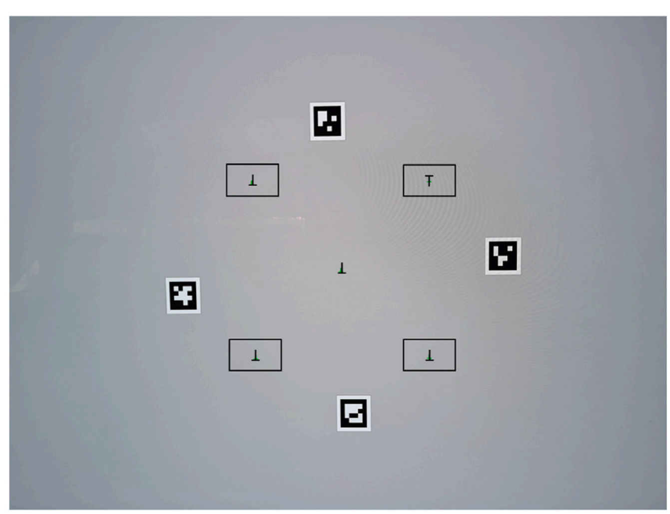

Fig. 1. The visual task. The fixation "T" in the middle, the four target "T″s and the four eye-tracker markers. The boxes surrounding each target "T" indicate the area of interest where glances in that area were used to calculate mean glance time.

3) 50-degree FoV with high contrast between stimuli and background (50H);
4) 50-degree FoV with low contrast between stimuli and background (50L).

All visual conditions were performed consecutively in one test block. In each condition, the pilots were instructed to concentrate on the fixation "T". At fixed intervals, the fixation "T" changed its orientation from upside-down to right-side-up. This was the trigger to scan the four target "T″s and determine as quickly as possible the number of target "T″s that had the same orientation (right-side-up) as the fixation "T". In case of an odd number of target "T″s (one or three) being right-side-up, the pilots pressed a right button, and in case of an even number of target "T″s (zero, two, or four) being right-side-up, the pilots pressed a left button. This ensured that the pilots scanned all four targets to be able to give the correct response. The pilots were allowed to correct their response by pressing either button again. This had to be done as fast as possible and before the fixation "T" changed its orientation to upside-down. The fixation "T" was in the upside-down position for 2 s and in the right-side-up position for 6 s. This change in fixation "T" orientation was repeated 48 times for each visual condition.

2.4. Study variables

The dependent variables of the visual task included:

1) Reaction time (RT), defined as the time between the moment that a stimulus was presented and the moment the pilot responded by pressing a left or a right button. In addition to RT measures, accuracy of the response (hits = correct identification of targets, misses = error or omissions of target, and corrections = correction of the initial response) were also recorded for analysis.
2) Mean glance time at the area of interest (i.e., an area around the visual stimuli), measured by a gaze tracker. Glance time was calculated by dividing the total glance duration by the number of glances at the area of interest during a visual stimulus presentation (i.e., from the moment a visual stimulus was presented to the moment the participant responded). Eye tracking data was analyzed in accordance with ISO-NORM 15007–1:2014 (ISO. Road vehicles, 2014). In accordance with this norm all glances shorter than 100 ms were excluded from the data analysis.
3) The pilots' self-perceived state of alertness was measured using the Stanford Sleepiness Scale (SSS) (Hoddes et al., 1973) (Table 1). The SSS is a seven-point Likert-type scale that ranges from "feeling active, vital, alert, or wide awake" (score = 1) to "no longer fighting sleep, sleep onset soon, and having dream-like thoughts" (score = 7). The pilots rated their alertness three times at each altitude.

For control purposes, the pilots' heart rate (HR) in bpm and oxygen saturation (SpO_2) in % were continuously monitored at both altitudes.

Table 1
Stanford sleepiness scale.

