Pol J Aviat Med Psychol 2014; 20(4): 5-10
DOI: 10.13174/pjamp.20.04.2014.1

ORIGINAL ARTICLE

HYPOXIA AND COGNITIVE PERFORMANCE

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Source of support: Own sources

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Introduction: The study investigated short-term effects of hypoxia on higher cognitive functions.

Methods: Stroop test (classic and Reverse Stroop task) was chosen as the assessment tool. The sample consisted of 29 paratroopers (males, mean age 33.97). They were subjected to hypoxia at a simulated altitude of 7500 meters during altitude training in a hypobaric chamber. Time of Useful Consciousness (TUC) for every subject was recorded. Each subject performed the Stroop test prior to entering the hypobaric chamber and about 30 minutes after hypoxia exposure.

Results: Although reaction times were significantly faster during posttest, the interference susceptibility in Reverse Stroop task increased ($t(28) = 2.16$, $p < 0.05$, Cohen's $d = 0.41$). While controlling for baseline performance, the increase of susceptibility positively correlated with TUC ($r(25) = 0.37$).

Discussion: The results are of academic and practical importance.

Conclusions: Results suggest that short, non-life-threatening hypoxia could affect higher cognitive functions even after exposure. The magnitude of this effect is associated with the time of oxygen shortage even among persons whose individual TUC was not exceeded.

Keywords: cognitive functions, hypobaric chamber, hypoxia, pilots, Stroop test

Figure: 1 • **Table:** 1 • **References:** 19 • **Full-text PDF:** http://www.pjamp.com • **Copyright** © 2014 Polish Aviation Medicine Society, ul. Krasińskiego 54/56, 01-755 Warsaw, license WIML • **Indexation:** Index Copernicus, Polish Ministry of Science and Higher Education

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INTRODUCTION

Hypoxia refers to the increasing shortage of oxygen that may be experienced by crew and passengers of an aircraft in the event of malfunction of flight's pressurization system or by a jet fighter pilot in case of oxygen-supply system breakdown. Acute hypoxia due to cabin decompression could have a lethal effect within few minutes, and might lead to severe dysfunction, also on the psychophysical level, even in non-lethal cases [5]. Therefore, predicting possible effects of hypoxia is an important subject in aviation psychology even for short-term exposures. Unfortunately, most studies on hypoxia are conducted under high-altitude mountain conditions [9,13], mainly for ethical reasons. They relate to long-term effects of oxygen shortage associated with changes in the natural environment, thus extrapolation of results to sudden situations specific for aviation should be done with caution. Only a few studies present data gathered under fully controlled conditions [15,18], making research presented in this paper particularly valuable. This study was possible and ethically legitimate since the data was gathered from a group of paratroopers who had already enrolled for their regular altitude training.

Most studies focus on reduced performance in hypoxic environment and there is a considerable amount of data showing deterioration of motor and cognitive function as a result of altitude hypoxia among high-mountain climbers [8,9]. It has also been proven that even moderate hypoxia could affect pilot's performance [17]. Our research was aimed to evaluate higher cognitive function not during, but after short-term exposure to reduced air pressure and oxygen shortage. The main question was whether, and to what extent, cognitive function could be impaired even some time after exposure to hypoxia. Fully controlled environmental conditions were obtained by conducting the study with the use of a hypobaric chamber.

There is data suggesting that hypoxia-related decline in performance could be the effect of central attention system impairment [2,3]. Therefore, a well-known Stroop test was chosen as a main tool to assess higher cognitive function. In this task individual is required to respond to one aspect of the stimulus (reading a name of a colour), while inhibiting additional incongruent information (colour of the letters). Such a task is often treated as a good test for selective attention and decision-making, has a long tradition in neuropsychology [10] and an established validity as a quick test for evaluation of executive function [6]. Neuropsychological data show that two cortical areas, namely the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC), are especially active in resolving the attention conflict [11]. Stroop test has not been traditionally used in hypoxia studies, but there is evidence that the level of concentration of oxygenated haemoglobin in the prefrontal cortex is strongly connected with performance in this task [7], thus substantiating the possibility that it could be especially vulnerable to hypoxia conditions.

