Title: Cognitive adaptation in hypobaric hypoxia

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Synopsis

Hypobaric hypoxia represents a critical physiological stressor in Isolated, Confined, and Extreme (ICE) environments, capable of severely impairing cognitive stability. The present study investigated emotional and cognitive alterations of operators during a multitasking protocol under hypoxic conditions by using a multimodal paradigm integrating behavioural metrics with neurophysiological monitoring and self-report tools. Preliminary results indicate condition-dependent performance degradation, particularly in visual reaction times and accuracy, in comparison to the reference condition. These findings highlight the vulnerability of executive functions to oxygen deprivation and contribute to defining objective biomarkers for monitoring cognitive and emotional adaptation in high-altitude scenarios.

Background

Operational environments characterized by hypobaric hypoxia, such as high-altitude flights and remote mountain outposts, constitute a distinct and critical category of Isolated, Confined, and Extreme (ICE) settings. In these contexts, the reduced partial pressure of oxygen imposes a severe physiological challenge, leading to arterial desaturation (SpO_2) and compromising cerebral oxygenation (1). This hypoxic stress specifically targets the prefrontal cortex, the brain region for high-order executive functions (2). Consequently, cognitive domains essential for operational safety, including working memory, decision-making, and multitasking efficiency, are prone to rapid degradation, often before the subject perceives subjective symptoms (3). Despite the operational risks, there is a lack of integrated methodologies to objectively quantify the onset of this decline in real-time. The present work aimed to address this gap by analysing performance during a multitasking protocol, selected as an ecologically valid approach that required the concurrent management of multiple information streams under time constraints. The task was embedded within a multimodal framework, integrating subjective, behavioural outcomes with neurophysiological and autonomic markers to reconstruct a comprehensive, objective profile of human adaptation to hypoxic stressors.

Methods

Experimental protocol design and participants

A total of nine healthy subjects from the Italian Air Force were initially recruited for this longitudinal study, which took place during a 5-day mission of progressive exposure to hypobaric hypoxia. Due to health complications arising during the mission, four participants were withdrawn; therefore, the final sample comprised five subjects. The experimental protocol included four data collection sessions (S1 ÷ S4) to monitor adaptation dynamics: pre-departure baseline (1191 m a.s.l.), ascent to 4554 m, descent to 3647 m, and return to baseline (1191 m). In each session, participants underwent a resting-state recording (1-minute eyes-open, 1-minute eyes-closed) followed by the

multitasking test (10 minutes) administered via tablet. The task consisted of two randomised phases:

- *Workload (WL) & Stress phase* adapted from Sciaraffa et al. (4): three difficulty levels (*easy*, *difficult*, *stress*), presented in a fully randomized order. Each level lasted 2 minutes and included four subtasks: mental arithmetic, auditory target tone detection, numeric reproduction through a keypad, and monitoring a filling coloured bar to trigger a planned response. In the easy condition, the four subtasks were executed sequentially (30 secs per subtask) and required minimal cognitive demand (e.g., arithmetic without carry, longer response windows). In the difficult condition, all four subtasks were performed simultaneously with increased task demands (e.g., arithmetic with carry, shorter response time). In the stress condition, participants performed the four concurrent subtasks at an even higher difficulty level and received trial-by-trial visual feedback about the correctness of their responses.
- *Emotion phase* adapted from Inguscio et al. (5): an emotional auditory categorization task where short excerpts of classical music from a validated database (6) were presented (mean duration of 15 secs) . Following each excerpt, participants categorized the stimulus as *happy, sad or neutral* using emoticons on a tablet interface. They were then asked to rate the perceived pleasantness and task difficulty on three-level scales.

Data acquisition

Throughout the multitasking execution sessions, accuracy and reaction times (RT) were recorded as primary indices of cognitive performance, and subjective ratings were collected as complementary measures. The following biosignals were acquired continuously during multitasking execution using wearable systems specifically selected on the basis of their low invasiveness and suitability for confined operational environments. The electroencephalographic (EEG) data was recorded by means of the wearable EEG Mindtooth System (www.mindtooth-eeg.com) with a sample rate of 250 Hz, on eight recording channels (*AFz, AF3, AF4, AF7, AF8, PZ, P3, P4*), referenced to the right mastoid and grounded on the left one. Concurrently, the skin conductance and cardiac activity were recorded using Galvanic Skin Response (GSR) and Photoplethysmography (PPG) sensors, respectively, acquired through the Shimmer3 GSR+ device (www.shimmersensing.com) with a sample rate of 64 Hz. GSR electrodes were applied on the index and middle fingers of participants' non-dominant hand, while PPG sensors were applied on the thumb.