Degree of Sleepiness	Scale rating
Feeling active and vital; alert; wide awake	1
Functioning at a high level, but not at peak; able to concentrate	2
Relaxed; awake; not at full alertness; responsive	3
A little foggy; not at peak; let down	4
Fogginess; beginning to lose interest in remaining awake; slowed down	5
Sleepiness; prefer to be lying down; fighting sleep; woozy	6
Almost in reverie; sleep onset soon; lost struggle to remain awake	7

2.5. Equipment

Altitude was simulated in the hypobaric chamber of the RNLAF. The hypobaric chamber is located at the RNLAF's Center for Man in Aviation (CMA) in Soesterberg, The Netherlands, and has a cylinder shape 12.5 m long and 3.0 m in diameter. During ascent, a vacuum pump sucks air out of the chamber, lowering the pressure within until the pressure simulates that of the desired altitude.

Visual stimuli were presented and pilots' responses were captured using PsychoPy® software (Open Science Tools, LTD., Nottingham, England) that was installed on an Intel NUC computer (NUC7i5BNH, Intel, Santa Clara, CA, USA). The visual stimuli were displayed on an LG 55-inch TV screen (OLED55GRLA LG, Seoul, South Korea) with a resolution of 3840 x 2130 pixels.

The contrast difference between the stimuli and background was determined using an LMT L1009 illuminance meter (LMT Lichtmesstechnik GmbH, Berlin, Germany) and a calibration slide displayed on the TV screen.

Gaze behavior was tracked with the Dikablis Glasses 3 Hardware Development Kit (Ergoneers Group, Egling, Germany) and data were acquired and analyzed using the Ergoneers D-Lab 6.0 software. In all visual conditions, four markers were displayed on the TV screen (Fig. 1) to improve the accuracy of the eye-tracking system. Two markers were assigned to each area of interest for the analysis.

Pilots' HR and SpO_2 were continuously monitored using a Nonin 3150 (Nonin Medical Inc., Plymouth, MN) worn on the right wrist, together with a Nonin 8000J Flex Sensor worn on the right hand ring finger. HR and SpO_2 were displayed on an IPhone 5S (Apple, Cupertino, CA, USA) that was connected via Bluetooth to the Nonin 3150 using the NoninConnect™ app. Nonin nVision® (version 6.5.1) software was used to convert the HR and SpO_2 data stored on the Nonin 3150 to a CSV file. To blind the pilots to the condition, the HR and SpO_2 parameters were not displayed on the Nonin 3150 screen, but on the IPhone 5S, which was only visible to the researcher.

2.6. Procedure

On test day, the pilots arrived at the CMA at 08:00, where the researcher briefed them on the procedures and answered their questions. Pilots who agreed to participate in the study then signed the informed consent form. Participants were seated in front of the TV screen and received instructions for the visual task. Then, the height of the table on which the chin rest and TV were placed was adjusted so that the pilots were sitting comfortably and their eyes were at the same level as the fixation "T". Next, the pilots were fitted with the Nonin 3150 monitor and the gaze tracker was mounted on their head and calibrated. The pilots then practiced the visual conditions several times until they were confident in their performance and had made no more than two incorrect and/or missed responses. Both altitude conditions took place on the same day. Climbing to and ascending from 4572 m (15,000 ft) was done at an approximate rate of 900 m/min (3000 ft/min). To mask the actual altitude in the sea level condition, the chamber was first brought to an altitude of 610 m (2000 ft) and then slowly lowered back to 92 m (300 ft). After reaching each altitude, and before starting the first visual test block, the pilots sat and rested for 10 min to reach a steady breathing state and a constant SpO_2. The pilots assessed their state of alertness using the SSS before the start of each test block and at the end of the second test block. Calibration of the eye-tracking cameras was controlled before the start of each test block. There were two test blocks for each altitude condition: the first at 10 min, and the second 40 min after the altitude was reached. The visual conditions were presented in a counterbalanced order and each visual condition lasted 4 min. There was a 1-min rest between the visual conditions, a 10-min rest between test blocks, and a 1-h rest between altitude conditions. The experimental protocol is summarized in Fig. 2.

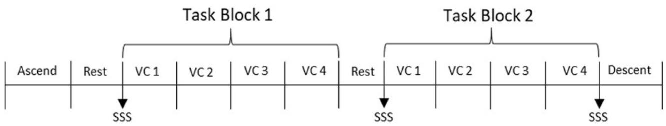

Fig. 2. The experimental protocol. Each test block comprised four visual conditions (VC 1, 2, 3, and 4) that were presented at a random order. Vertical arrows indicate the times at which the pilots rated their alertness.

