Biological Psychology 84 (2010) 157–160

Contents lists available at ScienceDirect

Biological Psychology

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

The effects of workload on respiratory variables in simulated flight: A preliminary study☆,☆☆

Maria Katsamanis Karavidas [a,*], Paul M. Lehrer [a], Shou-En Lu [a], Evgeny Vaschillo [b], Bronya Vaschillo [b], Andrew Cheng [c]

[a] University of Medicine and Dentistry of New Jersey-Robert Wood Johnson Medical School, United States
[b] Rutgers, The State University of New Jersey, United States
[c] Hi-Tech Systems, United States

ARTICLE INFO

Article history:
Received 28 April 2009
Accepted 27 December 2009
Available online 12 January 2010

Keywords:
Ventilation
Hypocapnia
Aeronautics
Workload

ABSTRACT

In this pilot study, we investigated respiratory activity and end-tidal carbon dioxide ($P_{et}CO_2$) during exposure to varying levels of work load in a simulated flight environment. Seven pilots (age: 34–60) participated in a one-session test on the Boeing 737-800 simulator. Physiological data were collected while pilots wore an ambulatory multi-channel recording device. Respiratory variables, including inductance plethysmography (respiratory pattern) and pressure of end-tidal carbon dioxide ($P_{et}CO_2$), were collected demonstrating change in CO_2 levels proportional to changes in flight task workload. Pilots performed a set of simulation flight tasks. Pilot performance was rated for each task by a test pilot; and self-report of workload was taken using the NASA-TLX scale. Mixed model analysis revealed that respiration rate and minute ventilation are significantly associated with workload levels and evaluator scores controlling for "vanilla baseline" condition. Hypocapnia exclusively occurred in tasks where pilots performed more poorly. This study was designed as a preliminary investigation in order to develop a psychophysiological assessment methodology, rather than to offer conclusive findings. The results show that the respiratory system is very reactive to high workload conditions in aviation and suggest that hypocapnia may pose a flight safety risk under some circumstances.

1. Introduction

Hypocapnia is the result of overbreathing behavior, the mismatch of breathing rate and depth. Hypocapnia can be a result of acidosis or overbreathing behavior and we are interested in the latter (Litchfield and Tsuda, 2006). Its consequences is respiratory alkalosis which may have profound immediate and long-term effects that trigger exacerbate, and/or cause a wide variety of perceptual, cognitive, attention, and physical deficits that may seriously impact health and performance (Hida et al., 1996; Li et al., 2008).

There has been speculation that impaired judgment caused by hypocapnia may have contributed to several air disasters (Gibson, 1984; Carley, 1999). We have surveyed civilian airline pilots through an industry newsletter, and, of 55 pilots returning questionnaires, three reported having experienced clinically significant in-flight hypocapnia symptoms, including some suggesting flight risk: in-flight experiences of dizziness, confusion, and blurred vision (Karavidas and Lehrer, 2009). There is considerable evidence for workload- and stress-related changes in respiratory ventilation in airplane pilots (Wilson, 1993), sometimes producing hypocapnia and its associated respiratory alkalosis (Suess et al., 1980). Respiratory pattern changes with an increase in task difficulty (Sammer, 1998). The current study assessed mechanical respiratory activity (volume and frequency of breathing) and end-tidal PCO_2, which correlates highly with partial pressure of arterial PCO_2 (Takano et al., 2003), across a sequence of simulated flight task periods.