In our study we were interested only in a subtle effect of hypoxia that could be present even if overall physiological state was not at risk, therefore the concept of Time of Useful Consciousness (TUC) was especially important. Such a measure (also known as: Reserve Time, Self Rescue Time or Effective Performance Time) could be defined as the time from the moment oxygen supply is interrupted to the loss of the ability to appropriately carry out required actions [19]. Usually it is marked by physiological and behavioural actions not involving more complex cognitive skills. It is then possible that a person could suffer from hypoxia-induced cognitive impairment, even if he/she seems fit from the TUC point of view. Given this possibility, the research question was formulated as follows:

Does hypoxia have prolonged effect on cognitive performance (operationally defined as susceptibility to interference in the task demanding attentional control, i.e. Stroop test) even if the time of exposure to hypoxia does not exceed person's TUC?

Data presented here were gathered during a pilot phase of the study, conducted at the Military Institute of Aviation Medicine in Warsaw (Poland). In the main study we plan to add more performance measurements and self-assessment tools to evaluate any subjective feelings that may be connected with hypoxia and hypoxia-related cognitive impairment.

METHODS

Subjects

The sample consisted of 29 paratroopers (males), mean age 33.97 (SD = 3.01), range 26–41 years. All subjects were in good health and participated in the study during their regular altitude training. They were informed about the purpose of additional psychophysical testing and gave their voluntary consent.

Experimental Task

Level of interference susceptibility in the Stroop test was taken as a measure of higher cognitive function. Stroop tasks were presented with the use of PC computer with SPD software (a system for computerized psychological assessment; konsorcjum-progres.pl). There were three tasks, each one consisted of 36 stimuli: one of four colour words ("red", "green", "blue" and "yellow") with the font colour congruent (e.g. word "red" written with the red font) in the first task or incongruent (e.g. word "red" written with a green font) in the second and third task. In each task stimuli were presented one at a time. Response time was recorded for every item and subsequently averaged for the whole set. Number of errors for every set was also recorded. Stimuli were presented centrally on a 19'' touch screen, subjects responded by touching one of four buttons (with words "red", "green", "blue" and "yellow" written in black font) located at the bottom part of the screen.

The first task contained only congruent stimuli; subjects had to respond to the stimuli by touching the corresponding button as fast as possible. Response time in this task was treated as a baseline for interference scores.

The second task consisted of incongruent stimuli, subjects had to respond to colour of the font only, ignoring the word. It is the classic Stroop task (ST). Longer response times in incongruent conditions are treated as the effect of interference, and difference between response time in such a condition and response time in congruent condition was taken as a measure of interference susceptibility.

As there is strong evidence that when ST is based on manual pointing instead of verbal responses a reverse effect can be observed [1], the third task consisted of incongruent stimuli and subjects now had to respond to the word only, ignoring the font colour. It is called the reverse Stroop task (RST). Difference of response time in such conditions and response time in congruent conditions was again taken as a measure of interference susceptibility.

All three tasks were checked for reliability of response time measures. For the congruent conditions, Cronbach's α was 0.92, for incongruent conditions in ST Cronbach's α was 0.88 and for RST Cronbach's α was 0.90.

Design and Procedure

Each subject was assessed with a Stroop test twice - firstly before entering hypobaric chamber (pretest) and for a second time about 30 minutes after exposure to hypoxia (posttest). Blood oxygen saturation, heart rate and chamber pressure were monitored during altitude training in hypobaric chamber. After about 30 minutes in normobaric conditions (denitrogenation phase), exposure to hypoxia followed at simulated altitude of 7500 meters, without use of supplemental oxygen. Each subject was monitored for physiological condition, subjective well-being, and psychomotor performance in a simple writing task (subtracting by two). Oxygen supply was restored and hypoxia was terminated at the first sign of decreased fitness.

Personal time of hypoxia exposure was recorded for every subject. Since exposition to hypoxia ceased before or immediately right after the first signs of reduced performance, this recorded time was treated as a measure of individual TUC.

RESULTS

Stroop Task Results

Error rate was similar for pretest and posttest and in any case did not exceed three errors per task, so it was omitted in further analysis. Mean pretest and posttest response times (baseline tasks and interference scores) are presented in

Tab. 1. Descriptive statisctics and paired student's T-tests of pretest and posttest result (N=29).

