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# Influence of carbon-dioxide concentration on human well-being and intensity of mental work

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**Abstract—**In the frame of experiments carried out at the Department of Building Service Engineering and Process Engineering of Budapest University of Technology and Economics BUTE the impact of $CO_2$ concentration in the air was examined. Subjects' well-being was evaluated by the aid of subjective scales, physiological variables were recorded, and subjects' mental performance was measured by a standard test. Results obtained in the experiments show that subjects evaluated air quality is less acceptable, more unpleasant, and became more exhausted when the $CO_2$ concentration increased up to 3000 ppm. 3000 ppm $CO_2$ concentration in the air proved to be less advantageous for mental performance than 600 ppm. Several physiological measures show that a mental task requires a greater effort from the subjects when the $CO_2$ concentration in the air reaches 3000 ppm. It was shown that human well-being as well as the capacity to concentrate attention are declining when subjects spend 2 to 3 hours in a closed space with 3000 ppm or higher $CO_2$ concentration in the air.

Standards accurately prescribe the values of fresh air, breathing, and inside air quality assuring the health protection at workplaces.

We examined the level of carbon-dioxide concentration above which the efficiency of mental work and the human well-being significantly declines.

*Key-words*: air quality, carbon-dioxide, IAQ assessment, measurement technique, mental work

## 1. Introduction

The comfort in closed spaces is usually understood as thermal, air quality, acoustical, and illumination engineering comfort. The office plays a special role in providing adequate comfort as workers spend a longer time in closed spaces performing intellectual work. In the air-conditioning of comfort spaces, the primary task is to provide a pleasant indoor microclimate for the people staying in the room. In addition to thermal comfort, air quality is also regulated by international requirements and standards. In the occupied zone, a sufficient amount of fresh air of appropriate quality must be provided for the people staying in the room. Hungarian technical regulations do not fully cover these aspects yet, hence the complaints frequently heard from employees working in air-conditioned spaces are the air has an unpleasant 'smell', they experience 'lack of air' or perhaps have headaches. Among pollutants, carbon-dioxide, a by-product of the human metabolism, is regarded as one of the key factors. The carbon-dioxide content of exhaled air is higher than that of the outdoor air, leading to an increase in the carbon-dioxide concentration in the closed space. $CO_2$ concentration influences human well-being. In closed spaces the allowed $CO_2$ concentration may be ensured by supplying the adequate amount of fresh air. The exact volume of fresh air varies in Hungarian and international literature, ranging from 20 to 120 $m^3$/person. This is also a matter of economic efficiency as the volume flow of fresh air has an impact on the energy use of the air conditioning system (*Kajtár et al*., 2001; *Kajtár* and *Hrustinszky*, 2002, 2003)

The fundamentals of the science of indoor air quality (IAQ) were laid down by Professor *Fanger* at the Danish Technical University. *Max von Pettenkoffer*, who published his research results in a medical journal in Munich in 1858, can be called the pioneer of IAQ. Using the $CO_2$ concentration in comfort spaces, his research focused on defining the average carbon-dioxide level below which human well-being is still ensured.

Further research conducted in the subject always investigated the joint impact of several factors influencing air quality, therefore the impact of carbon-dioxide on its own could not be determined.

We conducted studies concerning the impact of $CO_2$ on mental performance and well-being, at the same time determining the necessary fresh air demand.

## 2. Practical implications

In the present investigation, the influence of $CO_2$ concentration on human well-being and efficiency of mental work has been evaluated. These issues arise from time to time in connection with office work and the air-conditioning of office buildings. It is very important to find the optimal balance between the biological requirements of office employees concerning fresh air on the one hand and economic efficiency on the other hand. A reduction in fresh air supply is required according to the arguments for profitability, whereas an increase of fresh air supply is needed when subjects' well-being is taken into consideration.

*Table 1* shows the highest allowed $CO_2$ concentration in closed places provided by Hungarian and international standards and prescriptions.

*Table 1.* Maximum allowed $CO_2$ concentration in closed places

| **No.** | **Standards and prescriptions** | **Allowed $CO_2$ concentration [ppm]** |
|---|---|---|
| | **Comfort spaces** | |
| 1. | *MSZ 04.135/1-1982 | 1400.0 |
| 2. | MSZ 21875-2-1991 | 1066.6 |
| 3. | **DIN 1946/2 single office | 900.0 |
| 4. | DIN 1946/2 landscaped office | 733.3 |
| 5. | MSZ CR 1752 "A" cat. | 860.0 |
| 6. | MSZ CR 1752 "B" cat. | 1060.0 |
| 7. | MSZ CR 1752 "C" cat. | 1590.0 |
| | **Workplaces** | |
| 8. | ***TRGS 900 | 5000.0 |
| 9. | MSZ 21461 1-2 | 4830.0 |

*MSZ: Hungarian Standard
**DIN: Deutsches Institut für Normung
***TRGS: Technische Regeln für Gefahrstoffe

The above table indicates that the standards and prescriptions have not touched upon a wide range of $CO_2$ concentration from 1590 ppm to 4830 ppm. The aim of our research was to examine the influence of $CO_2$ concentration on human well-being and mental effort between 600 and 5000 ppm that was pointed in *Fig. 1*.

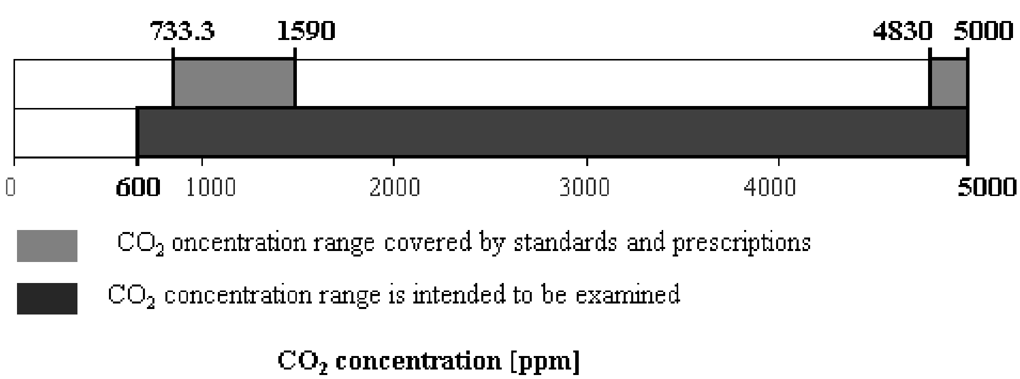


*Fig. 1.* The aim of our research.

The influence of $CO_2$ concentration on humans could be specified by means of examination of subjective comfort parameters and such objective parameters which were measured on humans and of performing experiments on subjects. The measuring-room that was built in Indoor Air Quality Laboratory of Department of Building Service Engineering and Process Engineering of BUTE were chosen for carrying out the experiments. Only this room could provide us that other air-polluting material did not influence the results of the measurements and subjects could stay in full thermal and air quality comfort during the measurements.

After finishing and evaluating the measurements, a maximum $CO_2$ concentration could be determined, under which there could not be any observable change in the human well-being and mental effort.

## 3. Methods

In the framework of our research, we investigated the impact of carbon-dioxide concentration on well-being and performance in the office. In the laboratory measurements we set the following $CO_2$ concentrations: 600, 1500, 2500, 3000, 4000, and 5000 ppm. The laboratory measuring room contained two carbon-dioxide sources: two main measuring subjects and carbon-dioxide, suitable for inhaling, fed from a bottle. The circuit diagram for the laboratory measurements is shown in *Fig. 2*.

