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Bachelor's Thesis

Microclimate in classrooms and lecture halls throughout the year and its impact on health and focus of students

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Hereby I would like to thank my supervisor RNDr. Naděžda Zíková, Ph.D. for providing me with very meaningful guidance and advice.

I declare that I have written the thesis by myself without unsuitable help from a second person.
All external sources are properly attributed.
I certify that this research thesis or any part of it has not been previously submitted for a degree or any other qualification.

Prague, 24. 5. 2016

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Abstract

There is a growing evidence that thermal comfort, light levels and carbon dioxide concentration can have significant impact on alertness and performance. We have documented microclimate (temperature, relative humidity, light intensity level and CO_2 concentration) in 7 different lecture rooms throughout the year. We have not measured any extreme conditions but on significant amount of lectures the microclimate conditions were not optimal. Out of 68 measured lectures 2 had median temperature below 19 °C and 13 lectures over 24 °C, i.e. out of the recommended values. On the cold lectures, students were observed to wear jackets and on the hot ones students were frequently opening windows which also suggest that the thermal conditions were suboptimal.. CO_2 concentrations were suboptimal mostly in winter, when 26 out of 39 lectures had median CO_2 levels above 1000 ppm which is, according to ASHRAE (American Society of Heating Refrigerating and Air-conditioning Engineers), an indicator for inadequate ventilation. Median CO_2 level for all lectures from both semesters was 1060 ppm. Even though window opening effectively lowers CO_2 concentrations, we found it to be as mostly a reactive behavior. It is very likely that if it would be done proactively, especially CO_2 levels could be kept significantly lower. Light levels were found to be very insufficient, but it is hard to draw any conclusions since the sensor did not properly measure indirect light.

Keywords: indoor air quality, thermal comfort, microclimate, lecture halls

Abstrakt

Existuje čím dál tím více důkazů, že tepelný komfort, intenzita osvětlení a koncentrace CO_2 může mít významný vliv na pozornost a produktivitu. Měřili jsme mikroklima (teplotu, relativní vlhkost, intenzitu osvětlení a koncentraci oxidu uhličitého) v 7 různých přednáškových místnostech v průběhu roku. Nezaznamenali jsme žádné extrémní hodnoty, ale u podstatného množství lekcí nebyly podmínky ideální. Z 68 sledovaných lekcí byl u 2 medián teploty nižší než 19°C a u 13 lekcí byl vyšší než 24 °C, tedy mimo doporučené hodnoty. Bylo zaznamenáno, že si studenti oblékají extra oblečení nebo naopak otevírají okna, což dále podporuje teorii, že teplotní podmínky nebyly optimální. Koncentrace CO_2 nebyly optimální zejména v zimě, kdy 26 ze 39 lekcí měly medián koncentrací CO_2 nad 1000 ppm, což je dle ASHRAE (American Society of Heating Refrigerating and Air-conditioning Engineers) indikátor nedostatečné ventilace. Medián pro všechny měřené lekce z obou semestrů byl 1060 ppm. Otevírání oken spolehlivě snižuje koncentraci oxidu uhličitého, ale dost často k tomu dochází příliš pozdě. Je dost pravděpodobné, že pokud by se jednalo o proaktivní zvyk, koncentrace CO_2 by se držely na významně nižších hodnotách. Intenzita světla byla také shledána jako nedostatečná, ale zde je těžké utvářet jakékoliv závěry, protože senzor u přístroje neměřil správně hodnoty nepřímého světla.

Klíčová slova: kvalita vnitřního ovzduší, tepelný komfort, mikroklima, přednáškové místnosti

Introduction

Interest in indoor air quality and thermal comfort has been on the rise in the last years. People of western countries spend more than 85% of their time indoors (NHAPS, 2001). We focus on the state of microclimate in lecture halls. Students do not tend to spend as much time indoors as office workers or industry workers but when they do they are often required to be very alert, recall a lot of previous knowledge and generally utilize a lot of deduction and induction in their thinking in order to properly gain new knowledge and perform well on tasks and exams. A Malaga university student time survey reports that students spent in average 4h and 2 minutes per day on lectures (Dolton *et al* 2003). Author of the thesis spent on average 3 h and 12 minutes in school per day in summer semester 2015 and 4h and 12 minutes per day in winter semester 2015. The microclimate is very likely to have both direct and indirect effect on student's capability to gain new knowledge and perform well in exams. Light, temperature and CO_2 concentrations can all directly influence brain functions and therefore performance and alertness. To this day there was not found any direct connection between relative humidity and mental performance but there could be an indirect effect on performance via health symptoms, especially in the long term.

The aim of the thesis is to collect data about microclimate throughout the year in classrooms and lecture halls. Discussed are potential impacts of temperature, relative humidity, light intensity and concentration of CO_2 on comfort and performance of students. Devices such as thermohygroscope, luxmeter, and CO_2 sensor, with the help of data loggers, were being used to collect data during lectures. Data are summarized and analyzed and so is the significance of variables such as size of rooms, ventilation, occupancy, and weather.

Our task is to assess the state of microclimate in different lecture rooms, compare them with specific guidelines, and discuss the results and possible improvements. If possible, we also compare the measured data with results from similar studies from high schools, secondary schools, universities and offices. We have collected data from summer semester and winter semester in year 2015 so we can compare the state of microclimate during the year. Because the data were collected on lectures, there is only one month of data for winter (December) and no data for summer because in January and February there is a winter exam period without lectures, similarly to June with summer exam period. Further, summer holiday takes place in July, August and September. There is also considerably less data of CO_2 levels in summer semester than in winter semester because the CO_2 sensor was available only from 10. 4. 2015 onwards.

We did not convey any questionnaires so we cannot assess opinions and subjective experiences of students on lectures. This data would certainly be useful but there was not a feasible way to collect them because filling out forms during lectures would cause inconvenient distraction. We can still make a few points and estimates based on the behavior – such as putting on clothes or opening windows.

Theoretical part

Illumination and its effects on human body

The most significant effect of light on the human body is probably its influence on circadian rhythm. Light is a main driver for circadian rhythm and it can offset or shift the start of a circadian phase (Duffy *et al.* 2009). Another important effect is connected to alertness. Light's ability to increase alertness has been confirmed in various studies, both subjectively and objectively. There have been reports of increased thalamic activity (Vandewalle *et al* 2006) which is tightly associated with increased or decreased alertness (Thomas *et al* 2000, Duffy *et al* 2009), reduction of EEG activity, and suppression of melatonin (Duffy *et al* 2009). Melatonin is a neurotransmitter that plays a major role in sleep induction. And while melatonin production is suppressed, light also tends to stimulate serotonin production which has a great impact on mood and general well-being (Young 2007). Light can also lower cortisol levels, but mostly in the beginning of the biological day (Jung *et al* 2010), which means at the time one would naturally wake up. Cortisol can impair retrieval of long-term spatial memory (de Quervain *et al* 1998). That could have an adverse effect on learning which depends on recalling previous knowledge. This suggests that making sure that lighting conditions are sufficient is especially important on morning lectures and in winter, when subjects did not get any light stimulation on the way to the building.

Probably the most significant factor in light conditions is the intensity of light. In a study by Smolders *et al*. (2014), 28 students were being observed under two lightning conditions: 200 lx and 1000 lx. They performed go no-go tasks when they were relaxed and also after induction of mental fatigue. After the fatigue induction, the results were significantly better at 1000 lx and subjects also reported better mood.

Another important factor is the frequency of light. Higher frequencies are likely to have higher melatonin suppression effect - after 6.5 hours of exposure the studied subjects reported higher levels of alertness, better reaction times and fewer lapses of attention (Duffy *et* al 2009). When the old university hall lights were replaced for high temperature bright lights, an increase in alertness and performance was observed in autumn but not in spring, probably because students already got stimulation from bright light outside during lunch breaks (Rautkylä *et* al 2010).