	Pretest		Posttest				
	M	SD	M	SD	t	p	Cohen's d
Reaction time (in ms)							
Congruent condition	1008.59	124.59	909.78	119.00	-6.224	< .001	1.16
Incongruent condition (reaction to colour) [ST]	1308.71	209.89	1192.97	167.79	-5.237	< .001	1.03
Incongruent condition (reaction to word) [RST]	1073.81	126.29	1013.43	139.57	-2.974	.006	0.56
Interference score							
Stroop task [ST]	300.12	181.26	283.19	105.61	-0.657	.517	
Reverse Stroop task [RST]	65.22	93.66	103.66	78.88	2.16	.039	0.41

Cohen's d computed with Morris and DeShon's [12] equation.

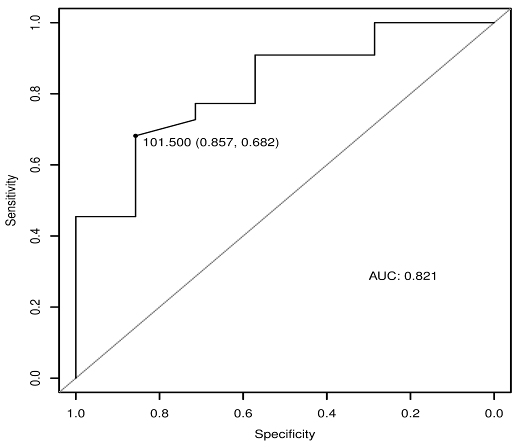

Fig. 1. ROC curve for the decrease in Reverse Stroop task interference scores. The optimal cut-off point (with sensitivity and specificity values in parentheses) is marked on the plot.

Tab. 1. All variables were tested for normality. Only interference scores for RST test presented slight deviation from normal distribution, as indicated by Lilliefors test.

There were significant differences between task results obtained in pretest (repeated measures ANOVA with a Greenhouse-Geisser correction $F(1.41, 56) = 58.145$, $p < 0.001$, eta2 = 0.68) and posttest ($F(2, 56) = 128.48$, $p < 0.001$, eta2 = 0.82). Post hoc tests using the Bonferroni correction revealed that mean reaction time for every condition differed significantly from each of the remaining two values, with reaction times being the slowest in ST and the fastest in congruent conditions, which was the expected effect.

For every condition (congruent, ST and RST) there was a significant decrease of response time in posttest measurements. However, there were no significant changes in the level of interference susceptibility in ST and even a significant increase of interference susceptibility in RST.

Stroop Task and TUC

TUC ranged from 32 to 152 seconds, with mean score of 101.03 (SD = 25.8) and with no significant deviation from normal distribution. To check its association with interference in Stroop test, change scores (difference between posttest and pretest results) for interference in ST and RST were computed, with positive values meaning increase in interference susceptibility.

For ST, mean change score was -16.93 (median at 7) and for RST mean change score was 38.43 (median at 46). In ST 15 persons (52%) presented a positive change score, meaning increase in susceptibility during posttest phase. In RST positive change scores were recorded for 22 persons (76%). The next step of the analysis was to estimate whether this increase/decrease in interference susceptibility could be connected with individually recorded TUC.

Because of high dependence of ST and RST change scores on average response times in pretest tasks (mainly in the form of correlations of change scores and reaction times in congruent conditions, with $r(27) = 0.31$ for ST and $r(27) = 0.39$ for RST), partial correlations of change scores and TUC were calculated.

Partial correlation of TUC and change score in ST, controlling for pretest scores of reaction time in congruent and incongruent conditions (reaction to colour), was $r(25) = 0.3$; however, it did not reach statistical significance ($p = 0.056$).

Partial correlation of TUC and change score in RST, controlling for pretest scores of response time in congruent and incongruent conditions (reaction to word), was $r(25) = 0.37$ ($p = 0.022$).

There was no significant correlation of TUC and change in reaction times both for congruent and incongruent conditions.

Since there was a significant correlation between TUC and susceptibility in RST, Receiver Operating Characteristic curve (ROC curve) was created to find the cut-off point where the decrease on cognitive functioning is most likely to appear. The curve is presented in Fig. 1., with area under the curve being 0.821 (95% CI: 0.648-0.995). This rather high value means that TUC could be treated as a good predictor of possible decrease in cognitive functioning even about 30 minutes after exposure to hypoxia. As shown, time period of one minute and 40 seconds, which is significantly below the average TUC at the altitude of 7500 meters (about 3 to 5 minutes, as reported in [14]), is the optimal cut-off point for the gathered data.