2. Methods

2.1. Participants

Eight male professional pilots (see Table 1), ages 34–60, were recruited for the study. Seven of the pilots were full time volunteer employees of the Federal Aviation Administration (FAA), and one was a volunteer research collaborator who was a commercial airline pilot. One participant was excluded from participation because of irregular heart beats and medication that met exclusion criteria. Thus, seven

☆ These authors wish to acknowledge Archie E. Dillard, Ph.D., Mike Sies, Larry W. Hackler, and Philaretos Karavidas for their assistance in this study and Peter M. Litchfield, Ph.D. for his review of this manuscript.
☆☆ This research was supported by #05-G-004 from the Federal Aviation Administration.
* Corresponding author at: University of Medicine and Dentistry of New Jersey-Robert Wood Johnson Medical School, Psychiatry, 671 Hoes Lane, Rm. D435, Piscataway, NJ 08873, United States. Tel.: +1 732 921 0565; fax: +1 732 235 4430.
E-mail address: mkaravidas@aol.com (M.K. Karavidas).

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doi:10.1016/j.biopsycho.2009.12.009

Table 1
Demographic information.

Participant ID	Age	Flight experience	Medication
000	35	13	No
001	44	23	No
002	49	33	Indapamide
003	52	30	Atorvastatin, calcium, aspirin
005	61	38	No
006	61	36	No
007	39	20	No

Note. All participants were Caucasian males. Except for one participant (000), all had had initial flight experience in the military. Participants 000 and 007 were non-FAA test pilots. One was an active commercial airlines pilot, although not certified to fly a 737B aircraft. The other was on furlough, and currently working for the U.S. Air Force.

Table 2
Flight tasks.

Takeoff phase
T1. Normal takeoff and departure to 5000′ (L-Baseline)
T2. Takeoff with engine fire just after getting airborne (preset 20–30′ for the fire) or just after entering the weather (100′) (M)
T3. Takeoff into a moderate to severe wind-shear (H)
T5. Lightweight takeoff with engine separation just after getting airborne (preset 20–30′ for the failure) (M)
In-flight phase
F1. Normal climb and acceleration from 8000′ to 13,000′, or normal descent and deceleration from 13,000′ to 8000′ (L-Baseline)
F2. Descent from 10,000′ with severe wake turbulence resulting in a nose-low upset starting at 8000′ (disable flight freeze for entry) (H)
F5. Traffic Collision Avoidance System-Resolution Advisory (TCAS RA) (near-miss) at 10,000′ (M)
Approach and landing phase
L1. Normal visual landing from 6 Nautical Miles (L-Baseline)
L3. Manual reversion or elevator quadrant jam landing (H)
L4. Landing into a moderate to severe wind-shear (M)
L6. Landing with one main gear stuck up (H)

Note. L = low; M = medium; H = high.

volunteers completed the study procedures. Participants were informed that the experiment concerned the suitability of physiological measurements for measuring workload. Inductance pneumography measures were collected on all participants, but end-tidal carbon dioxide ($P_{et}CO_2$) data were available for only four participants across all tasks listed in Table 2.

2.2. Equipment

We tested seven participants in a Boeing 737B flight-800 Level D flight simulator located in the FAA Mike Monroney Aeronautical Center, Oklahoma City. During the simulator evaluation, participants wore the LifeShirt (VivoMetrics, CA, USA), a non-invasive, lightweight (8 oz.), comfortable nylon shirt designed to collect physiological variables. Respiratory inductance plethysmography (Hill et al., 1982; Leino et al., 2001) was used to assess respiration rate and volume, from a pair of insulated coils sewn into an elastic vest (LifeShirt; Vivometrics, Ventura, CA). The apparatus was calibrated from three breaths into an 800 ml bag. $P_{et}CO_2$ was collected from a VitalCap Capnograph (Oridion, MA, USA) via a nasal/oral canula. $P_{et}CO_2$ is equivalent to alveolar PCO_2. The sensor collected exhaled air from both the nose (through a canula) and a small tube to the mouth. By examining the capnographic tracing, it was determined whether breaths were completed or not. Only in those breaths that reached a distinct plateau was $P_{et}CO_2$ measured. Average $P_{et}CO_2$ was calculated across each task. Hypocapnia was defined as $P_{et}CO_2$ less than 32 mmHg (Marangoni and Hurford, 1990; Rahn et al., 1946).