2.7. Data analysis

Data analysis were based on data gathered from 18 pilots which were included in the study. From the originally planned 20 participants, two pilots had to withdraw and could not be replaced within the planned study time. Data were analyzed using IBM SPSS 28. The normality of the data was checked using frequency distributions, and non-normally distributed data were analyzed with a non-parametric test. A repeated measures analysis of variance (ANOVA) was used to test whether a difference existed in RT and alertness between the two altitude conditions during the four visual tasks. If the pilots corrected a response, the RT measured at the correction was used for the analysis.

We combined the glance time of all four target "T″s and analyzed the average glance time of these four locations. Glance time during the two altitude conditions was compared using a linear mixed model. We used a diagonal covariance structure for the repeated measures analysis because it fitted best to the data (Schwartz's Bayesian Criterion = −553.266). A diagonal structure assumes heterogeneous variance for each trial and no additional correlation between elements. Other covariance structures such as autoregressive and compound symmetry were tested, but these did not improve the fit of the model. The fixed factors used in the analysis were altitude, FoV, contrast, and test block. A bivariate correlation test was conducted to examine the relationship between glance time and RT.

The total number of hits and missed and corrected responses during each visual condition were compared between the two altitude conditions using a Wilcoxon signed-rank analysis. Average HR and $Sp0_2$ values were calculated from the beginning till the end of the flight at each simulated altitude. Differences in HR and SpO_2 values between the altitude conditions were analyzed using a paired-samples *t*-test. The level of significance for all comparisons was set at $p < .05$.

3. Results

3.1. Reaction time

A repeated measures ANOVA showed no significant difference in RT between the first and second test blocks of each visual condition at both altitudes. To simplify the statistical model, we combined the results of both blocks at each altitude condition and used the mean RT for further analysis. Results of the repeated measures ANOVA analysis are summarized in Table 2.

Table 2
Summary of the repeated measures ANOVA analysis of effects of hypoxia, field of view, and contrast on reaction time.

Factor	degrees of freedom (numerator, denominator)	*F*	*p*	Partial Eta Square (η_p^2)
Hypoxia (H)	1, 17	5.315	.034*	.238
Field of view (F)	1, 17	64.228	<.001*	.791
Contrast (C)	1, 17	210.301	<.001*	.925
H x F	1, 17	.107	.748	.006
H x C	1, 17	.051	.825	.003
F x C	1, 17	7.158	.016*	.296
H x F x C	1, 17	5.440	.032*	.242

*$p < .05$.

The results in Table 2 show a significant effect of altitude, FoV, and contrast on RT. There was also a significant two-way interaction between the FoV and contrast, and a significant three-way interaction between altitude, FoV, and contrast. No significant interaction was found between altitude and FoV or between altitude and contrast. A post-hoc analysis of the three-way interaction comparing simple main effects with Bonferroni confidence interval adjustment showed that mean RTs were significantly longer in the 30H and 50L visual conditions under hypoxic conditions than under baseline conditions ($p = .025$ and $p = .019$, respectively). However, RTs were not significantly different for the 30L and 50H visual conditions under hypoxic and baseline conditions ($p = .119$ and $p = .153$, respectively). Under baseline conditions, the mean ± SD RT values for each visual condition were 2.0 ± 0.2 s in 30H, 2.2 ± 0.2 s in 30L, 2.2 ± 0.2 s in 50H, and 2.5 ± 0.2 in 50L. Under hypoxic conditions, these values were 2.1 ± 0.2 s in 30H, 2.3 ± 0.3 s in 30L, 2.3 ± 0.3 s in 50H, and 2.6 ± 0.2 in 50L. Fig. 3 illustrates the mean RT values for all visual conditions at both altitude conditions.

The analysis also showed significantly longer RTs at both altitude conditions and at both contrast levels in the 50-degree FoV than in the 30-degree FoV ($p < .001$). RT was also significantly longer at low contrast than at high contrast ($p < .001$) at both altitudes, and in the 30-degree and 50-degree FoV.