Besides artificial lighting, we could recognize climate, time of the year, latitude, and window surface area as significant factors in the indoor light intensity levels. A 2006 study observed more than 988 office workers, students, and industrial workers from several countries and assessed how changes in light levels during seasons of the year affect mood and performance. In Sweden and the UK, the subjects reported to be significantly more tired and sleepy during the winter season. These changes in mood were not observed in countries closer to the equator. The distance of working space to window also tended to have a significant effect on mood (Kuller *et al*. 2006).

During these long-term studies it is however especially difficult to recognize whether the effects credited to light are physiological or psychological, e. g. did the light itself triggered a neurochemical reaction that lead to changes of performance and mood or was it the perceived visual information that triggered particular response in the brain? Or combination of both? Bright colors and diversity of colors in rooms also tend to have positive effect on mood especially in combination with higher light levels (Kuller *et al* 2006). It is very likely that even if the artificial lightning indoors was of the same intensity and spectral composition as sunlight, it would not still be as effective as natural light coming from windows, simply because view into sunlit landscape has an uplifting effect that is hard to imitate.

Thermal comfort

Connection between mental performance and thermal comfort has been studied consistently in previous decades. A lot of studies focus on workers in industrial workplaces and observe workers deep body temperatures, environment temperature and its effect on frequency of mistakes, productivity and other factors of performance. These studies generally discuss the effects of ambient temperatures over 30 °C and the physiology of heat stress which is often not relevant to the school environment, but some results could be applied anyway. They find that simple tasks are less vulnerable to heat stress than complex tasks and also that females can better withstand the negative effect of heat stress than males at tasks based on short-term memory (Hancock 2003).

There are several key mechanisms that body can utilize to adapt to both high and low temperatures. Heat shock proteins (HSP) which bind to other proteins and tissue and protect them from damage have been found to increase and decrease in different seasons in many organisms. It is very likely that such seasonal changes in HSP occur in humans as well (Moseley 1997). Entirely different role in heat adaptation is brown adipose tissue. It is essential for generating both basal and inducible heat. It affects whole-body metabolism and can also affect insulin sensitivity. This tissue has been found to be more frequent in men than women and it is also more frequent in young people (Cypess *et al* 2009).

When body temperature is elevated to such extent that body cannot sufficiently cool itself, heat stress occurs. This happens in workplace environment generally at temperatures of 29.4 °C or higher (Hancock 2003). We have not recorded such high temperatures in our measurements, but they can be common in other countries. For example, during April and May 2014, the temperatures ranged between 30 °C and 37 °C in large educational halls in Egypt. Majority of students reported discomfort caused by high temperature, inadequate ventilation and direct sunlight (Abdallah 2015). Quite high temperatures were also recorded in temperate regions of Japan. Naturally ventilated classrooms had median temperature of 26.9 °C while air conditioned were at 24.0 °C (Kwok 2003).

Later studies examine the effect of only mildly elevated temperatures on performance, which is relevant to most of school and office environments. Sepannen *et al* (2006) found a 2% decrease in performance per a degree of temperature increase in the range of 25 - 32 °C (Sepannen *et al*., 2006). That makes 24 °C an upper limit for optimal thermal conditions. But in some cases, the performance decreasing effect has been observed already at 23 °C (Sepannen *et al*.2006). On the other hand, other studies, especially from temperate regions, report subjects feeling comfortable even in temperatures as high as 28 °C (Kwok 2003). This suggests that the top 24 °C comfort limit holds true mostly for colder and mild climate regions.

Effect of low temperatures (21°C and below) is problematic to assess. Activation of sympathetic nervous system and brain arousal was observed at 20°C (Kwok 2008) but the exposure time was 247 minutes and subjects reported discomfort so there is a possibility that slightly cool temperatures may be stimulating but causing fatigue in the long term.

Occupants of naturally ventilated classrooms seem to be generally less critical about indoor air temperature. From psychological perspective, it has been suggested that thermal comfort and satisfaction is shaped by our own expectations (Kwok 2003). Another study observed industrial workers for two seasons of the year and documented their heart rate, body temperature and blood pressure. One half of them spent their time in air conditioned environment and the other half in naturally ventilated environment. Workers in naturally ventilated environment had significantly higher body temperature in summer and workers in air conditioned environments had significantly lower blood pressure in winter, which is considered positive because blood pressure generally tends to be higher in winter (Kristal-Boneh *et al* 1995).

Most of the studies observe the short term effect of temperature on performance and they do not observe how temperature affects mood and energy levels of subjects throughout the whole day.

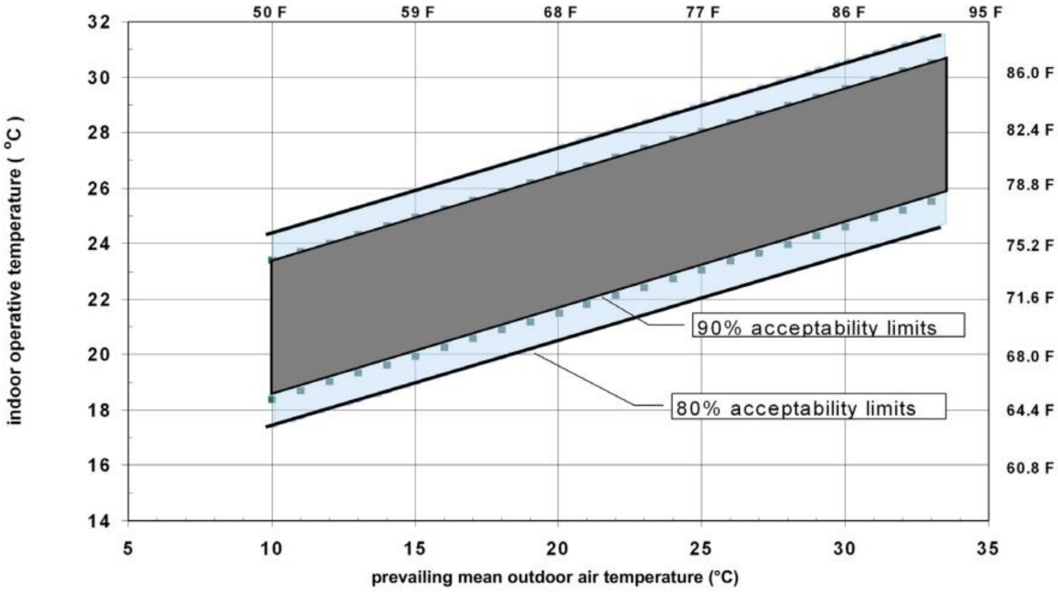


Figure 1. ASHRAE (American Society of Heating Refrigerating and Air-conditioning Engineers) Standard 55-92 relationship between thermal comfort and mean outdoor air temperature

The capability of adaptation is also taken into account by ASHRAE which bases indoor operative temperature based on prevailing outdoor air temperature as it can be seen in Figure 1. 80% bounds are normative and 90% are informative.

Humidity levels

Even though at this point there is no research on direct connection between insufficient relative humidity levels and mental performance or alertness, relative humidity might still be quite important factor because in if inadequate it can adversely affect health.

A study using guinea pigs as model host found that influenza virus spreads most easily at relative humidity levels of 20 – 30%. And it almost ceases to spread at RH of 70% and higher (Lowen 2007). The same study also says that the virus did not spread at all at temperatures over 30 °C. That goes well with information from different studies that the ability of the virus to spread decreases as the absolute humidity goes up rather than relative humidity (Pitzer *et al* 2010, Barecca *et al* 2012). RH was also observed to influence indoor microbial exposure along with indoor and outdoor temperature and air exchange rate (Mika *et al* 2012).