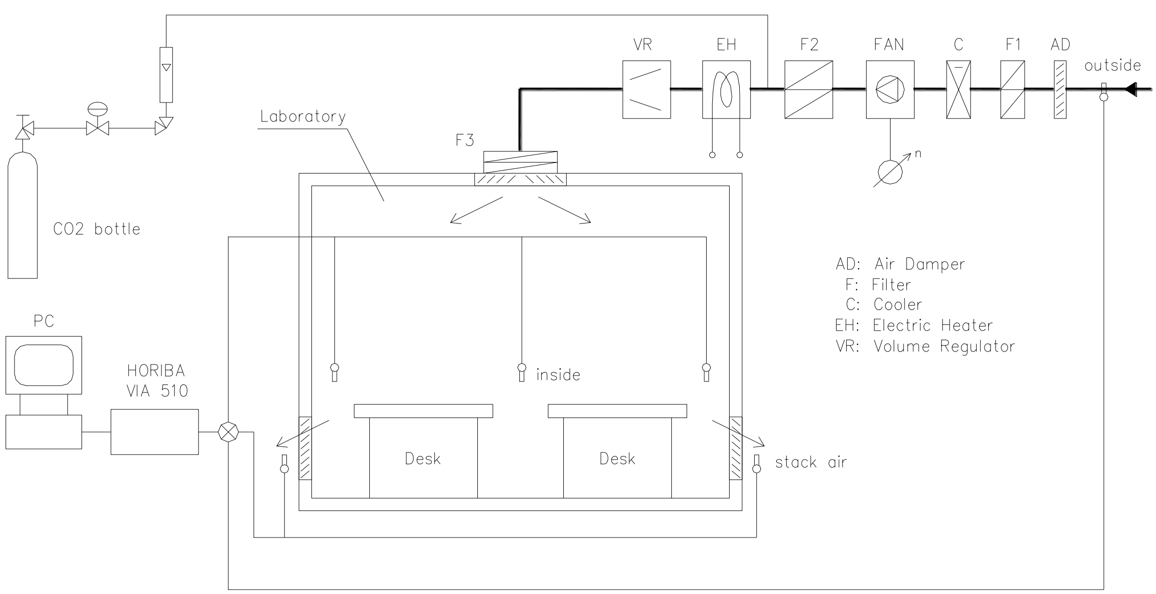


*Fig. 2.* Circuit diagram of the laboratory measurements.

The carbon-dioxide was fed into the measuring room mixed with 120 $m^3/h$ fresh air. During the measurements, the carbon-dioxide concentration had to be kept at a constant level, therefore, the feeding valve had to be set accordingly. The share of carbon-dioxide sources is contained in *Table 2*. The carbon-dioxide concentration of outdoor air was 360 ppm.

*Table 2*. Carbon-dioxide sources in the measuring room

| **Measuring room $CO_2$ concentration [ppm]** | **Source of carbon-dioxide** | | **Share human/total [%]** |
|---|---|---|---|
| | **Total [ppm]** | **Human [ppm]** | |
| 600 | 240 | 240 | 100.0 |
| 1500 | 1140 | 240 | 21.0 |
| 2500 | 2140 | 240 | 11.2 |
| 3000 | 2640 | 240 | 9.1 |
| 4000 | 3640 | 240 | 6.6 |
| 5000 | 4640 | 240 | 5.2 |

Carbon-dioxide fed from the bottle, was a gas of 99.995 V% cleanness, suitable for inhaling. Owing to their slight share, other pollutants in the carbon-dioxide gas ($O_2 \leq 25$ vpm, $N_2 \leq 25$ vpm, $HC \leq 1$ vpm, $CO \leq 1$ vpm, $H_2O < 5$ vpm) did not influence the results of the measurements. The pressure reducer and other armatures did not pollute the carbon-dioxide gas as their use is permitted in case of a gas of greater cleanness (99.998 V%).

In the present paper, two series of experiments are presented:

1. series of experiments carried out in 2001,
2. series of experiments carried out in 2002.

Both series of experiments were conducted in a laboratory constructed for the above purposes in the Department of Building Service Engineering and Process Engineering of the Budapest University of Technology and Economics. Inodorous air of appropriate, cleanliness, thermal comfort, as well as appropriate acoustic conditions have to be ensured in the laboratory.

In order to meet the requirements concerning air quality, the laboratory was built using specific low emitting building materials generally used in operating rooms, with practically no emission of contaminant substances.

To produce fresh air supply of the required cleanliness, a two-step filtration has been applied (G4 and F7). Air ducts as well as the filter unit at the second step of filtration were made from rust-proof steel plates.

During the various investigations in the laboratory, a high ventilation rate prevents the indoor air from becoming stale. Overpressure has been induced to prevent the influx of contaminating substances from outside (*Kajtár* and *Hrustinszky*, 2002, 2003).

Main data of the laboratory outlined above:

| | |
|---|---|
| Floor area: | $2.1 \times 3.3\ m = 6.9\ m^2$ |
| Inside height: | 2.5 m |
| Volume: | $17.3\ m^3$ |
| Volume flow of supply air: | $1\,000\ m^3/h$ (maximum) |
| Ventilation rate: | 57.8 l/h (maximum) |
| Filters: | G3, F7. |

During experiments, a HORIBA VIA 510 infrared gas analyzer has been used. Main technical parameters of the instrument:

- Measuring range: $0-1\,000$ ppm, $0-2\,500$ ppm, $0-6\,000$ ppm, $0-10\,000$ ppm
- Measuring accuracy: $\pm 1.0\%$. Measurements were carried out by the aid of two parallel infrared rays. Automatic data collection was carried out by a data-collector developed by us. In this way data were stored and processed by a PC.

To measure comfort parameters, the following instruments were used:

- thermal comfort PMV meter: Thermal Comfort Meter 1212,
- air temperature and humidity meter: TESTO Testotor 175 Logger,
- wall surface temperature meter: TESTO Quicktemp 824-2,
- acoustics meter: ROLINE RO-1350 Sound Level Meter.

Instruments used to record physiological data:

- ISAX instrument,
- blood pressure monitor: wrist model,
- skin surface temperature meter: TESTO T2.

### *3.2. Subjects and procedures*

In the laboratory measurements, a pleasant thermal, acoustic, and illumination technology comfort was provided to ensure that human well-being is only impacted by air quality (carbon-dioxide gas).

A pleasant thermal comfort was ensured for all live subjects by regulating the air temperature and individually selecting the clothing. The sound level in the measuring room was 36.6–37.0 dB(A).

The set carbon-dioxide concentrations were unknown to the subjects.

The number of subjects was defined through an empirical way (*Wyon* and *Bánhidi*, 2003), consequently 10 subjects were enough because significant differences could be found among the results.

#### *3.2.1. First series of experiments*

Ten subjects participated in the study (5 males and 5 females, mean age = 22.5 years). Each subject participated in four experimental sessions with different pre-set $CO_2$ concentrations (600, 1500, 2500, and 5000 ppm). Sessions succeeded each other in the following manner: session 1 (1500 ppm $CO_2$), session 2 (2500 ppm), session 3 (600 ppm), session 4 (5000 ppm). Each session consisted of $2 \times 70$ minutes mental work periods. The mental work involved the reading of a text manipulated for this purpose and the search for typographic errors. Performance of subjects was characterized by the number of rows read by the subjects (quantity aspect), and the percentage of misspelled words found by them (quality aspect). Prior to and following the work periods, questionnaires were to be filled in for evaluating subjective comfort and well-being, as well as physiological tests were carried out and measurements of skin temperature were taken.

#### *3.2.2. Second series of experiments*

The same measuring stand was used as in the 1st set of experiments. Ten subjects participated in the study (4 males and 6 females, mean age = $21.3 \pm 1.5$ years). Each subject participated in 4 experimental sessions with different pre-set $CO_2$ concentrations (600, 1500, 3000, and 4000 ppm). Sessions succeeded each other in the following manner: session 1 (1500 ppm $CO_2$), session 2 (3000 ppm), session 3 (600 ppm), session 4 (4000 ppm). Two sessions (with 1500 and 4000 ppm $CO_2$ concentration) consisted of $2 \times 70$ minutes mental work periods. Two sessions (with 3000 and 600 ppm $CO_2$ concentration) consisted of $3 \times 70$ minutes mental work periods. Subjects had to perform a mental work slightly different from the mental work performed in the 1st series of experiments. Prior to and following the work periods questionnaires were to be filled in for evaluating subjective comfort and well-being, as well as physiological tests were carried out and measures of skin temperature were taken.

The exposure time was longer only for two levels of $CO_2$ (600 and 3000 ppm). Periods with corresponding exposure time were compared. The measuring stand was the same as in the first session (*Fig. 1*).