3.2. Response accuracy

As shown in Table 3, the number of times in which the participants corrected their first response did not significantly differ between the two altitude conditions. However, there was a significant difference in the total number of corrected responses over the four visual conditions ($z = -2.265$; $p = .024$) between baseline conditions (median = 4; IQR = 2–11) and hypoxic conditions (median = 6; IQR = 2–18). Overall, the pilots corrected their responses 192 times (2.8% of total responses) in the hypoxia condition compared with 132 times (1.9% of total responses) in the baseline condition. As shown in Table 3, there was no significant difference in missed (z = -.813; $p = .416$) and incorrect (z = -.852; $p = .394$) responses between the baseline and hypoxia conditions.

3.3. Glance time

We had issues in the calibrating process of the eye tracking system in four pilots, that resulted in large deviations of their glance locations from the areas of interest. Therefore, glance data of these four pilots was excluded from the analysis. Fig. 4 illustrates the glance time for each visual condition at both altitude conditions. The fixed factors altitude, FoV, and contrast significantly affected glance time (F(1, 141.892) = 5.52, $p = .020$; F(1, 141.892) = 29.94, p = <.001 and F(1, 141.892) = 54.156, $p < .001$ respectively), but test block did not (F(1, 141.892) = .097, $p = .756$). Under the baseline condition, the mean glance time was 0.34 ± 0.04 s for the 30H condition, 0.38 ± 0.03 s for the 30L condition, 0.37 ± 0.04 s for the 50H condition, and 0.41 ± 0.05 for the 50L condition. Under the hypoxia condition, the mean glance time was 0.35 ± 0.03 s for the 30H condition, 0.40 ± 0.04 s for the 30L condition; 0.38 ± 0.04 s for the 50H condition, and 0.43 ± 0.06 for the 50L condition. There was a positive correlation between glance time and RT ($r(206)$ = .664; $p < .001$) and the effect size for glance time was $r^2 = .44$, indicating that it accounted for 44% of the variability in RT.

3.4. Stanford Sleepiness Scale (SSS)

The measurement point and altitude had a significant effect on the SSS rating (F(2,34) = 24.874; p = < .001; $\eta_p^2 = .594$) and F(1,17) = 35.593; $p < .001$; $\eta_p^2 = .680$, respectively). There was also a significant interaction between measurement point and altitude condition, which affected the SSS rating ($F(2, 34) = 6.852$; $p = .003$; $\eta_p^2 = .287$). A post-hoc analysis comparing simple main effects with Bonferroni confidence interval adjustment showed a significant difference in SSS rating

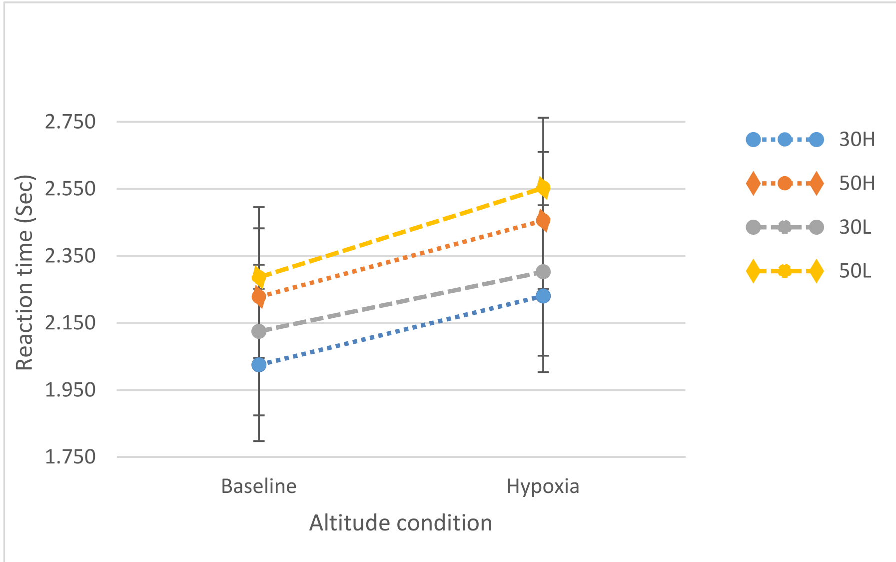

Fig. 3. Mean RT (with standard deviation) at both altitude conditions and for each field of view and stimuli contrast level.

