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Cerebral blood flow, fatigue, mental effort, and task performance in offices with two different pollution loads

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ABSTRACT

The effects of indoor air quality on symptoms, perceptions, task performance, cerebral blood flow, fatigue, and mental effort of individuals working in an office were investigated. Twenty-four right-handed Danish female subjects in an office were exposed in groups of two at a time to two air pollution levels created by placing or removing a pollution source (i.e. a used carpet) behind a screen. During the exposure, the subjects performed four different office tasks presented on a computer monitor. The tasks were performed at two paces: normal and maximum. When the pollution source was present, the air quality was perceived to be worse and more errors were made when subjects typed text at the maximum pace. No other changes in subjective responses, performance, or physiological measurements were associated with different exposures. Although cerebral blood flow and voice analysis did not detect any effects caused by modifying pollution exposure, they were well correlated with increased mental effort when the tasks were performed at maximum pace and subjectively reported fatigue, which increased during the course of exposure, respectively.

1. Introduction

Reducing the pollution load on indoor air or increasing the outdoor air supply rate decreases dissatisfaction with air quality and the intensity of some sick building syndrome (SBS) symptoms, and improves the performance of simulated office work by adults [1,2]. Increasing the outdoor air supply rate also improves schoolwork performance by children [3]. However, the mechanisms underlying the decreased performance of simulated office tasks owing to indoor air pollution remain inadequately studied [4]. One potential mechanism involves the need for greater mental effort to maintain a constant level of performance in a poor indoor environment, which can consequently lead to increased fatigue [5]. Mental effort is defined as the amount of mental and perceptual activity required to perform a given task. Two non-invasive methods have been proposed to examine this mechanism: (1) near-infrared spectroscopy (NIRS) measurements of changes in cerebral blood oxygenation to quantify the effects on mental effort and (2) measurements of Lyapunov numbers quantified by voice quality analysis to examine effects on fatigue.

At present, NIRS is primarily used to monitor the cerebral oxygenation state of patients during surgery. However, the local concentration of oxygenated haemoglobin (oxy-Hb) in the prefrontal cortex typically increases during mental tasks, because the metabolism of brain blood is required to maintain brain activity [6]. The measurements of Lyapunov numbers quantified by voice quality analysis are used to detect fatigue in air traffic controllers. The human voice generally has chaotic fluctuations; the time series of these fluctuations are expressed as chaotic attractors in a Takens plot [7]. The magnitude of the fluctuations of the chaotic attractors can be quantified using the Lyapunov exponent. An increase in the Lyapunov exponent suggests an increase in fatigue [8]. A tool for predicting fatigue and drowsiness has been developed on the basis of the calculation of the Lyapunov exponent after recording the voice quality of a person. Therefore, NIRS and voice analysis can be applied to examine the effects of indoor environmental quality on mental effort and task performance.

In case of NIRS measurements, near-infrared light is produced by laser diodes and carried to the tissue via optical fibres [9]. The instrument measures the absorption of the light at four wavelengths in the infrared region [10]. As the light is partly scattered, some rays reflect onto the NIRS instrument with reduced strength [11]. The

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Abbreviations

Δdeoxy-Hb change in the concentration of the chromophore in deoxygenated haemoglobin
Δoxy-Hb change in the concentration of the chromophore in oxygenated haemoglobin
Δtotal-Hb change in total haemoglobin concentration
LD Levenshtein distance
NASA-TLX National Aeronautics and Space Administration Task Load Index
NIRS near-infrared spectroscopy
pCO_2 partial pressure of CO_2
SBS sick building syndrome
TOI tissue oxygenation index
TSV thermal sensation vote

light emerging from the tissue is returned to the instrument via another optical fibre by a detector, and the incident and integrated values of the transmitted light intensities are recorded every second. The distance between the emitter and detector is 4 cm, and the system can perform measurements at a depth of 0.9 cm from the brain surface. The volume of venous blood is highest in the forehead area. Therefore, a reduction in infrared light primarily reflects the rate of change of the concentrations of oxygenated and deoxygenated haemoglobin of cerebral venous blood. In particular, changes in the concentrations of the chromophores in oxygenated haemoglobin (Δoxy-Hb) and deoxyhaemoglobin (Δdeoxy-Hb) can be calculated using the modified Beer–Lambert equation in μM [12]. The changes in total haemoglobin concentration can be calculated as an index of the rate of change of cerebral blood flow: Δtotal-Hb = Δoxy-Hb + Δdeoxy-Hb. The tissue oxygenation index (TOI), which is the ratio of oxygenated haemoglobin to total haemoglobin, i.e. how much oxygen is carried by the blood, can be measured by spatially resolved spectroscopy [13].