### *3.3. Measurement of objective microclimatic characteristics*

The following objective microclimatic parameters were examined:

- Measurements of $CO_2$ concentration were carried out with the aid of a HORIBA VIA 510 infrared gas analyzer for which the department has developed a data collector to be connected to a computer. Measurements were carried out during the entire experimental session with 30s sampling intervals.
- PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) values are objective measurements concerning thermal comfort which were conducted with a PMV meter. Data were read every 70 min in a work period.
- Temperature of the supply air, as well as temperature of exhaust air were measured with two temperature data collectors. Temperature and relative humidity in the occupied zone were also measured with the aid of a temperature and humidity data collector. Measurements were carried out during the entire experimental session, with 30s sampling intervals.
- Surface temperature of the four side walls of the floor and the ceiling was measured using a laser surface thermometer. Sampling was done at the start of the session, before the breaks, and at the end of the session.

### *3.4. Evaluation of subjective comfort*

The following parameters were examined in the evaluation of subjective comfort:

- *Fanger scale*: subjects had to report whether they find air quality acceptable or unacceptable by marking +1 (clearly acceptable) and –1 (clearly unacceptable) on a scale (*Fanger* and *Wargocki*, 2002).
- *Hedonic scale*: subjects' comfort was measured in the range of pleasant (5) and unbearable (1) (*Fanger* and *Wargocki*, 2002).
- *Air Quality scale*: analogue scale for evaluation of freshness of the air. The endpoints of the scale were fresh and very unpleasant sensation.
- In the examination of human well-being changes in subjects' freshness, tiredness and concentration were surveyed.

The above measurements were carried out in each session at the beginning, at the end, and in the breaks between the 70 minutes working periods. These way questionnaires were filled in three times during sessions in the first series of experiments. In the second series of experiments, questionnaires were filled in three times during session 1 (1500 ppm $CO_2$) and session 4 (4000 ppm $CO_2$) consisting of two working periods, while during sessions consisting of three working periods (session 2 with 3000 ppm $CO_2$, and session 3 with 600 ppm $CO_2$), measurements were carried out four times.

The following measurements were carried out at the beginning and end of each session:

- Subjective evaluation of surface temperature of human skin: subjective thermal comfort was recorded with the help of a 7-grade scale (very hot: 3; pleasant: 0; very cold: –3) at 5 different points: forehead, nose, chest, right hand, and left hand.
- Subjective evaluation of general thermal comfort: subjects' thermal comfort was examined using an analogue scale.

*3.5. Study of objective physiological parameters for humans*

The following physiological and psycho-physiological parameters were measured and computed: systolic blood pressure (SBP), diastolic blood pressure (DBP), pulse rate, skin temperature.

During each session, SBP, DBP, and pulse rate have been taken at the beginning and end of the session, as well as in the pause between 2 reading periods by the aid of a wrist digital sphygmomanometer. The surface temperature of the human skin was measured with a surface thermometer at the beginning and end of the sessions (measured points: forehead, nose, chest, and both hands).

Heart periods (HP) or RR-intervals were collected continuously during sessions (HP is the time elapsed between 2 subsequent R waves of the ECG, this practically means time elapsed between adjacent heart beats). The variation of HP-s is largely determined by a balance between levels of activity of the cardiac sympathetic and parasympathetic nerves. Spectral analysis of heart period variance (HPV) allows the contributions of these autonomic nerves to be isolated providing insight into the actual balance of the activity of autonomic nerves. It has been shown (*Hyndman et al.*, 1971; *Luczak* and *Laurig* 1973; *Mulder* and *van der Meulen*, 1973; *Sayers*, 1971, 1973; *Womack*, 1971; *Akselrod et al*., 1981, 1985;) that short-term (time-scale of seconds to minutes) fluctuations in heart periods is concentrated in several principal peaks (low-frequency (LF), mid-frequency (MF), and high-frequency (HF) components of HPV). The HF component of HPV is the so called respiratory component of HPV, it reflects the respiratory rate and it is influenced by the volume of respiration. HF component is mediated solely by the vagus nerve, while MF component of HPV is mediated jointly by sympathetic nerves and n. vagus (*Akselrod*, 1988; *Akselrod et al*., 1981, 1985; *Lombardi et al*., 1987; *Pagani et al*., 1986; *Pomeranz et al*., 1985; *Weise et al*., 1987). Thus, the relative power of these spectral components as well as the ratio of MF and HF components can be used to monitor the actual balance of autonomic nerves (*Lombardi et al*., 1987; *Pagani et al*., 1986). For more about spectral analysis of HPV see the reviews by *Láng* and *Szilágyi* (1991), *Eckberg et al*. (1997).

A number of studies has shown that increasing mental load causes a decrease in heart rate variance (*Luczak* and *Laurig*, 1973; *Mulder* and *van der Meulen*, 1973). *Sayers* (1971, 1973) found that consistent changes occur in the heart period spectrum especially in the band from 50 to 150 mHz. According to *Mulder et al*. (1973), the mid-frequency band of HPV (70 – 140 mHz) appeared to be more sensitive to mental workload than total variance or respiratory fluctuations.

It is believed that mental load (when the task requires explicit effort) operates like a defense reaction. The defense reaction is characterized by a decrease in sensitivity of the baroreflex which results in a decrease of HRV, because changes in the blood pressure will be less reflected in changes in HR. Defense reaction involves suppression of the vagal component of the reflex (*Mulder*, 1980).

Spectral analysis of heart period variance (HPV) is extensively used as a mental effort monitor in the field of ergonomics and psychophysiology (*Itoh et al*., 1989; *Izsó* and *Láng*, 2000; *Izsó*, 2001; *Mulder*, 1980; *Mulder et al*., 2000).

It was hypothesized that in unfavorable environmental conditions, such as higher concentration of $CO_2$ in the air, mental task might request more mental effort.

To assess the actual balance of the autonomic nervous system on the basis of spectral analysis of heart period variance (HPV), an integrated system (ISAX) has been developed and validated (*Láng* and *Horváth*, 1994; *Láng et al*., 1994, 1997).

It consists of:

- a portable , easy to use equipment for 24-hour ambulatory measurement and storage of heart period (HP) beat by beat and, optionally, other bio-signals, plus
- a user-friendly software package for spectral analysis (autoregressive model) of the stored data in a single personal computer, algorithms to evaluate parameters of the significant spectral components of the power spectra of HPV, and plain text table output for further statistical purposes (*Láng et al*., 1998).

The acquisition module is a small (300g) portable plastic box that can be mounted on the patient by a clip, and connected to the sensors. The ambulatory recorded data are stored in the built in NVRAM. Two channels serve the purposes of event-marking in order to be able to identify data sequences recorded in special conditions. The recorded data are read and processed by a host computer. Processing of RR-interval series by the ISAX program consists of steps as follows: RR-interval series are interpolated for the sampling procedure (1 Hz). RR-interval time functions are displayed for interactive selection of appropriate analysis frame. A sufficiently long stationary and representative part of the RR-interval function is selected for spectral analysis. The RR-interval function marked for analysis is converted into zero-mean process. An all-pole auto-regressive model is fitted to the data set (*Akaike*, 1969; *Itakura* and *Saito*, 1969) using a modified Burg algorithm (*Gray et al.*, 1980). More compact characteristics of spectral peaks (such as central frequencies and bandwidths) are computed from the numerically determined poles of the synthesis model.

For compatibility with the conventional analysis methods, sub-band powers (low-, mid-, and high-frequency) are calculated by integrating the spectra over sub-band boundaries specified. Using default, the software calculates the spectral power ($ms^2$) of heart period variability for predetermined frequency ranges [low-frequency range: 10 mHz – 70 mHz (LF); mid- frequency range: 70 mHz – 150 mHz (MF); high-frequency range:150 mHz – 450 mHz (HF)] (*Láng et al.*, 1998). In the recent study the following non-spectral and spectral parameters were computed for further statistical analysis: RR-interval mean (ms) (mean of the analysis frame), MF-power ($ms^2$), HF-power ($ms^2$) of the HPV spectrum. Relative powers were expressed in normalized units by dividing each component by the sum of their powers (sum = HF-power + MF-power). Thus, HF-relative = HF-power/sum, MF-relative = MF-power/sum.