Table 3
Median and inter-rate quartile of corrected, missed, and incorrect responses for each visual conditions and for cumulative conditions under the baseline and hypoxia conditions.

Visual condition	Variable	Baseline		Hypoxia		*Z*	*P*
		Median	IQR	Median	IQR		
30H	Corrected	3	2–5	5	3–7	−1.30	.194
30L		4	2–4	3	3–6	−1.511	.131
50H		4	3–6	5	3–8	−378	.705
50L		5	2–7	4	2–7	−730	.465
Cumulative	Corrected	4	2–11	6	2–18	−2.265	.024*
	Missed	0	0–0	0	0–1	−.813	.416
	Incorrect	0	0–2	0	0–3	−.852	.394

*$p < .05$ compared to values at baseline.

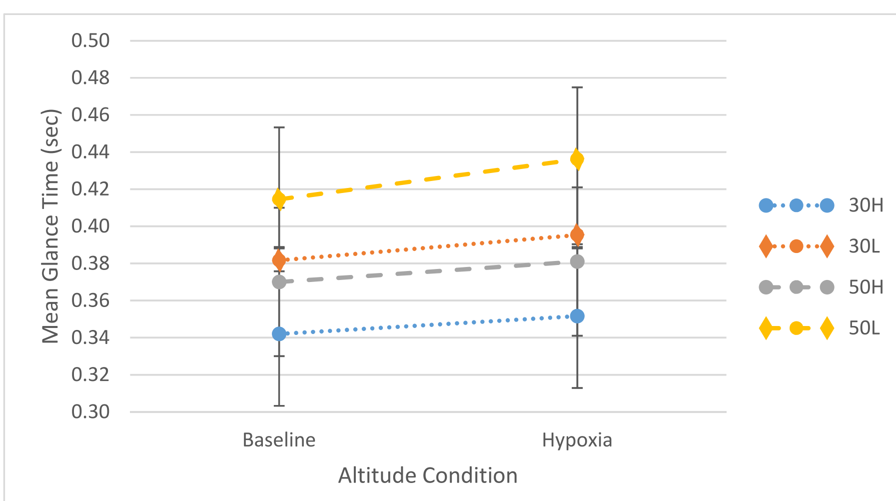

Fig. 4. Glance time for each visual conditions at both altitudes. Results are presented as mean and standard deviation.

between the hypoxia condition and the baseline condition at the start of the first test block ($p = .004$), at the start of the second test block ($p < .001$), and at the end of the second test block ($p < .001$). Before the start of the first test block, the average SSS rating was 1.0 ("feeling active, vital, and alert") in the baseline condition and 2.0 ("functioning at high level, but not at peak") in the hypoxia condition. At the start of the second test block, the average SSS rating was 2.0 ("functioning at high level, but not at peak") in the baseline condition and 3.0 ("relaxed; awake; not at full alertness; responsive") in the hypoxia condition, and at end of the second test block the average SSS rating was 2.0 ("functioning at high level, but not at peak") in the baseline condition and 4.0 ("somewhat foggy, let down") in the hypoxia condition.

Further analysis showed that, in the baseline condition, there was a significant difference in SSS rating between the start of the first test block and the start and end of the second test block (p = .048 and p = .003, respectively). In the hypoxia condition, there was a significant difference in SSS rating between the start of the first test block and the start and end of the second test block ($p < .001$ and $p < .001$, respectively), and between the start and end of the second test block (p = .005). An overview of the SSS ratings measured at both altitudes is shown in Fig. 5.

3.5. Physiological data

SpO_2 (%) levels were significantly lower at 4572 m than at 0 m (78 ± 3 versus 98 ± 1; t(17) = 24.07; $p < .001$). A significant difference was also found in HR (bpm) between 0 m and 4572 m (70 ± 10 versus 80 ± 12; t(17) = −5.44; $p < .001$).