There are also reported correlations between high relative humidity levels and prevalence of asthma symptoms (Weiland *et al* 2003). In a study that simulated RH conditions levels of 20 – 30% and 30 – 40% found out that at 30-40 % setting office workers reported significantly less dryness and irritation of eyes, throat and nasal passages (Reinikainen *et al* 1992).

Therefore relative humidity could adversely indirectly affect alertness and performance and the strength of the effect would be strictly tied to fitness of the subject. Some sort of physical predispositions are likely needed for the negative effect to occur.

As for recommended humidity levels, ASHRAE only states that humidity should not exceed 65% in ventilated rooms (ASHRAE Technical FAQ). OHSREP (Occupational safety and health representatives) states that optimal humidity range is 40 – 60% and sufficient range is 30 – 70%. (OHSREP, Web). Czech ordinance 343/2009 states that RH in schools should be kept within 30 – 65% range.

CO_2 concentrations and mental performance

CO_2 (CO_2) is not a typical indoor pollutant, but yet there are quite a few commonalities with the classical pollutants (carbon monoxide, benzene, volatile organic compounds (VOC) and others). The main difference is that the sources of this pollutant in the indoor environment are people themselves. CO_2 is generated by cellular respiration as a waste product of Krebs cycle. Another indoor sources might be other living organisms (plants, pets) and combustion processes - fireplaces, heat stoves, open fires etc. Just like typical pollutants, CO_2 can cause acute as well as chronic toxicity. Significant health risks are possible not only by exposure to very high concentration levels, but even mildly elevated concentrations (less than 2000 ppm) that are very common in indoor environments can have a significant negative impact. This is especially important due to a fact that people in western countries spend up to 90% of their time indoors (NHAPS 2001).

Generation and regulation of CO_2 in organisms

CO_2 generation occurs naturally during cellular respiration. Glucose is being broken down into pyruvate which enters the Krebs cycle and is further broken down. During those reactions there is a waste carbon that is quickly oxidized into CO_2 which releases energy that is quickly used to form ATP (adenosine triphosphate) in oxidative phosphorylation (Avissar 2013).

The generation of CO_2 is therefore never-ceasing and the speed of production is proportional to the speed of metabolism. At rest, average human produces roughly 200 milliliters of gaseous CO_2 per hour (Cronyn *et al* 2012). CO_2 is transported in blood where it bonds to red blood cells. It is often transformed to carbonic acid or hydrogen carbonate ion. The concentration always tends to rise and the body needs to do continuous effort to get rid of it. That is in practice done by gas diffusion in pulmonary alveoli in lungs. Even though diffusion might be quite slow process, it is effective as a whole, because pulmonary alveoli in an adult can have as much as 75 m^2 of surface (Avissar 2013).

CO_2 has an important role in the whole gas exchange process and in homeostasis. It acts as lewis acid and it forms carbonic acid and hydrogen carbonate ion with water (Abolhassani *et al*. 2008):

$CO_2 + H2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO^{3-}$. (Equation 1)

This reaction is a very significant source of hydrogen ions and therefore greatly affects blood pH level. If for some reason the respiratory system is not working correctly, CO_2 can accumulate in blood which results in acidosis (Abolhassani *et al*. 2008).

Concentration levels of CO_2 and oxygen are the main factors for intensity of spontaneous breathing. CO_2 stimulates chemoreceptors in the brain stem directly and also indirectly by altering the blood pH level. Excitation of these chemoreceptors causes changes in spontaneous breathing patterns. This is a key process for maintaining homeostasis. When the blood pH levels are decreased, breathing becomes stronger and CO_2 exits the body at a faster rate. If the blood is alkaline, the breathing tends to be very slow or not active at all. Thus the blood pH level tends to stay around the value of 7,36 (Nattie 1999).

Acute toxicity

Just like the CO_2 can diffuse from blood to alveoli, the external CO_2 can diffuse from alveoli into blood. The higher concentration levels of CO_2 are, the harder it is for the body to get rid of the excessive CO_2 and to sustain a stable blood pH level. If the blood fails to stay alkaline, overabundant H+ ions are getting bonded to hemoglobin molecules. Intensity of breathing increases quickly. If the acidosis stays for longer period of time, kidneys start to excrete hydrogen carbonate ions from the blood (Salt Creek Phases 2006).

Higher blood CO_2 concentrations also lead to elevated blood pressure and cerebral blood flow. That can cause headaches or in worse cases loss of consciousness and death (Salt Creek Phases 2006). Severe symptoms related to CO_2 toxicity can be present in concentrations of 20 000 ppm and higher. Concentrations higher than 70 000 ppm can be fatal. (Cronyn *et al* 2012)

Long-term exposure to elevated CO_2 concentrations levels

People in western countries are exposed to slightly elevated CO_2 levels on daily basis for most of their lives. Even though the pollutant is not as toxic as other pollutants, its impact on life quality is high due to long lasting exposure. In last couple of years, there have been multiple studies on the negative impact of even low CO_2 concentrations levels. Although physical symptoms manifest only at very high concentrations levels, any elevation of the CO_2 levels is stressful to the human body (Ezraty *et al*. 2011, Abolhassani *et al*. 2009).

At low concentrations, the main way how the CO_2 affects the body is by decreasing the blood pH level. Changes in pH can have a great effect on speed rates of many biochemical processes and it can, among other things, lead to oxidative stress and inflammation. Intracellular oxidative stress has been documented for example on neutrophil granulocytes, where the pH had great influence on the production rate of IL-8 protein, which plays an important role in chemotaxis and inflammatory processes (Coakley *et al*. 2002). Strong inflammatory effect has been observed in the respiratory system, where is a connection between CO_2 concentration level and amounts of several types of cytokines (Abolhassani *et al*. 2009). Harmful effect of CO_2 concentrations as low as 40 ppm has been documented in vitro on E.coli, in particular its ability to increase toxicity of H_2O_2 and other reactive oxygen species ($HO^{\bullet}$, $O_2^{\bullet-}$). It affects the Fenton reactions as so:

$$H_2O_2 + Fe^{2+} \Rightarrow HO^{\bullet} + HO^{-} + Fe^{3+}. \qquad \text{(Equation 2)}$$

Hydroxyl radicals can afterwards react with CO_2 metabolites:

$$HCO^{3-} + HO^{\bullet} \Rightarrow CO^{3\bullet-} + H_2O, \qquad \text{(Equation 3)}$$

$$CO_3^{2-} + HO^{\bullet} \Rightarrow CO_3^{\bullet-} + HO^{-}. \qquad \text{(Equation 4)}$$

Even though this carbonate radical has lower oxidative potential than ROS (Reactive Oxygen Species), in some reactions it can be a more effective oxidation agent than ROS (e. g. oxidation of some amino acids derivates). These reactions were tested in vitro, where they were observed as fluorescent lesis of DNA. The frequency of the lesis as well as mortality significantly increased with the increase of CO_2 concentrations. The effect was much more outstanding after artificial increase of H_2O_2 concentration (Ezraty *et al*. 2011).