One of the problems of spectral analysis is the issue of non-stationarity of the time series to be analyzed. In ISAX program this problem has been attacked by an approach called by *Mulder* (1988) spectral profile method. Spectral computations are carried out on short time segments (20 – 60 seconds.) By shifting such segments over the time series to be analyzed, and by introducing a certain overlap (90% or more), series of spectral values are obtained. Spectral power of a selected frequency band versus time is the so-called "spectral profile" of this frequency band (*Izsó* and *Láng*, 2000).

### *3.6. Statistical analysis*

Statistical analysis on the above variables was performed using SPSS 10.00 for Windows program package. Differences between sessions, as well as changes appearing during the same session (differences between measurements of the same session) were revealed using analysis of variance with repeated measurements and appropriate contrasts. Differences were considered significant when $p < 0.05$. More about analysis of variance see in Appendices (*Ferguson*, 1988; *Rosenthal* and *Roskov*, 1987; *SPSS Advanced Statistics 7.0 update*, 1996).

The repeated measures procedure provides analysis of variance when the same measurement is made several times on each subject or case. In repeated measures analysis, all dependent variables represent different measurements of the same variable for different values (or levels) of a within-subjects factor (*SPSS Advanced Statistics 7.0 update*, 1996).

In our case, all dependent variables represent different measurements of the same variable for different levels of $CO_2$ concentration in the air.

## ***4. Results and discussion***

### *4.1. Results of the first series of experiments*

Results of the first series of experiments described in section 3.2. are discussed in this section. Concentrations of $CO_2$ were set at 600, 1500, 2500, and 5000 ppm.

#### *4.1.1. Results concerning evaluation of subjective comfort*

When comparing corresponding measurements of different sessions using the *Fanger scale* the analysis of variance revealed significant differences between sessions with 600 and 5000 ppm $CO_2$ already at the beginning of the sessions: subjects evaluated air quality less acceptable during the session with 5000 than with 600 ppm $CO_2$. Between sessions with 5000 and 1500 ppm $CO_2$ a significant difference appeared only at the end of sessions, that is after 140 minutes: subjects evaluated air quality less acceptable during the session with 5000 than with 1500 ppm $CO_2$ (*Fig. 3*).

Similar results were found with the *Air Quality scale.*

In the case of *Hedoni*c *scale* subjects evaluated air with 600 and 1500 ppm $CO_2$ significantly less unpleasant than air with 5000 ppm $CO_2$.

Concerning *freshness, tiredness* scales difference between the first and the last measurements of the same session was the greatest in the case of session with 5000 ppm $CO_2$, showing that subjects became the most exhausted in this session. In this respect the difference between session, with 5000 and 600 ppm $CO_2$ concentration reached the level of significance.

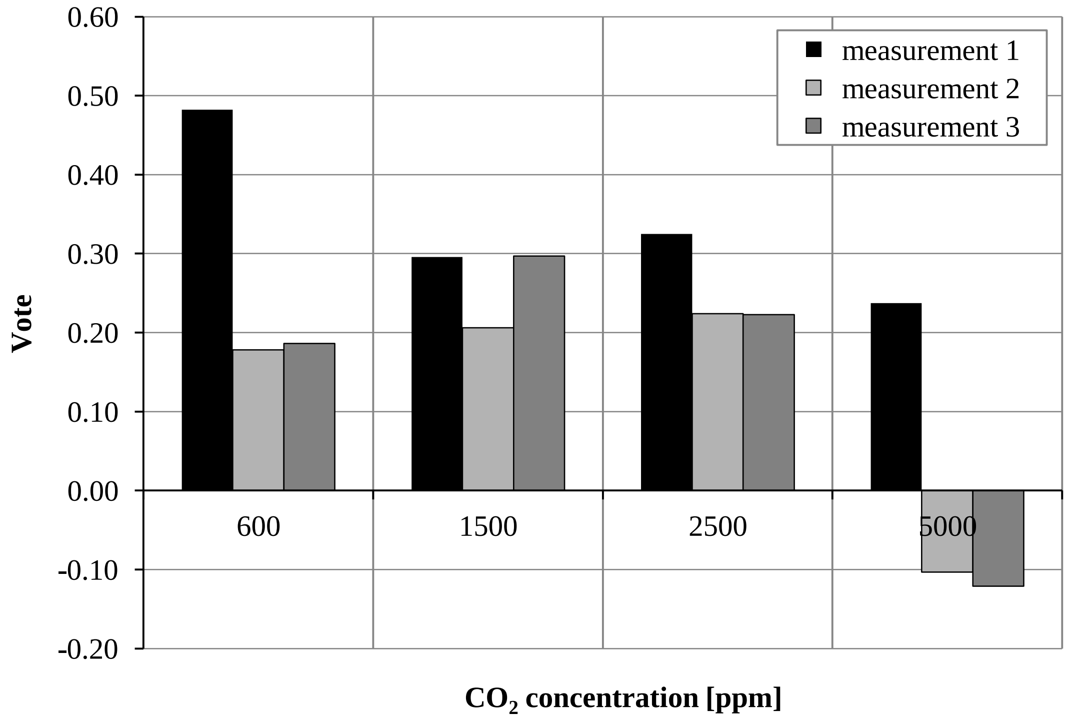


*Fig. 3.* Results of measurements with *Fanger scale* (acceptable {+1}, unacceptable {-1}). Measurement 1, 2, and 3 were carried out in each sessions at the beginning, before the breaks, and at the end of each session, respectively.

*Fig. 4* shows the results of measurement on the tiredness scale.

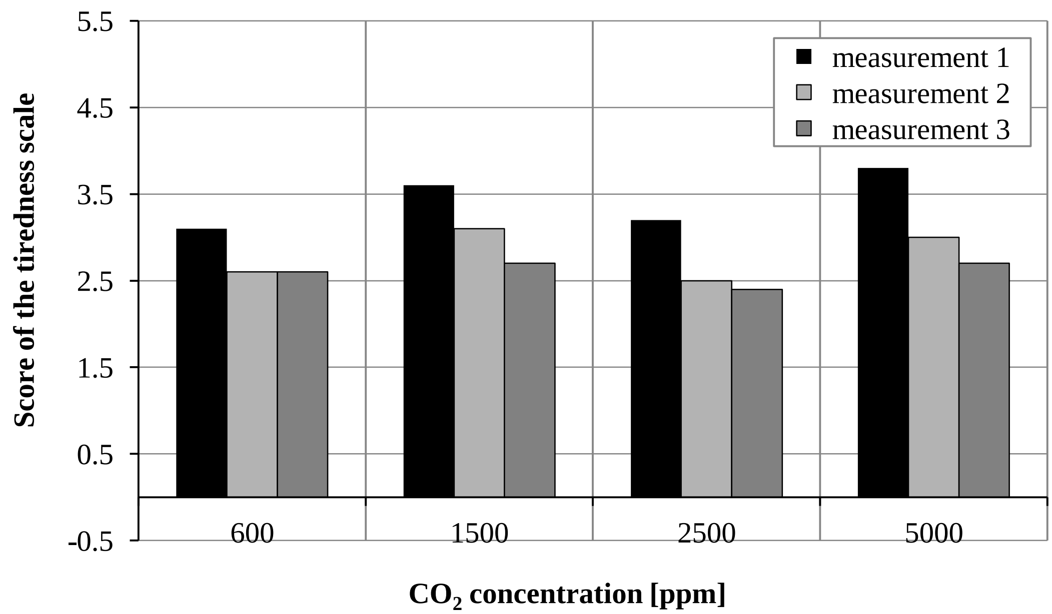


*Fig. 4.* Results of measurements with tiredness scale. Measurement 1, 2, and 3 were carried out in each sessions at the beginning, before the breaks, and at the end of each session, respectively.

*4.1.2. Results concerning mental workload*

Subjects' performance characterized by the number of rows read during the session (quantity aspect), as well as the percentage of mistakes found by the subjects (quality aspect of performance) was not significantly impacted by the degree of $CO_2$ concentration.