4. Discussion

We investigated the effect of hypoxia on pilots' RT and response accuracy in a visual choice reaction task that corresponds to the scanning of HMD symbology. The results demonstrate that RT and glance time were significantly longer during the hypoxia condition than during the baseline condition. Contrary to our expectation, this effect on RT was not exacerbated by decreasing stimulus contrast or increasing stimulus FoV. In addition, RT correlated positively with glance time. There was no significant difference in response accuracy between the two altitude conditions. Finally, the sleepiness ratings indicated that alertness was significantly lower during the hypoxia condition than during the baseline condition.

The observed effect of hypoxia on RT is in line with previous studies on hypoxia and choice reaction tasks (Dart et al., 2017; Dykiert et al., 2010; Phillips et al., 2015). We also found that a lower stimulus contrast and higher stimulus FoV increased the RT. Although we observed a significant three-way interaction between hypoxia, stimulus contrast, and FoV, the effect on RT seemed to be mainly determined by the significant interaction between stimulus contrast and FoV because the interactions between hypoxia and stimulus contrast and between hypoxia and stimulus FoV were not significant. Thus, we did not find strong evidence that the effect of hypoxia on RT was exacerbated by decreasing stimulus contrast or increasing stimulus FoV. Instead, our results suggest a mere additive effect of these factors.

This means that we could not confirm the hypoxia-induced degradation of visual contrast sensitivity or narrowing of the visual field that has been found in previous studies (Fowler and Nathoo, 1997; Kobrick, 1974, 1975). This discrepancy may be explained by differences in the task. For example, in the studies of Kobrick, 1974, 1975, the participants had to detect a peripheral stimulus while fixating on a central location, whereas in our study the pilots had to actively scan the peripheral stimulus. This means the stimulus was always in the pilots' central visual field, which is known to be less affected by hypoxia than the peripheral visual field is (Connolly and Hosking, 2008; Ernest and Krill, 1971; Horng et al., 2008). Another possible explanation is a difference in the level of hypoxia between the studies. In the study of Fowler and Nathoo (1997), the average SpO2 of the participants was 65%, compared with 78% in our study. Lower SpO2 levels have been associated with larger effects on visual contrast sensitivity (Pescosolido et al., 2015) and RT (Dart et al., 2017).

Regarding the pilots' gaze behavior, we found that glance time explained 44% of the variance in RT. Although glance time was significantly longer during the hypoxia condition than during the baseline condition, lowering the stimulus contrast and increasing the stimulus FoV also increased the glance time. However, there was no significant interaction between hypoxia and stimulus contrast, or between hypoxia and stimulus FoV. This suggests that, similar to RT, the hypoxia-induced increase in glance time cannot be attributed to degradation of visual contrast sensitivity or narrowing of the visual field.

The longer RT and glance time we observed in the hypoxia condition may have been due to impaired cognitive performance. Hypoxia is known to affect cognitive performance (Petrassi et al., 2012; Yan, 2014) and has been shown to negatively affect the performance in choice reaction tasks (Dart et al., 2017; Dykiert et al., 2010; McMorris et al., 2017; Phillips et al., 2015). The SSS ratings in our study show that the hypoxia condition significantly lowered the pilots' alertness compared with the baseline condition. Sleep deprivation studies have shown that reduced alertness impairs cognitive processing and negatively affects the speed and accuracy of performance in choice RT tasks (Alhola and Polo-Kantola, 2007; Whitney and Hinson, 2010). In the present study, pilots corrected significantly more responses during the hypoxia condition than during the baseline condition, but the difference in corrected responses between the two conditions was less than 1% (2.8% in hypoxia and 1.9% at baseline). Taken together, these results show that the pilots tried to make fewer mistakes by trading response speed for greater response accuracy.