DISCUSSION

Among response time measurements, there was significant improvement noted for every condition (congruent and incongruent), suggesting a training effect that was not suppressed by exposure to hypoxia (or at least, influence of hypoxia was not strong enough to fully abolish the training effect). Careful examination shows that this improvement was noted only for individuals with relatively short exposure to hypoxia, while subjects with longer TUC showed poorer results. One minute and 40 seconds seems to be an optimal time threshold for distinguishing between these two groups. Correlation analysis delivers additional evidence for hypoxia effect, showing moderate positive relationship between duration of hypoxia and decrease in executive function (while controlling for baseline psychomotor ability during pretest). Both correlations (for ST and RST) with TUC were in the expected direction and at similar levels, reaching statistical significance for RST and being nearly significant for ST (assuming moderate strength of analysed relationship, it is possible that small sample size could be accounted for non-significant correlation coefficient in ST).

It should be noted that overall exposure to hypoxia (measured by TUC) was below average according to the norms for paratrooper qualification, with only five subjects exceeding a two-minute period. Perhaps cognitive performance would be stronger with greater variability in the exposure times and with more above average results the relationship. Therefore, it is important to obtain more data from people with longer TUCs to assess full range of association between oxygen shortage and cognitive performance. Results also suggest that adding a control group could be of great value, allowing for better control of possible training effect in the Stroop task.

Despite the above limitations, obtained results are of both academic and practical importance. Beside a well-known fact that acute hypoxia decreases cognitive function, which may be an additional risk factor during e.g. aviation incidents, these results show that the effect of hypoxia poses a considerable threat to the pilot's safety even when the danger directly connected with aircraft malfunction has ceased, because even short-term, non-life-threatening periods of oxygen shortage could have prolonged effect on attention control and decision-making processes. Strength of this effect is a function of the time of oxygen shortage and is not directly related to a decrease in physiological function as long as personal TUC is not exceeded, so the persons exposed to longer hypoxia times are more likely to suffer from cognitive deficits than subjects with shorter TUC, even if they seem equally fit by the medical standards. This effect should be taken into consideration during development of emergency procedures.

From the theoretical point of view, it is interesting that the observed effect was stronger for RST task, since reverse Stroop effect is usually weaker than the classic one. In the literature on the subject there is still a discussion whether the mechanism behind classic and reverse Stroop effect is similar [1,4]. One of the questions is: whether the conflict that causes the observed interference is mainly at the response level or at the level of cognitive representation. In the current study, with pretest and posttest design, the strengthening of reverse Stroop effect appeared without change in the structure of the task, supporting the models that emphasize the role of internal representations [16], not only the stimulus-response competition [10]. There is a possibility that hypoxia does not affect (or not only) the attention control system itself, but rather selectively impairs the cortical regions connected with constructing verbal and visual representations. Careful analysis of hypoxia-induced impairment from the neuropsychological point of view (i.e., what cortical regions are most vulnerable to oxygen shortage? which cognitive processes are the first to be impaired?) could probably deliver important arguments to this discussion. In our opinion however, more research is needed to reach definite conclusions.

CONCLUSIONS

1. Even short-term, non-life-threatening hypoxia could have prolonged effect resulting in impairment of executive functions.
2. The strength of this effect is directly related to the length of oxygen shortage even if it does not exceed individual Time of Useful Consciousness.

AUTHORS' DECLARATION:

Study Design: Piotr Zieliński, Robert Drozdowski, Marcin Piotr Biernacki; **Data Collection:** Piotr Zieliński, Robert Drozdowski, Marcin Piotr Biernacki; **Statistical Analysis**: Piotr Zieliński; **Manuscript Preparation:** Piotr Zieliński, Marcin Piotr Biernacki; **Funds Collection:** Piotr Zieliński, Robert Drozdowski, Marcin Piotr Biernacki. The Authors declare that there is no conflict of interest.

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ACKNOWLEDGEMENTS

The views, opinions, and findings contained in this article are our own and should not be construed as an official Polish Air Force position, policy, or decision, unless so designated by other official documentation.

Cite this article as: Zieliński P, Drozdowski R, Biernacki MP. Hypoxia and Cognitive Performance. Pol J Aviat Med Psychol 2014; 20(4): 5-10. DOI: 10.13174/pjamp.20.04.2014.1