*4.1.3. Results concerning physiological parameters*

*Heart rate (pulse rate)* showed a decreasing tendency during each session. This is usually the case when subjects are sitting quietly for hours, the mental task does not require a high mental effort, and the temperature of the air does not increase substantially. The degree of this decrease of the heart rate (difference between measurements at the beginning and end of the same session) was significantly less expressed in the case of session with 5000 ppm $CO_2$ concentration as compared with sessions with lower $CO_2$ concentration. Changes of the heart rate within sessions (difference between the heart rates observed at the end (measurement 3) and beginning (measurement 1) of the same session) are illustrated by *Fig. 5*.

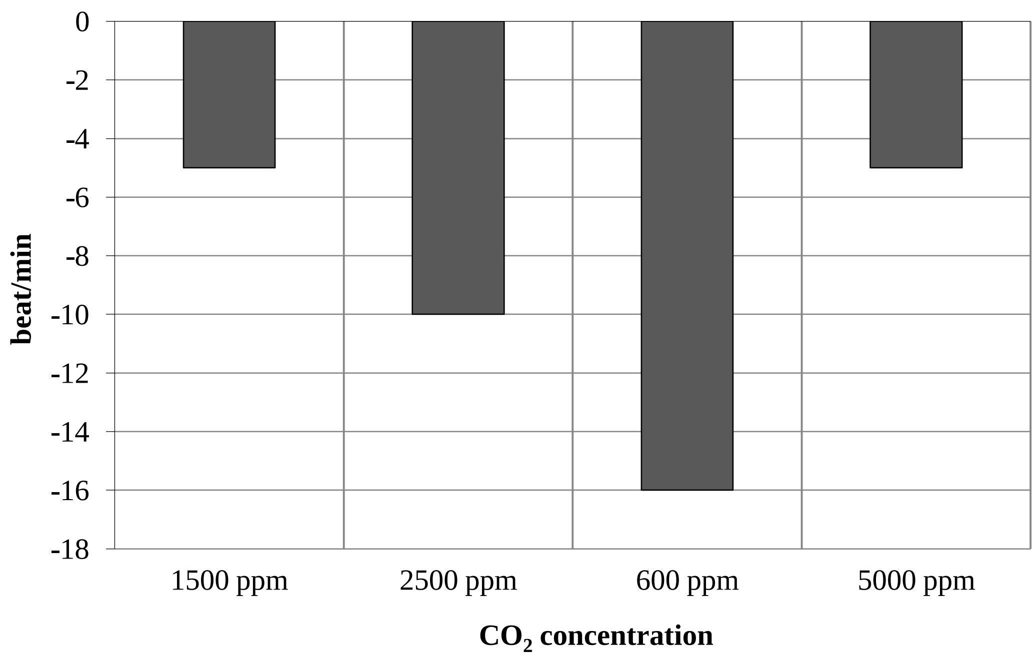


*Fig. 5.* Changes of the heart rate during the same session.

The analysis of variance revealed a small but significant increase of the *diastolic blood pressure* (*DBP)* during the session with 5000 ppm $CO_2$ concentration. Concerning the degree of DBP changes within sessions (difference between measurements at the beginning and end of the same session), sessions with

600  and 5000 ppm $CO_2$ concentration were significantly different from each other. Increase of DBP usually is caused by the increase of total peripheral resistance due to constriction of blood-vessels (vasoconstriction). It may be supposed that 5000 ppm $CO_2$ concentration in the air slightly raised the vasoconstrictor tone of subjects.

*Fig. 6* illustrates the changes of DBP within sessions (difference between the DBP values observed at the end (measurement 3) and beginning (measurement 1) of the same session).

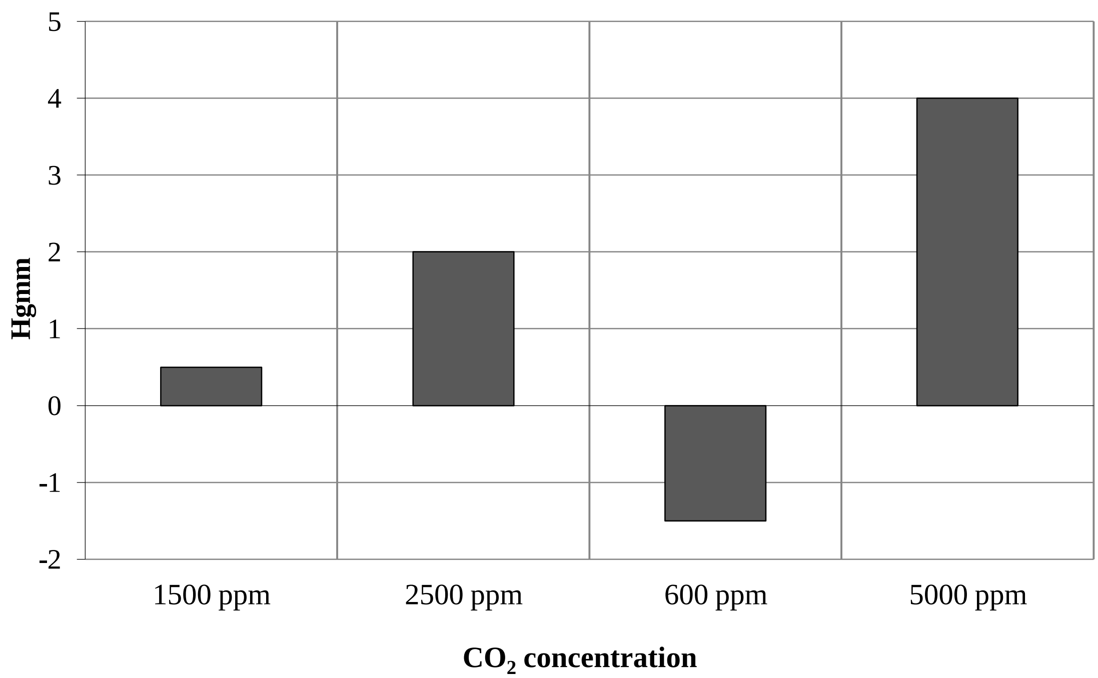


*Fig. 6*. Changes of DBP within sessions.

By the aid of the ISAX system, it was revealed that the respiratory frequency and the volume of respiration of the majority of subjects were higher in the session with 5000 ppm $CO_2$ concentration than in the session with 600 ppm. *Fig. 7* shows that the HF component of HPV was significantly higher in the session with 5000 ppm $CO_2$ concentration than in the session with 600 ppm $CO_2$ concentration.

In the case of subjects who became very exhausted according to the *freshness, tiredness* scales in the session with 5000 ppm $CO_2$ concentration but did not show any decrease in mental performance, the HPV analysis revealed a higher mental effort during mental load. As it was mentioned in Section 3 the suppression of MF component of HPV reflects the mental effort invested by the subjects. Thus, it might be concluded that in the case of the above subjects the mental task might require more mental effort in unfavorable environmental conditions such as higher concentration of $CO_2$ in the air.

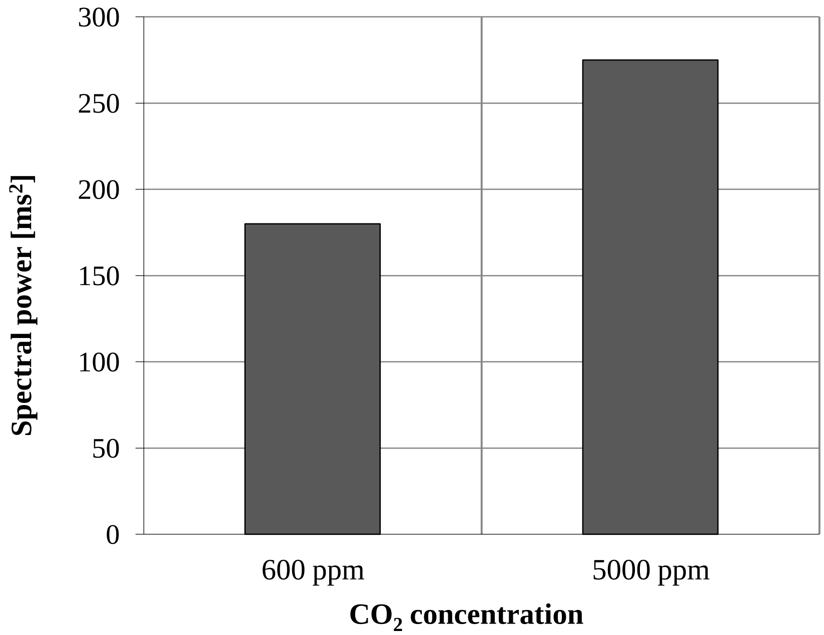


*Fig. 7.* Spectral power of the HF component (respiratory component) of HPV.