Nishihara and Tanabe [14] introduced the use of NIRS to monitor changes in cerebral blood oxygenation in order to examine the brain response of subjects performing arithmetic calculations. They observed a significant correlation between subjectively assessed mental effort and the total Hb concentration in the left hemisphere in the right-handed subjects.

Studies examining how changes in indoor environmental quality affect cerebral blood oxygenation evaluated the effect of a moderately warm environment on workers' productivity; these studies included Δtotal-Hb measurements as an index of mental effort [15–17]. In one study, the subjects performed addition and multiplication for 5 min each under two different conditions with environmental temperatures of 26.0 °C and 33.5 °C; the clothing insulation corresponded to 0.76 clo, and the total exposure time was 90 min. The average thermal sensation votes (TSVs) of subjects at 33.5 °C and 26 °C were 2.3 and 0.2, respectively [15]. Although there was no significant difference in task performance between these conditions, Δtotal-Hb was significantly higher at the higher temperature, suggesting that greater mental effort is required under such conditions. In another study, the subjects performed multiplication for 90 min under three conditions with operative temperatures of 25.5 °C, 28.5 °C, and 31.5 °C; the clothing insulation was 0.57 clo, and the total exposure time was 170 min. The average TSVs at 25.5 °C, 28.5 °C, and 31.5 °C were −0.01, 0.83, and 1.93, respectively [16]. This time, no significant differences in Δtotal-Hb were observed between conditions. Nonetheless, at the highest temperature, task performance tended to decrease during the course of the experiment. Consequently, it may be surmised that mental performance at elevated temperatures or when thermal warmth discomfort occurs requires increased mental effort. Such conditions may result in increased fatigue and consequently reduced performance as illustrated in the study of Lan et al. [18].

In such studies, subjects usually perform tasks at a normal pace. Therefore, whether performing tasks at a faster pace, i.e. the maximum pace at which subjects are able to perform, affects cerebral blood flow was examined [17]. In the previous study, subjects were exposed to three operative temperatures of 25.5 °C, 28.5 °C, and 31.5 °C and performed triple-digit multiplication tasks at two paces: maximum and normal. Δtotal-Hb was higher at the maximum pace than the normal pace at both 28.5 °C and 31.5 °C, suggesting that more mental effort is required to maintain task performance at the maximum pace, especially at higher temperatures. These corroborate the notion that greater mental effort affects brain activity as postulated by literature [6,14].

Voice quality is used as an indicator of fatigue in studies examining the effect of light intensities of 800 and 3 lx on performance [19]. These studies show that reducing light intensity does not affect the performance of typical office tasks but increases fatigue as measured by changes in voice quality [19]; mental effort is also affected as indicated by cerebral blood flow measurements [5]. These results further suggest that increased mental effort is required to maintain performance, especially when the indoor environment is of poor quality, which can lead to increased fatigue and consequently decreased performance.

Therefore, the present study further investigated the hypothesis that poor indoor air quality alters cerebral blood flow, increases fatigue, and reduces performance.

2. Methods

2.1. Approach

Task performance, cerebral blood flow, fatigue, and mental effort were measured while subjects performed typical office work tasks at both normal and maximum paces in a room with two different air quality levels. The experiment was conducted in an ordinary low-pollution office with a volume of 40 m^3 in which all materials were specifically selected to be low polluting [20]. Two subjects in the office were simultaneously exposed to one of two air pollution levels created by placing or removing a pollution source behind a screen. The pollution source was a tufted boucle carpet that had been used in a previous study by Wargocki et al. [1]; it was made of 100% polyamide fibres and a latex backing. Strips of carpet with a total surface area of 56 m^2 were attached back-to-back and hung behind a partition on stainless steel racks on wheels for easy transportation. The exposures were balanced with respect to the order of presentation, and subjects were blinded to interventions.

The following conditions were maintained throughout the experiment in both pollution exposure conditions: operative temperature, 23 °C; relative humidity, 30%; air velocity, <0.2 m/s; and outdoor air supply rate, 10 L/s per person, corresponding to an air change rate of 1.8 h^{-1}. The air in the office was heated using electric oil heaters and humidified by ultrasonic humidifiers. The study was carried out in March, when outdoor temperatures range between 1.2 °C and 13.6 °C. All protocols conformed to the Declaration of Helsinki, and institutional review board approval was received. Informed consent was obtained from all subjects prior to participating in the experiment.

2.2. Subjects

Twenty-four right-handed Danish female subjects were recruited. Most right-handed people have an advantage in