Concentration levels in various public spaces & recommended values

Recommended values and limits tend to differ in various countries. Most of the states of the American continent accepted the standards from ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). ASHRAE standard states that sufficient ventilation should keep the concentration level below 1000 ppm. European standard EN 13779 dissects indoor environment into four categories: IDA 1, IDA 2, IDA 3 and IDA 4. For each category, there are different limits and recommendations as it can be seen in Table 1

Table 1 - Recommended levels of CO_2 for public space by standard EN 13779

Category	Concentration difference of CO_2 (ppm) from outside levels	Description
IDA1	≤ 400	High IAQ
IDA2	400 - 600	Medium IAQ
IDA3	600 - 1000	Moderate IAQ
IDA4	> 1000	Low IAQ

Levels of concentrations of CO_2 vastly differ in various types of indoor environments. They tend to be lower in new buildings, especially in public buildings and office spaces. Study evaluating indoor environment in Danish school observed much higher concentrations in schools built before 1950 (median 1700 ppm) than in new schools build after 2000 (median 1000 ppm). Office spaces also more frequently tend to have air conditioning and a smaller amount of people per unit square then schools or libraries. Especially in smaller classrooms the concentrations tend to rise dramatically through the day in winter months. Multiple studies report concentrations as high as 5000 ppm (Conceicao 2013, Jones *et al* 2012). Statistically lower concentrations were also at mechanically ventilated buildings (median: 1000 ppm) than at manually ventilated schools (1600 ppm). Same trend was observed in similar study in Athens, where mechanically ventilated schools had a median of 910 ppm, while manually ventilated schools were at 1410 ppm.

There are less studies on the air quality in large lecture halls and other large spaces. In six large lecture halls in Egypt with occupancy ranging from 26 to 120 the concentration did not reach over 1000 ppm (Abdallah 2015). In a cinema hall in Poland with 230 occupants the concentration level raised from 920 ppm to 1219 ppm during a 159 minute film (Demianiuk *et al* 2010). On the University of Melbourne, one lecture hall with 100 occupants was observed for 1 hour and 50 minutes. Highest concentrations - 900 ppm - were measured in the back of the hall, where the sensor (and also the occupants) was in the highest position. After a period of time, the concentrations stabilized in the whole hall on 600 ppm - 800 ppm. In a more modern lecture hall with 30 occupants, the concentrations leveled from 400 - 800 ppm and highest values were again measured in the back of the hall (Halgamuge *et al* 2009). Data from studies from school and university environment are summarized in Table 2.

Table 2 - Comparison of CO_2 concentration levels in schools in different countries.

Country	Study location	CO_2 concentration [ppm]		Study period
		average	maximum	
Denmark[(a)]	389 elementary schools 820 rooms	1340*	2813	2015
South Korea[(b)]	38 elementary schools	813**	2063	2015
Greece[(c)]	402 elementary schools 1187 rooms	1070**	2600	2008
Portugal[(d)]	51 elementary schools 81 rooms	1942	5320	2011
UK[(e)]	5 elementary schools 16 rooms	1302	4336	2012 - winter
Serbia[(f)]	5 elementary schools 15 rooms	1264	3614	12/2012
Portugal[(g)]	1 elementary school 2 rooms	797		12/2011
Finland[(g)]	2 elementary schools 6 rooms	651		12/2011

*.. average from 3 medians

** .. median

Sources: [a]Toftum *et al* 2015, [(b)]Yang *et al* 2015, [(c)]Santamouris *et al* 2008, [(d)]Ferreira *et al* 2013, [(e)]Jones *et al* 2012, [(f)]Turanjanin *et al* 2014, [(g)]Canha *et al* 2013

Impact on cognitive performance

Cognitive performance under influence of elevated CO_2 has been studied several times in the last few years. In a study from 2013, 22 students were placed into an exposure chamber. CO_2 concentrations levels in this chamber were artificially stabilized on predefined values. Students spend two and a half hours working on the SMS (Strategic Management Simulation) test (Fisk *et al* 2012). The results strongly suggest that the concentration levels of CO_2 have great impact on cognitive performance of exposed subjects. On the other hand, the study should probably be replicated with higher amount of subjects, test versions and repeats to rule out other potential variables (differences in test difficulty, mood and fatigue of subjects etc.)

Another study from 2015 (Allen *et al*. 2015) observed 24 employees over the period of one week in a controlled setting of office space. For two days, the air conditioning was set on 40 cfm (cubic feet per minute) per person and the CO_2 level was stabilized on 550 ppm. For next two days, air conditioning was set to 20 cfm/p and CO_2 concentrations level was stabilized on 945 ppm. For the remaining three days, CO_2 was stabilized on 1400 ppm. In average, the results were 61% better on 945 ppm day and 101% better on 550 ppm day. In some parts of the test there were as much as 288% better results on 550 ppm days (Allen *et al*. 2015). Compared to the previous study, there is much higher duration of exposure which is closer to the real life situation, when subjects spend whole day in a certain indoor environment. On the other hand, there are again quite a few factors that could have had a great impact. Even though it was probably CO_2 that had the largest impact on cognitive performance, because the concentration level was regulated by air exchange, not only CO_2 concentrations levels were different on different modes, but also VOC, NOx, ozone and other pollutants. And also it could be possible to argue that there is a natural trend of performance decrease in a workweek from Monday to Friday as the fatigue increases.

Study from 2002, which documented length of phone calls in a call center, on the contrary observed no connection between ventilation and work performance (Federspiel *et al*. 2002).

Practical part

Methods

Instrumentation

Temperature and relative humidity

Thermo-hygrometer (Comet D3121) was used to collect temperature and relative humidity values. Accuracy of measurement of the device is ±0.4 °C for temperature and 2.5 % for relative humidity. The device comes with a data logger.

CO_2

CO_2 / Temperature monitor (Telaire 7001) was used to collect CO_2 concentration values in parts per million units. Accuracy of measurement of the device is ± 50 ppm.

Light intensity

Light sensor (Vernier Light Sensor) together with Go!Link USB sensor interface was used for collecting light intensity values in lux units. The device has to be connected to a computer with Logger Pro software running to collect data. We have used custom made tripod to consistently collect data under the same angle - so the sensor is always perpendicular to the ground. The device was set to collect values in the 0-600 lux range and therefore the resolution was 0.1 lux.

Data collection process

The author of the thesis was carrying all the previously mentioned devices with him on the lectures he was attending. Sensors were placed on the table ranging from 80 to 120 cm high consistently at the same place, usually in the middle of the room to avoid the influence of windows, either due to bright light or ventilation and to accurately document average microclimate conditions in the room. All the sensors were turned on at the official time of start of the lecture. At that point relevant information about the condition of the room was documented: whether lights were being turned on or off, number of people being present in the room, outside weather conditions, if doors or windows were opened and if any object blocked the light from outside. Temperature and relative humidity were being logged with the help of a data logger in 2 minute intervals. Light intensity values were being logged in 1 minute intervals and CO_2 concentrations were being logged manually at 10 minute intervals. Any significant events during the data collection time were being also documented. Those usually were: people arriving and leaving, window and doors opening and closing, and lights being turned off and on.

Weather conditions were evaluated subjectively by the author of the thesis. Three options were available: sunny, somewhat cloudy and cloudy. Sunny when the sky was mostly clear and direct sunlight was present for most of the lecture. Somewhat cloudy when there was not intensive cloud coverage or when the weather changed frequently during the lecture. Cloudy when the sky was covered by clouds for most of the lecture.

Outdoor RH and temperature values were gathered from a 3rd party service (Wunderground.com - https://www.wunderground.com) and manually fitted to our own data.. We have chosen history values for weather station Kbely Airport located about 10 km away from measured location so that the value fits in the interval of the time of the lecture.

Data analysis process

A database was used to store all measured data. Data were structured into lectures, values and events and they were connected by relationships. Lecture collections contained type and time of the lecture and median values for relevant data. Events were used to record turning off and on lights, opening windows and so on. This way it was possible to quickly filter between various conditions and study correlations. Custom scripts computed (and recomputed) median values for individual lectures and also for median values for lecture rooms for measured period (winter or summer semester). For median values for lecture rooms, interquartile range was computed.