Similary to the measurements of skin temperature and the subjective evaluation of surface temperature and general thermal comfort, the analysis of variance did not reveal significant differences between sessions with different $CO_2$ concentrations.

*4.1.4. Summary of results obtained in the first series of experiments*

Significant differences were obtained concerning subjective evaluation of air quality and human well-being between work periods with 600 and 5000 ppm $CO_2$ concentration, showing a decline of well-being when $CO_2$ concentration in the air reaches 5000 ppm. At the same time, no significant differences were found concerning mental performance between work periods at different $CO_2$ concentrations. HPV analysis (MF component) revealed, however, that a mental task required more mental effort under 5000 ppm $CO_2$ as compared to 600 ppm.
Moreover, the respiratory component of HPV reflected an increase in respiratory volume and respiratory frequency at 5000 ppm $CO_2$ concentration.

### *4.2. Results of the second series of experiments*

Results of the second series of experiments described in Section 3.2. are discussed in this section. Concentrations of $CO_2$ were set at 600, 1500, 3000, and 4000 ppm.

#### *4.2.1.Results concerning evaluation of subjective comfort*

The analysis of variance with repeated measurements using the *Fanger scale* revealed significant differences between measurements of the same session. Subjects evaluated air quality less acceptable at the end than at the beginning of the same session. In the case of session with 600 ppm $CO_2$, subjects evaluated air quality less acceptable only after the second working period, while subjects' well-being already declined following the first 70-minute working period during other sessions.

Using the *Air Quality scale, s*imilar results were found as in the case of *Fanger scale.* At the same time, there were differences between the sessions. When comparing corresponding measurements of different sessions using the *Fanger scale* the analysis of variance showed that significant differences appeared between sessions only following the second working period, that is after 140 minutes. Subjects evaluated air with 3000 and 4000 ppm $CO_2$ significantly less acceptable than air with 600 ppm $CO_2$. Air with 1500 ppm $CO_2$ concentration was judged as significantly more acceptable than air with 4000 ppm $CO_2$. In the case of sessions with 600 and 3000 ppm $CO_2$, three 70-minute working periods were used. After the third working period (210 minutes) air was denoted significantly less acceptable during session with 3000 ppm $CO_2$ as compared to session with 600 ppm $CO_2$ (as it was the case already after 140 minutes). *Fig. 8* shows the results of measurements with the *Fanger scale*.

Using *Air Quality scale* similar results were found as in the case of the *Fanger scale*, with the only advantage, that after 140 minutes air with 1500 ppm $CO_2$ concentration was judged as significantly fresher than air with 3000 ppm. *Fig. 9* shows the results of measurements with the *Air Quality scale*.

The analyses of variance performed on scores on *freshness, tiredness,* and *concentration* scales revealed significant differences between measurements of the same session in the case of sessions with higher $CO_2$ concentration than 600 ppm, showing that subjects get more tired, became less fresh, and their capability to focus their attention was declining in the course of the session. Concerning scores on *freshness* and *tiredness* scales, when comparing corresponding measurements of different sessions, the analysis of variance showed that significant differences appeared between sessions with 600 and 3000 ppm $CO_2$ concentration only following the third working period, that is after 210 minutes. Subjects became more exhausted at the end of session with 3000 ppm than at the end of session with 600 ppm $CO_2$ concentration.

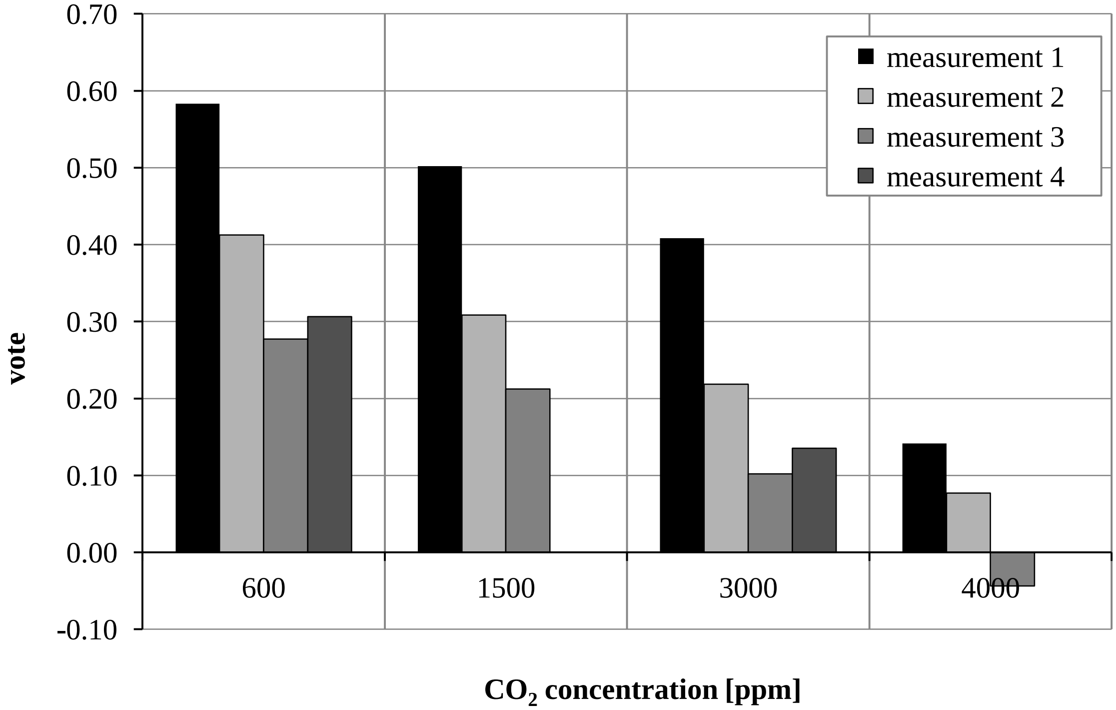


*Fig. 8.* Results of measurements with Fanger scale (acceptable {+1}, unacceptable {-1}). Measurement 1, 2, 3, and 4 were carried out in each sessions at the beginning, before the breaks, and at the end of each session, respectively.

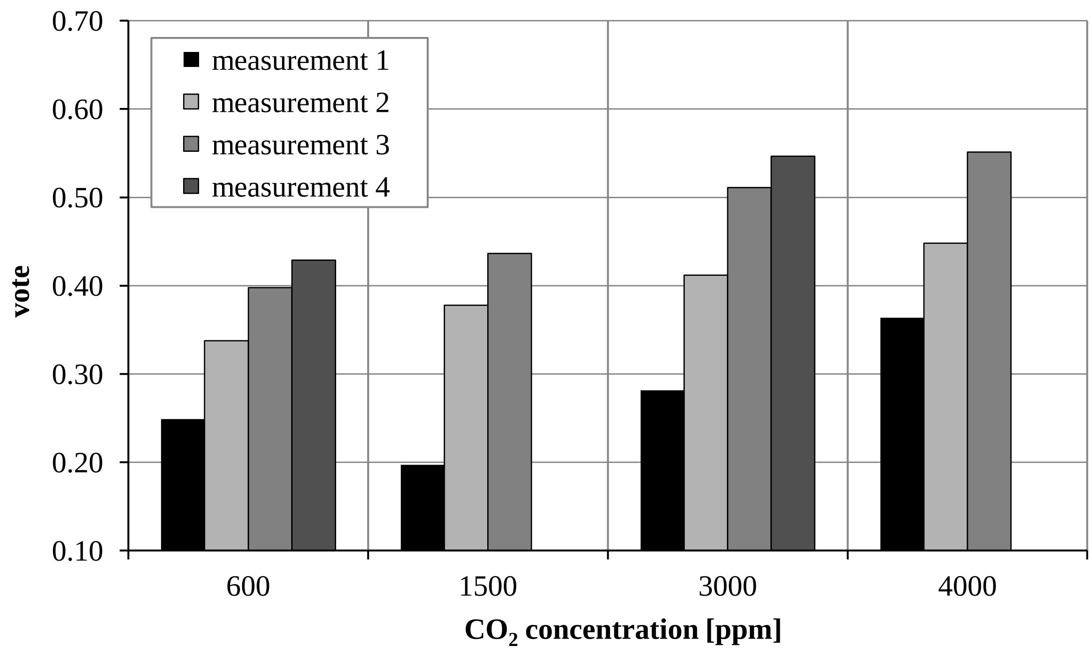


*Fig. 9.* Results of measurement, with *Air Quality scale* (fresh {0}, very unpleasant sensation {+1}). Measurement 1, 2, 3, and 4 were carried out in each sessions at the beginning, before the breaks, and at the end of each session, respectively.