Results

Behavioural data were analysed comparing the three experimental phases (S2, S3 and S4) to the pre-departure baseline (S1). The variation in Performance Index (∆PI) revealed distinct task-dependent trends (**Errore. L'origine riferimento non è stata trovata.**). The Visual task exhibited the most significant decrement, with a ∆PI of -5.4% in S2, -0.9% in S3, and -3.0% in S4. In the descent phase (S3-S1), while Math and Telephone tasks maintained positive trends (+5.9% and +5.0% respectively), a sharp decline was observed in the Auditory task (-4.6%). Notably, the Visual task remained the only condition to exhibit consistently negative performance relative to baseline across all sessions, even after returning to normoxic conditions (S4). However, statistical comparison of the Visual task across the four acquisition points revealed no significant difference ($p = 0.232$).

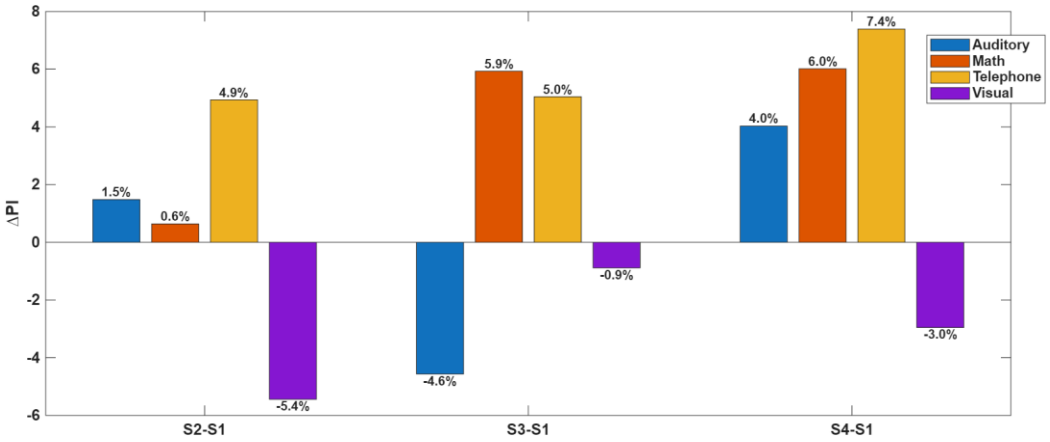

Figure 1. Absolute difference of task-related PI index (ΔPI) relative to the baseline (S1) across the experimental sessions.

Discussion

The study aimed to identify objective biomarkers for cognitive adaptation in hypobaric - hypoxic environments. The analysis revealed a distinct dissociation between cognitive domains under hypoxic stress. Specifically, the Visual task exhibited a consistent negative trend in performance across all experimental phases (ascent, descent, and recovery) compared to baseline. Although this reduction did not reach statistical significance ($p=0.232$), likely due to the limited sample size ($N=5$) characteristic of extreme operational field studies, the persistent negative direction of the ΔPI contrasts sharply with the other tasks. This suggests that visual processing speed and accuracy may be particularly vulnerable to oxygen deprivation, or less responsive to compensatory mechanisms, potentially serving as a sensitive qualitative indicator of operator state. This result is confirmed by previous works (7). Conversely, the progressive improvement observed in Math and Telephone tasks suggests that for certain executive functions, task habituation or sport activity effects may mitigate hypoxia effects (8). The behavioural results reinforce the necessity of a multimodal approach. In this regard, the analysis of neurophysiological data will be critical to determine whether the preserved performance in non-visual tasks came at a higher cognitive and emotional cost, potentially revealing underlying impairments masked by compensatory effort, sport activity prior the ascent.

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