Monitored places

We have monitored 7 different lecture rooms in 3 different buildings (illustrated in Figure 2, and Figure 3). Lecture rooms varied with size, orientation and window surface area. Only Brauner's Lecture Hall was monitored both in summer and winter, the rest of the halls was monitored either in winter or summer semester. Lecture rooms where monitored only on specific times during lectures that the author of the thesis attended. Lectures usually took between one and two hours and most common measurement duration was 90 minutes. More in-depth overview offers Table 3. Some lectures had a break in between which resulted in occupants leaving the room and other notable events.

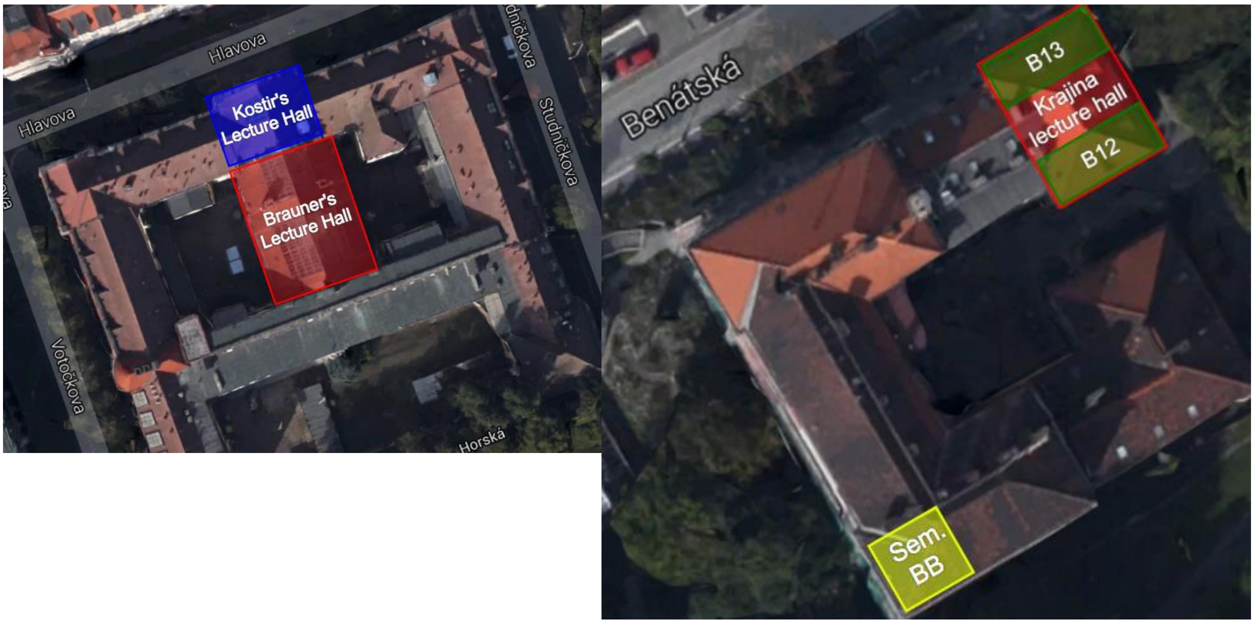


Figure 2: Monitored places with highlighted lecture rooms – Hlavova 8 (left) and Benátská 2 (right)

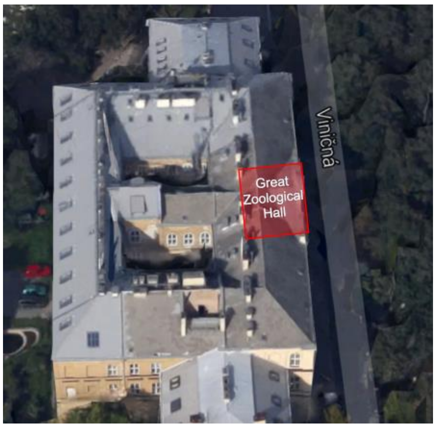


Figure 3 Monitored place with highlighted lecture room – Viničná 7

Table 3 – overview of monitored places, times of measurement, and additional information on the halls.

Lecture room	Measured lectures	Time of the lecture	Semester	Median occupancy	Window surface [m^2]	Volume [m^3]	Windows Orientation
Brauner's Lecture Hall (LH)	13	Wednesday 14:00 – 14:30 (Winter) Wednesday 8:10 – 9:30 (Summer)	Winter and Summer	22	68	1732	SW + NE
Krajina's LH	18	Thursday 11:00 – 12:30 (Winter) Wednesday 9:00 – 10:30 (Winter)	Winter	18	35	370	NE
Kostir's LH	7	Tuesday 16:30 - 18:00	Winter	38	41.0	840	NW
Great Zoological Hall	8	Friday 12:30 - 14:00	Summer	18	N/A	N/A	E
B13	7	Wednesday 13:10 - 14:30	Summer	17	24.7	185	NW
B12	6	Tuesday 11:30 - 13:00	Summer	14	24.7	153	SE
Seminarium BB	9	Thursday 14:00 - 15:30	Winter	15	19.7	155	SE

Results

Light levels

Because the light sensor did not properly detect indirect light and detected mostly direct light (artificial illumination), there is a great difference in measurements when the lights are on or off. That is mostly the reason why light levels tended to be higher in winter (Table 4). The median for light levels when the lights where off is 67 lx, while with the lights on it is 318 lx. Therefore the two datasets were compared separately.

Real light levels for lectures where lights were off were probably higher than we measured, because the sensor did not sufficiently measure indirect light. It is still very likely that the light levels are indeed low. Lecture halls subjectively feel often dark when the lights are off. In most of the lectures many windows blinds are closed which greatly affects indoor light levels. The main reason is mostly so that the projected presentation can be properly visible. Nearly all lecturers nowadays use computers and projectors in their lectures and while the technology can be very beneficial for transmission of information, its indirect decreasing effect on indoor natural light level is undeniable. This way, the projection technology could have negative indirect effect on alertness of students.

Table 4 – overview of measured light intensity levels in winter and summer semester 2015

Winter Semester 2015			
Place	**Median lightning level [lx]**	**Lecture time**	**Measured lectures**
Kostir's Lecture Hall	215 (201 *)	Tuesday 16:30 - 18:00	6
Seminarium BB	103 (95 *)	Thursday 14:00 - 15:30	9
Krajina's Lecture Hall	322 (260 *)	Wednesday 9:00 - 10:30	7
Krajina's Lecture Hall	84 (175 *)	Thursday 11:00 - 12:30	9
Brauner's Lecture Hall	448 (81 *)	Wednesday 14:00 - 14:30	5
Summer semester 2015			
Great Zoological Hall	61 (35 *)	Friday 12:30 - 14:00	8
Brauner's Lecture Hall	51 (61 *)	Wednesday 8:10 - 9:30	8

B13	87 (29 *)	Wednesday 13:10 - 14:30	7
B12	96 (46 *)	Tuesday 11:30 - 13:00	6

* … Interquartile range

Measured data suggest a few more things. Firstly, the light levels tended to be higher at larger lecture halls. As it can be seen in Figure 4 and Figure 5, larger lecture halls tend to have higher window surface area and the data suggest that the lights are more likely to be on. As the occupancy in the room increases, the lecturer may feel more compelled to turn the lights on or pull the window blinds up.