*4.2.2. Results concerning mental workload*

As it was mentioned in Section 3, a different text was used in the second series of experiments. In the first series, neither the number of rows read by the subjects, nor the percentage of mistakes found by the subjects were influenced by the degree of $CO_2$ concentration. Therefore, we decided to use a more difficult text in the second series of experiments.

Subjects' performance characterized by the number of rows read during the session (quantity aspect) was not significantly impacted by the degree of $CO_2$ concentration. Concerning this variable, the *time effect* (learning) was found: subjects' performance related to the quantity of read rows increased from the first to the last session. The quality aspect of performance (percentage of mistakes found by the subjects), however, proved to be more sensitive to the concentration of $CO_2$. The analysis of variance revealed that during the second 70-minute working period, the percentage of mistakes found by the subjects was significantly higher in session with 600 ppm $CO_2$ than in the corresponding working period of session with 4000 ppm $CO_2$ concentration. Moreover, during the third 70-minute working period of session with 600 ppm $CO_2$, the percentage of mistakes found by the subjects was almost significantly higher than in the corresponding period of session with 3000 ppm $CO_2$ concentration. In this case, the number of rows read by the subjects in the session with 600 ppm $CO_2$ also exceeded the number of rows read in the corresponding period of session with 3000 $CO_2$ concentration. That means that the third working period with 600 ppm $CO_2$ proved to be more advantageous for both aspects of mental performance than 3000 ppm $CO_2$ concentration (*Fig. 10*).

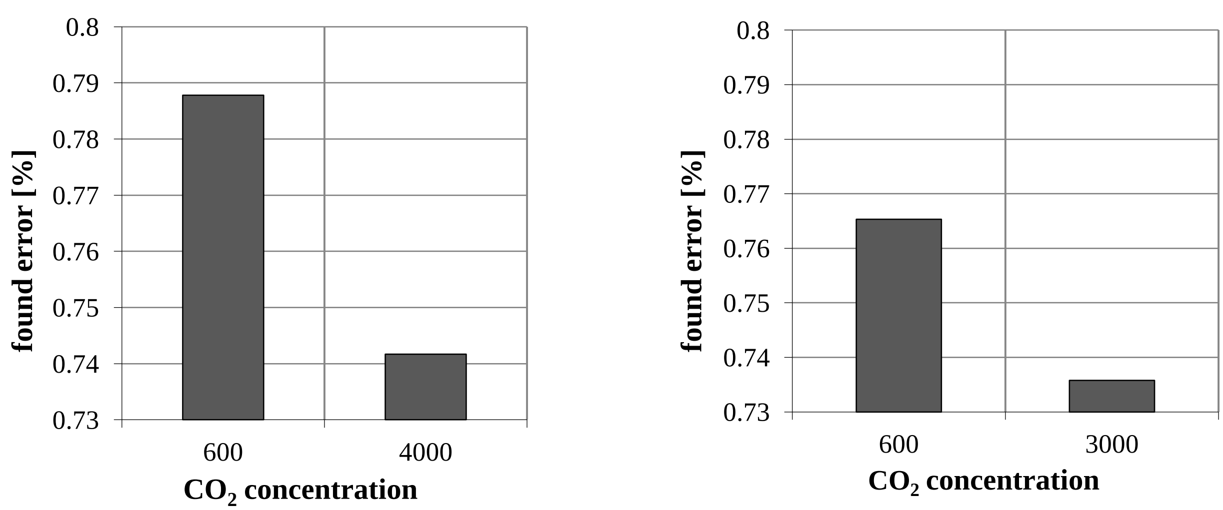


*Fig. 10.* Influence of $CO_2$ concentration on percentage of errors found by subjects in the second( left) and third( right) 70-minute working periods.

The quality aspect of mental work expresses the ability to concentrate attention. It seems that human well-being as well as the capacity to concentrate attention decline when $CO_2$ concentration increases up to 3000 ppm.

### *4.2.3. Results concerning physiological parameters*

The analysis of variance did not reveal any significant effect of $CO_2$ concentration in air (in the range of 600 to 4000 ppm) on the systolic blood pressure (SBP), and diastolic blood pressure (DBP). In these experiments, these parameters were not sensitive enough to show the impact of $CO_2$ concentration in air under 4000 ppm. For this reason, in the analysis of physiological parameters we preferred to use the ISAX system, which is based on measuring heart period parameters.

The analysis of variance revealed that heart periods (HP) (time elapsed between two heart beats) increased during each session from the beginning to the end. This means that the pulse rate decreased from the beginning to the end of each session. This is a typical phenomenon when subjects are sitting quietly for hours. Concentration of $CO_2$ had no impact on the HP. Absolute and relative values of MF (mid-frequency component) of heart period variability (HPV) are used to measure mental effort requested by the task. The less the value of the MF component, the more pronounced the effort invested by the subjects along the mental tasks. As it was mentioned in Section 3., MF component of HPV was proposed to be used as an objective psycho-physiological measure of actual mental effort invested by the subjects (*Mulder*, 1980; *Izsó* and *Láng*, 2000; *Izsó*, 2001).

As a tendency, the lowest values of the MF component could be seen during the session with 4000 ppm $CO_2$, while the highest values of MF component were obtained in the session with 600 ppm $CO_2$. Concerning HF component, just the contrary was the case. HF component reflects the frequency of respiration and might reflect the volume of respiration. A significant difference was revealed between sessions with 600 and 4000 ppm $CO_2$ by the analysis of variance performed on the MF/HF ratio, as well as on relative values of MF and HF components. Increase of HF component indicates increased volume of respiration in sessions with 4000 ppm $CO_2$ concentration. Decrease of MF component and MF/HF ratio indicates more effort invested by the subject in sessions with 4000 ppm $CO_2$ concentration. This is in accordance with the declining ability to concentrate attention in sessions with 4000 ppm $CO_2$ as shown by the scores on *freshness* and *tiredness* scales as well as by the decrease of mental performance.

*Figs. 11* and *12* show that the relative value of MF of each subject reaches a higher value in sessions with 600 ppm than in sessions with 4000 ppm $CO_2$.