The purpose of this study was to examine learned workload-induced respiratory changes in a flight simulator with experienced airplane pilots and to determine whether behavioral hypocapnia (Litchfield and Tsuda, 2006) can be triggered by high workload tasks in a flight simulator.

2.3. Procedures

Research procedures were approved by the Institutional Review Board of the University of Medicine and Dentistry of New Jersey. Following verbal and written informed consent, physiological recordings were initiated. Then the following tasks were administered in a single session, each task lasting for approximately 5 min: (1) a standardized "plain vanilla" baseline task (Jennings et al., 1992) with minimal stimulation, designed to keep participants awake and focused on a standard task; and (2) 11 flight tasks as described in Table 2. *A priori* values of workload (high [H], medium or moderate [M], or low [L]) were assigned by a senior FAA staff from their prior experience with these tasks in assessing pilots in this simulator.

2.3.1. Evaluator score

Pilot performance was rated on a 5-point ad hoc scale by an experienced test and check pilot, who also programmed the various tasks on the flight simulator. Higher scores reflected better task performance, using criteria of successful task completion (no crashes), and maintenance of heading, altitude, and approach into handling emergency (timing, etc.). This was a subjective rating given by a senior pilot with 20 years experience of flight evaluation. Pilots were rated after each consecutive task. They were not provided with feedback from the evaluator until completion of the test series. The ratings consisted of: 0 = failed task/crash, 1 = poor, 2 = adequate, 3 = good, 4 = excellent and 5 = outstanding.

2.3.2. Self-report measure of work load

The National Aeronautics and Space Administration Task Load Index (TLX) scale (Hart and Hauser, 1987) was administered after each task. The TLX scale is a well-validated self-report scale that provides an overall work load score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration measures work load. The TLX has been tested in a variety of experimental tasks including simulated flight, supervisory control simulations, and laboratory tasks (Gibson, 1978; Van Diest et al., 2000).

2.4. Statistical model

Mixed model analysis was applied to evaluate the association between difficulty levels of task load (high vs. medium and low) and respiratory measures, controlling for vanilla baseline measure. Mixed model analysis was also applied to evaluate the association between evaluator scores and respiratory measures, controlling for the vanilla baseline measure. A mixed model analysis was used to estimate the association between the respiratory measures and TLX total score. Respiration measures were treated as dependent variables and TLX scores as the exploratory variable, controlling for baseline respiration rate. Statistical significance was defined as p-value <0.05. Data analyses were performed using SAS® v 9.1.

3. Results

3.1. Respiration rate

Respiration rate increased in all flight tasks relative to baseline values, but the increase tended to be greater in tasks with high demand (see Fig. 1). The high-demand landing tasks evoked a greater increase in respiration rate than the takeoff or flight tasks, and were better differentiated among levels of task demand. Mixed model analysis, controlling for the vanilla baseline, found that mean respiration rate was 1.78 breath/min higher for High than for the combined medium and low-load tasks ($p = 0.02$) (see Table 3). Mixed model analysis, evaluating the association between evaluator scores and respiration rate, and controlling for the vanilla baseline measure, revealed a statistically significant association ($R^2 = -0.16$, SE = 0.05, DF = 48, $p = 0.002$)[1] where higher evaluator scores are associated with lower respiration rates.

3.2. Minute ventilation (V'_E)

V'_E was higher in high-demand than low-demand tasks, reflecting greater ventilation. V'_E was particularly high in two of the three high-demand landing tasks, L3 and L6 (elevator quadrant jam and landing gear stuck up). The high-demand landing tasks evoked a greater ventilatory response than the high-demand takeoff or flight tasks. Mixed model analysis, controlling for the vanilla baseline, found that the mean minute ventilation difference was higher for High than for the combined medium and low-load tasks ($p = 0.014$). Mixed model analysis, evaluating the association between evaluator scores and minute ventilation, controlling for

[1] Regression coefficient, standard error of the mean, degrees of freedom, and significance levels reported.