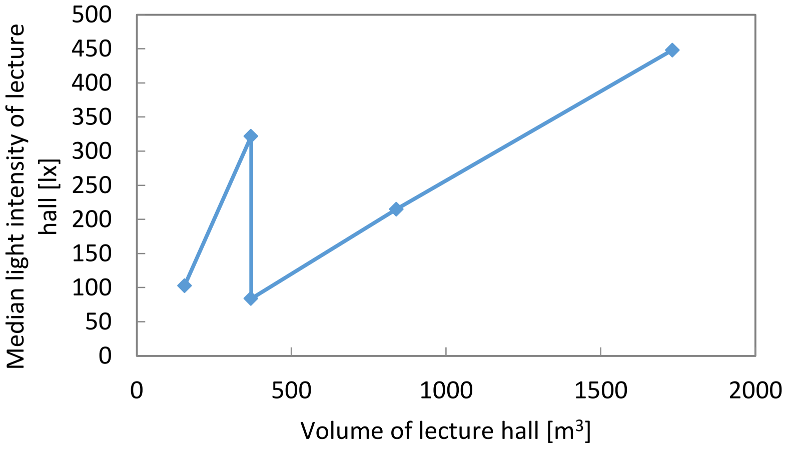


Figure 4 – Relationships between lecture hall volume and median light intensity in lecture rooms in winter semester 2015

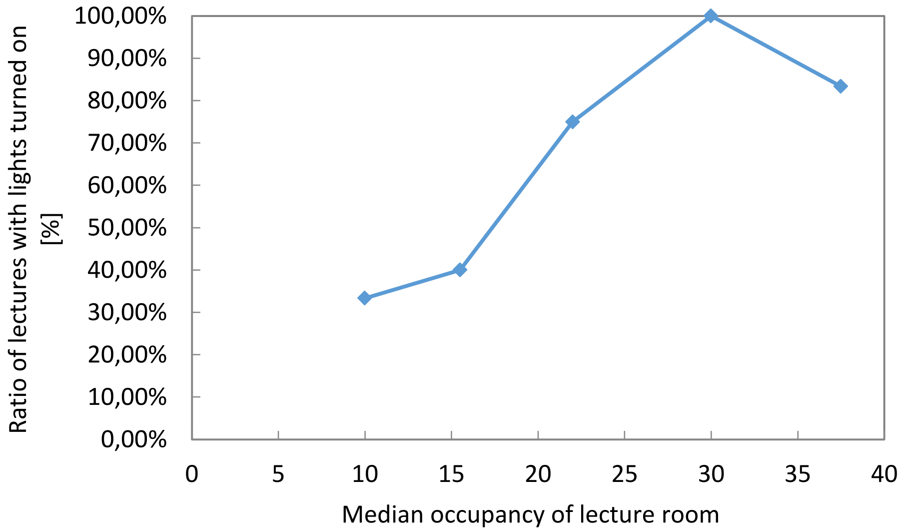


Figure 5 – Monitored lecture rooms in winter semester 2015 and the ratio of lectures with lights turned on.

To improve learning conditions it is good to seek a good balance between letting enough natural light in while the projected presentation materials are still properly visible. If natural light is not enough to provide sufficient light levels, lights should be turned on. In the measured lectures, lights were being turned on mostly in November and December, but they should be turned on more often especially in March and October. In winter semester lights were turned on 19 out of 36 lectures, while in summer semester lights were not being turned on on any recorded lecture.

Outside conditions definitely had great impact on indoor light levels but it is difficult to assess the range of the impact due to the type of light sensor that did not measure indirect light properly, especially with the lights being turned on. Still, for summer data when the lights were being turned off, there is a clear difference between lectures that happened during sunny weather and those during cloudy weather. Median for light levels in summer lectures when it was sunny was 80 lx while for cloudy weather it was 40 lx. During winter lectures with lights turned off, the light intensity was found to be 111 lx for sunny weather and 75 lx for cloudy weather.

Local ordinance of Prague (where Charles University is located) establishes that indoor lighting should provide at least 300 lx of light intensity (Prague local ordinance 410/2005 Sb § 14). For 19 lectures (that had lights turned on) 10 had median value above 300 lx. The local ordinance also states that light intensity on the floor level should be at least 100 lx (with or without lights turned on) (Prague local ordinance 410/2005 Sb § 14). Only 26 out of 66 lectures would meet this condition. But then again, it is hard to draw any conclusions because the light sensor did not properly measure indirect light and another measurement would have to be done to prove this point.

Temperature

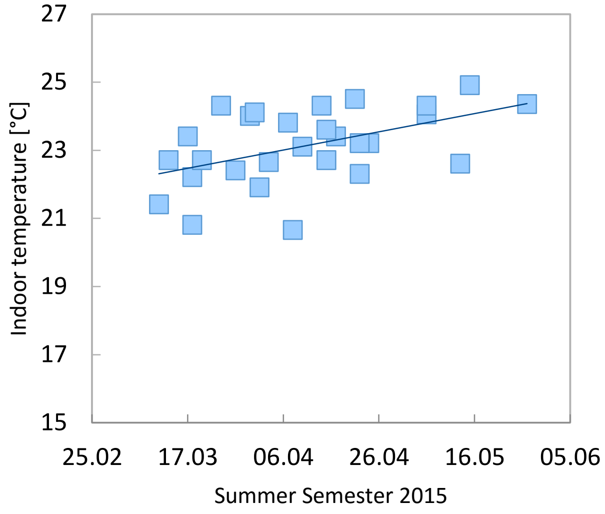
There is an indoor temperature difference between winter and summer semester but it is not as great as expected (Table 5). Median for 34 winter lectures is 22.2 °C, while for summer semester it is 23.2 °C.

In summer semester, median temperature exceeded the 24 °C limit for thermal comfort in mild climate regions in 9 out of 29 lectures. In winter semester it was 4 out of 34 lectures. 2 lectures in the winter semester had median temperature below 19 °C. That implies that 52 out of 63 lectures had sufficient thermal conditions.

Table 5 – overview of temperature in lecture rooms in winter and summer semester 2015.

Place	Average temperature (median) [°C]	Lecture time	Measured lectures
Winter Semester 2015			
Kostir's Lecture Hall	20.5 (2.7 *)	Tuesday 16:30 - 18:00	6
Seminarium BB	23.1 (1.7 *)	Thursday 14:00 - 15:30	7
Krajina's Lecture Hall	21.3 (3.2 *)	Wednesday 9:00 - 10:30	7
Krajina's Lecture Hall	23.2 (1.4 *)	Thursday 11:00 - 12:30	9
Brauner's Lecture Hall	21.7 (0.7 *)	Wednesday 14:00 - 14:30	5
Summer Semester 2015			
Great Zoological Hall	23.1 (1.4 *)	Friday 12:30 - 14:00	8
Brauner's Lecture Hall	22.7 (2.7 *)	Wednesday 8:10 - 9:30	8
B13	22.9 (2.1)	Wednesday 13:10 - 14:30	
B12	24.3 (0.4)	Tuesday 11:30 - 13:00	

* … Interquartile range



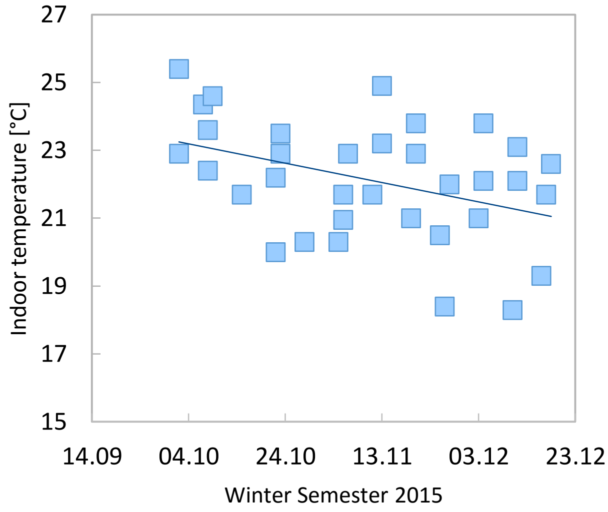


Figure 6. indoor temperature of lectures in summer semester (left) and winter semester (right).