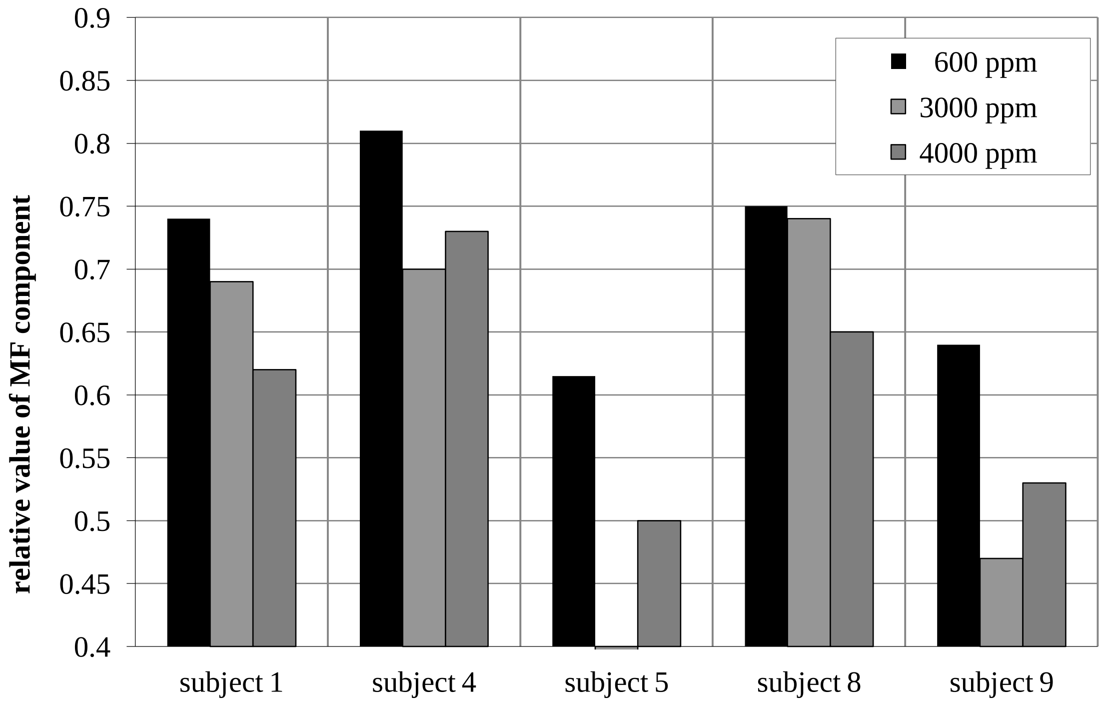


*Fig. 11*. Impact of $CO_2$ concentration on the relative value of MF component of HPV in 5 subjects.

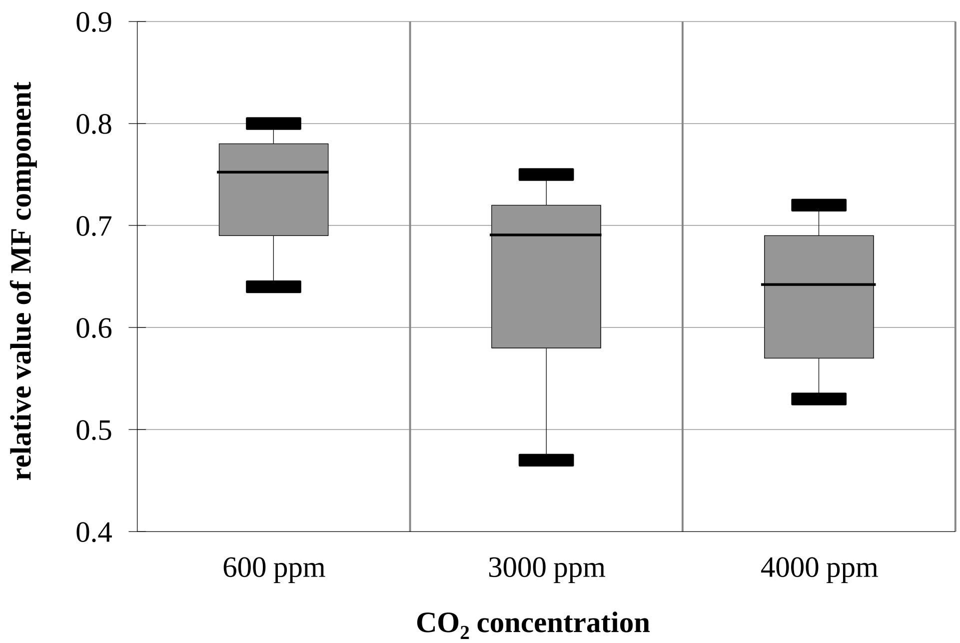


*Fig. 12*. The relative value of MF component of HPV in sessions with different $CO_2$ concentration.

Concerning measurements of skin temperature and the subjective evaluation of surface temperature and general thermal comfort, the analysis of variance did not reveal significant differences between sessions with different $CO_2$ concentration.

### *4.2.4. Summary of results obtained in the second series of experiments*

Significant differences were obtained concerning subjective evaluation of air quality and human well-being between work periods with 600 and 4000 ppm $CO_2$ concentration after 140 minutes. After 210 minutes, significant differences appeared between work periods with 600 and 3000 ppm $CO_2$ concentration showing a decline in human well-being in closed spaces with 3000 ppm $CO_2$ concentration in the air. The same was true for results concerning mental workload: during the second 70-minute working period, the percentage of mistakes found by the subjects was significantly higher in sessions with 600 ppm $CO_2$ than in the corresponding working period of sessions with 4000 ppm $CO_2$ concentration. Concerning the third 70-minute working period, sessions with 600 ppm $CO_2$ proved to be more advantageous for both aspects (quantity and quality aspects) of mental performance than 3000 ppm $CO_2$ concentration. These results are in accordance with the objective psycho-physiological measurements of actual mental effort derived from HPV spectra.

## *5. Summary and conclusions*

A specific laboratory and measuring stand was constructed to investigate the impact of $CO_2$ concentration in the air on human well-being and office work intensity, and to determine the necessary fresh air demand. Air of appropriate cleanliness, thermal comfort, as well as appropriate acoustic conditions were ensured in the laboratory.

Objective microclimatic characteristics were measured during experimental sessions. Two series of experiments were conducted with different pre-set $CO_2$ concentrations in the air.

Various standard scales were used in the evaluation of subjective comfort concerning air quality and human well-being changes indicating the subjects' freshness, tiredness, and concentration. Subjects participating in the investigations were performing a mental task in order to measure their mental effort and efficiency. In addition, objective physiological variables were measured. Data were processed and statistically analyzed. Experience gained from the first series of experiments was taken into consideration when designing the second series of experiments.

It was shown that subjects evaluated air quality less acceptable, more unpleasant, and they became more exhausted when $CO_2$ concentration increased up to 3000 ppm. 3000 ppm $CO_2$ concentration in the air proved to be less advantageous for mental performance than 600 ppm. Several physiological measures (spectral components of HPV) show that the mental task required more effort from the subjects when $CO_2$ concentration in the air reached 3000 ppm.

It was shown that human well-being as well as the capacity to concentrate attention decline when subjects spend 2 – 3 hours in a closed space with 3000 ppm or higher $CO_2$ concentration in the air.

***Aknowledgements***—This study was carried out in the frame of the 'Insurance of indoor air quality in climatized places, required indoor air quality and evaluation method of climate systems' project (T 029451) and received financial support from the Hungarian Scientific Research Fund.

## *Appendix*

The analysis of variance is used to test the significance of the differences between the means of a number of different samples. The null hypothesis is formulated that the samples are drawn from populations having the same mean. Assuming that the treatments applied are having no effect, some variations are expected between means, due to sampling fluctuation. If the variation cannot reasonably attributed to sampling error, we reject the null hypothesis and accept the alternative hypothesis that the treatments applied are having an effect. With only two means, this approach leads to the same result as the obtained from the *t* test for the significance of the difference between means of two samples. If the variation between means is not small and of such magnitude that it could arise in random sampling in less than 1 or 5 per cent of cases, then the evidence is sufficient to warrant rejection of the null hypothesis and acceptance of the alternative hypothesis that the variation differs in yield. The problem of testing the significance of differences between a number of means results from experiments designed to study the variation. For this, the *F* ratio is calculated ($S_b^2 / S_w^2$) and referred to the table of *F*.

If the probability of obtaining the observed *F* value is small (less than 0.05 or 0.1), the null hypothesis is rejected.

Following the application of an *F* test, a meaningful interpretation of the data may require a comparison of pairs of means. These differences between some pairs may be significant, while other differences may not be. A number of alternative methods exist for making such comparisons (*Ferguson*, 1988).

Contrasts are the significance tests of focused questions. By a focused test (as opposed to an omnibus test), we mean any statistical test that addresses precise questions, as in any 1 *df F* test or *t* test. Omnibus tests, on the other hand, are tests of significance that address diffuse (or unfocus) questions, as in *F* test with numerator $df > 1$. Contrasts allow us to answer planned comparisons instead of the overall analysis of variance (*Rosenthal* and *Rosnow*, 1987). In our case series, pair-wise comparisons were performed between treatment means.

Contrasts are used to test the differences among the levels of a factor (in our case the factor is the $CO_2$ concentration in the air). Contrast types used in the study were: simple contrast (compares the mean of each level to the mean of the first or last category of the reference) and repeated contrast, which compares the mean of each level (except the last) to the mean of the subsequent level (*SPSS Advanced Statistics 7.0 update*, 1996).

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