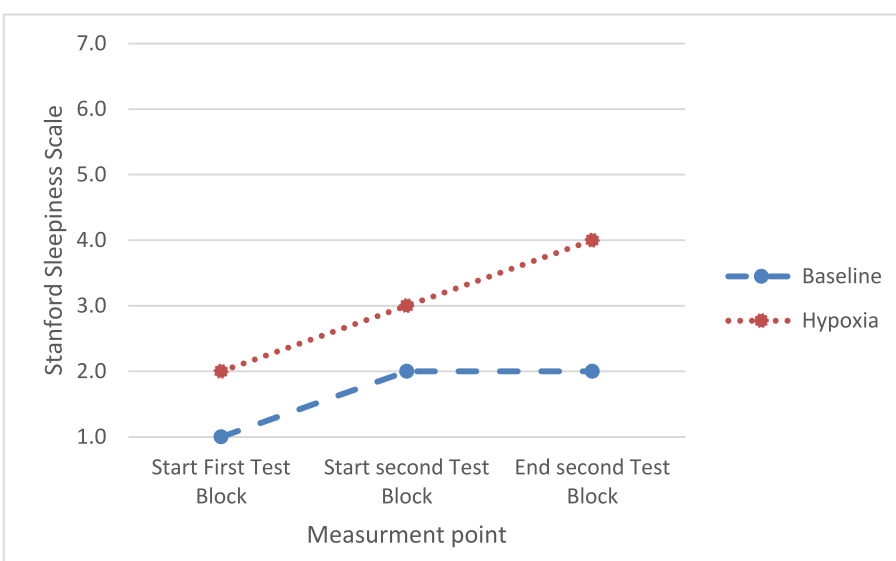

Fig. 5. Illustration of the mean Stanford Sleepiness Scale ratings at the three measurement points at both altitudes.

There was no difference in the number of missed responses between the two altitude conditions. This indicates that the pilots were able to scan all four stimulus locations and maintain their response accuracy despite reduced alertness, which can impair visual scanning behavior (Watling and Home, 2022). The ability of pilots in this study to keep scanning all stimuli locations concurs with a study by Previc et al. (2009), which showed that instrument scanning by pilots was unaffected after 34 h of being awake, despite reduced alertness. This may suggest that visual scanning of HMD symbology might be resistant to the effects of reduced alertness under acute hypoxic circumstances.

Several limitations of this study need to be considered. First, we used only two stimulus FoVs (30 and 50°) and two contrast levels (10% and 100%). With only two points it is not possible to determine whether the relationship between FoV and contrast is linear or not. A future study could determine this relationship in more detail by using more levels of stimulus contrast and FoV. Second, this is a preliminary study assessing the effect of hypoxia on pilots' RT in a visual task that corresponds to the scanning of HMD symbology. The visual task and targets in our study were simpler than the more complex information (numbers and symbols) displayed in a HMD of helicopter pilots. This may have resulted in an underestimation of the effect of hypoxia on the RT because pilots may need more time to comprehend the information in a real HMD. Future studies should determine the effect of hypoxia on RT during scanning of HMD symbology under dynamic conditions that represent real operational flight; for example, in a flight simulator.

A practical implication of this study is that the pilots' accuracy on the visual task and their ability to keep scanning all four stimuli locations were unaltered by hypoxia. This suggest that scanning of HMD symbology may be resistant to the effect of acute hypoxia. Our results also have implications for technological advancements, particularly with regard to increasing the FoV of future HMDs. Our results demonstrate that, even under normal oxygen conditions, the RT to a visual stimulus increases when it is presented further into the visual periphery. Therefore, increasing the FoV of the HMD may increase the RT, especially when the symbology is displayed at random locations, and not at fixed locations such as in our set-up. Therefore, the benefits gained by increasing the HMD's FoV should be weighed against the longer RT.

5. Conclusion

Our results demonstrate that hypoxia increases the RT and glance time, presumably because of reduced alertness rather than impaired visual performance. Reducing stimulus contrast and increasing stimulus FoV had a larger effect on RT and glance time than hypoxia did. However, the response accuracy on the visual task was not affected by hypoxia. This finding suggest that visual scanning of HMD symbology may be resistant to the effects of acute hypoxia.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The opinions expressed in this article are solely those of the authors and do not reflect the views of the Dutch Air Force, the Dutch Defense Department, or any other department of the Dutch government.

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