Figure 6 documents, that indoor temperature generally tends to rise during spring and summer and decrease during autumn and winter. This is expected, because monitored buildings did not have any advanced air conditioning systems installed so the temperature tends to rise or decrease in connection to outdoor temperature. Data for outdoor temperature can be seen in supplementary material in Figure 10 and Figure 11.

Low temperatures were mostly measured during morning lectures both in winter and summer semester (Figure 7). Temperature in the building then tends to rise throughout the day. In summer semester mostly because of rising temperatures outdoors and in winter mostly because of heat accumulation from heating systems.

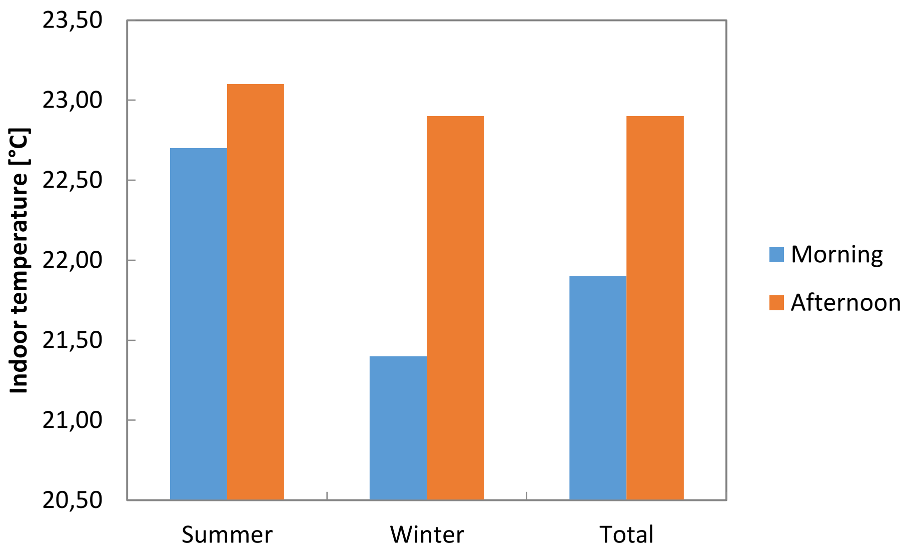


Figure 7Temperature difference between lectures in the morning and in the afternoon

Even though no questionnaire was part of this data collection and we do not have data on subjective perception of temperature in classrooms, we can still make a few points based on other data. In all the measured morning lectures that had temperatures below 19C, there were people wearing jackets, indicating that they felt cold. Similarly, when temperatures went over 24°C, occupants tended to open windows more frequently.

Effect of weather on temperature seems present but not that significant. In summer semester, temperature was on average 23.7 °C in sunny weather lectures, while for cloudy weather lectures it was 23.3 °C, i.e. a 2% difference. In winter it is 23.4 °C in sunny weather and 22.1 °C in cloudy weather (5% difference).

Relative humidity

Indoor relative humidity was found to be significantly lower in summer semester than in winter semester (Table 6). Median for summer lectures was 33.4% and winter 41.8%. In comparison with the OSHREP guidelines, in summer semester 21 out of 29 lectures did not meet the sufficient recommended values because the humidity was too low and only 3 out of 29 fell into the optimal recommended range (40 – 60%). In winter all lectures had sufficient relative humidity and 22 out of 34 lectures had optimal humidity levels. We did not record any lecture that would exceed 70% RH (top limit introduced by ASHRAE 2005).

There is no great difference between lectures that had opened windows and lectures that had windows closed. In summer the RH was on average 1% higher with windows opened and in winter it was 3.7%.

Table 6 – overview of relative humidity values for winter and summer semester 2015

Place	Median RH [%]	Lecture time	Measured lectures
Winter Semester 2015			
Kostir’s Lecture Hall	47.8 (9.9 *)	Tuesday 16:30 - 18:00	6
Seminarium BB	41.4 (7.1 *)	Thursday 14:00 - 15:30	7
Krajina’s Lecture Hall	43.6(12.2 *)	Wednesday 9:00 - 10:30	7
Krajina’s Lecture Hall	41.8(9.2 *)	Thursday 11:00 - 12:30	9
Brauner’s Lecture Hall	41.6(11.2 *)	Wednesday 14:00 - 14:30	5
Summer semester 2015			
Great Zoological Hall	33.2(5.2 *)	Friday 12:30 - 14:00	8
Brauner’s Lecture Hall	29.7(13.1 *)	Wednesday 8:10 - 9:30	8
B13	37.9(11.9 *)	Wednesday 13:10 - 14:30	7
B12	34.2(10.8 *)	Tuesday 11:30 - 13:00	6

*… Interquartile range

On the other hand, when the windows were opened, there a strong correlation (R^2=0.83 Figure 12 in the supplementary material) has been found between outdoor and indoor relative humidity. Moreover, average relative humidity for cloudy weather was 41.30% and for sunny weather it was 34.20%. Opening windows can likely have both increasing and decreasing effect. Its effect depends on outside relative humidity, temperature and indoor temperature. The way how indoor RH is influenced by outdoor RH through window opening is complex as not only RH changes after window is opened, but also indoor temperature that has a great impact on RH. When the indoor temperature decreases, RH generally tends to rise and vice versa. Correlation would probably be even stronger if we had RH data from a more proximal location. Distance between the university and Kbely Airport is about 10 km.

Besides ventilation and temperature, there are other factors that can have influence on indoor relative humidity levels. Occupants themselves can increase indoor humidity levels by breathing and so can plants. There could not be found any correlation between occupancy and indoor RH levels, though(R^2 = 0.11 for lectures with windows and doors closed) Regarding plants, there was only one lecture room that had significant amount of plants: Seminarium BB; and the measured RH actually scored lowest among lecture rooms that were being documented in winter semester. The ratio of mass of plants to occupancy would probably have to be much greater to take effect. In crowded rooms the ventilation is too intensive for the transpiration of plants to be significant. Houseplants can have a significant effect when ventilation levels are low as it is evident from a study of 82 Japanese newly-built households. 42 of these households had houseplants installed and the rest had none. After 90 days, homes with houseplants had in average 53% relative humidity while the other homes had 45.4%. This was measured during January when the ventilation was minimal (Young-wook *et al* 2009).

CO_2 levels

The results clearly indicate that CO_2 levels tend to be higher in the winter (Table 7). Median for 39 measured lectures in winter semester (September - December) is 1258 ppm, while in summer semester (14 measurements during April and May), the median is 872 ppm. Median for all 53 lectures is 1060 ppm.

Table 7 – overview of CO_2 concentrations in winter and summer semester 2015

Place	Average CO_2 level (median) [ppm]	Average occupancy (median)	Lecture time	Measured lectures
Winter Semester 2015				
Kostir's Lecture Hall	1411 (431 *)	37.5	Tuesday 16:30 - 18:00	7
Seminarium BB	1304 (413 *)	15	Thursday 14:00 - 15:30	9
Krajina's Lecture Hall	910 (90.25 *)	11	Wednesday 9:00 - 10:30	9
Krajina's Lecture Hall	1412 (349 *)	23	Thursday 11:00 - 12:30	9
Brauner's Lecture Hall	1101 (417 *)	30	Wednesday 14:00 - 14:30	5
Summer semester 2015				
Great Zoological Hall	1035 (366 *)	18	Friday 12:30 - 14:00	4
Brauner's Lecture Hall	622 (37 *)	22	Wednesday 8:10 - 9:30	4
B13	987 (536 *)	17	Wednesday 13:10 - 14:30	4
B12	902 (99 *)	14	Tuesday 11:30 - 13:00	2

* …Interquartile range

During the winter semester occupancy tended to decrease over time. Yet concentrations levels did not tend to decrease at all (Figure 8), although a moderate correlation (0.52) between CO2 concentrations and occupancy was found (Figure 9).

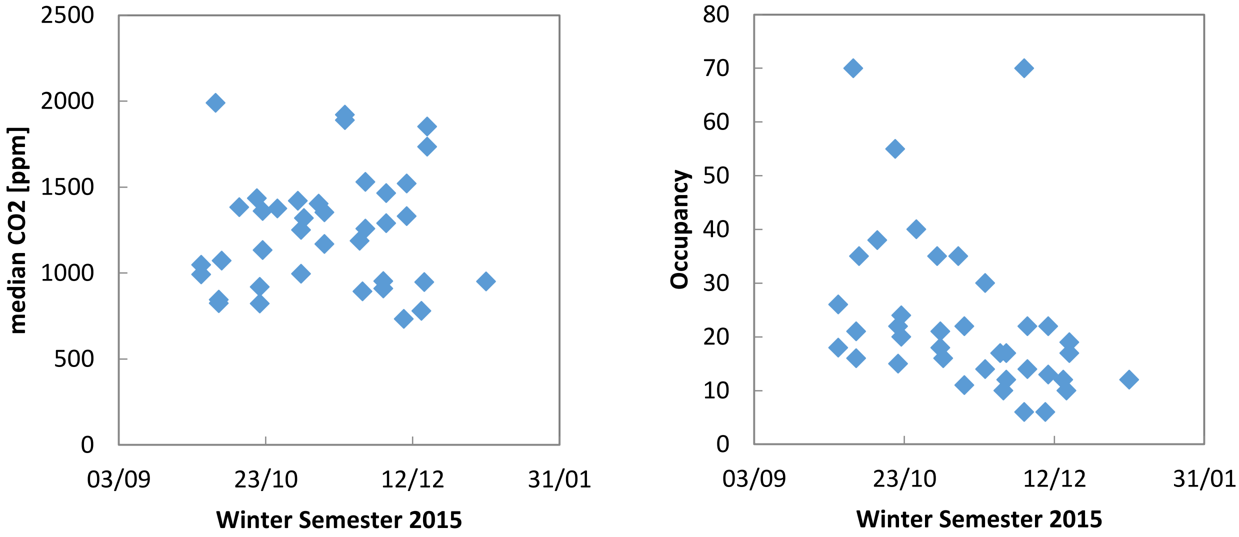


Figure 8 median CO_2 (left) and occupancy of lectures (right) in winter semester 2015

To illustrate that the change is not caused just by the change of occupancy, we introduce a variable that takes into account both occupancy and CO_2 levels. The occupancy/CO_2 factor is defined like:

F = (CO_2(Measured) - CO_2(Ambient))/N, (Equation 5)

where N is amount of people present. This factor has been computed for every lecture. Ambient level for CO_2 has been set as 400 ppm, which is an approx. average measured value on Mauna Loa observatory for year 2015 (ESRL 2016). This value works as a baseline, even though the actual ambient levels tend to be higher in cities (Jacobson 2010). The factor was 36 ppm for summer semester and 42 ppm for winter semester and it can be read as such: on average, one occupant caused an increase of 36 ppm and 42 ppm in CO_2 levels in summer and winter semester, respectively.. This may indicate that ventilation rates tend to be lower in cold months. This to some level correlate with indoor and outdoor temperature. Because in most measured places all the ventilation was done manually, it was determined by occupants behavior and occupants tend to ventilate less if the indoor and/or outdoor temperature was low.

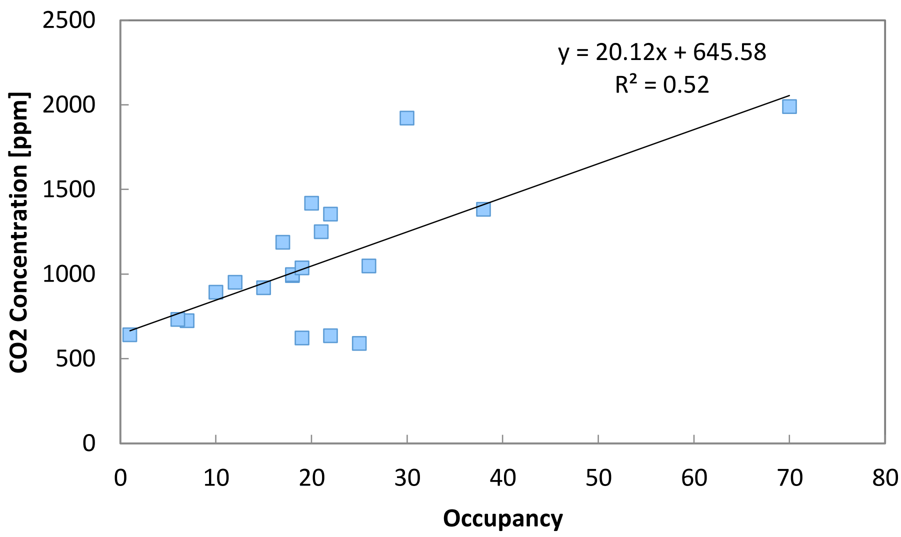


Figure 9 Occupancy and CO_2 levels correlation on lectures with windows and doors closed

Table 8 – CO_2 levels on different modes of ventilation

Windows opened	**Doors opened**	**Semester**	**Median CO_2 concentration [ppm]**
Yes	Yes	Winter and Summer	1419
Yes	No	Winter	1304
Yes	No	Summer	918
No	No	Summer	796
No	No	Winter	1175

As can be seen in Table8, CO_2 levels were actually higher on lectures with doors and windows open. This suggests that manual ventilation, if not executed to moderate indoor temperature, is mostly done when the CO_2 level is already very high so it is reactive behavior and not a proactive one.

The CO_2 concentration differed not only during year, but during the day as well. Lowest CO_2 values were generally recorded in the mornings. CO_2 levels then rised throughout the day in the classrooms and probably also in the building as a whole (Figure 13 in supplementary material). Multiple studies record peak values around the time of noon (Canha *et al* 2013, Turanjanin *et al*, 2014). In Brauner's hall in March, the CO_2 levels were ranging only between 590 and 640 ppm, because the lecture started as early as 8AM and occupancy was rather low in this quite large lecture room. Larger lecture rooms had lower

CO_2 concentrations in general. Kostir's Lecture Hall had high CO_2 values on the start of the semester (reaching as much as 2069 ppm on the first lecture) and then the concentrations were dropping rapidly throughout the semester as the occupancy decreased. Concentrations in smaller lecture rooms did not decrease as much throughout the semester and highest value of 2423 ppm was recorded in November in Seminarium BB, which was the smallest monitored lecture room.

So while no lectures reached the 5000 ppm limit introduced by ASHRAE, 3 out of 14 lectures in summer semester and 26 out of 39 lectures in winter semester had median CO_2 level above 1000 ppm which is, according to ASHRAE, an indicator for inadequate ventilation.

Aside from occupancy and ventilation, there were little to no other factors that would influence CO_2 levels. Large lecture rooms had burners available for chemical reaction purposes, but they were not being used in any of the measured lectures. Lecture room "Seminarium BB" had quite a lot of plants inside which can affect CO_2 levels by cellular respiration and Calvin cycle during photosynthesis. Yet this effect is probably nearly negligible if the room is as crowded as it is during lectures. Houseplants were documented to have slightly decreasing effect on CO_2 levels in apartment buildings (Young-wook *et al* 2009) where the ratio of plants to occupants is much higher than in public spaces and the ventilation rates are much lower.

The main way to improve indoor CO_2 levels would therefore be improving ventilation. Mechanical ventilation leads to lower CO_2 levels; if the ventilation is done manually, it needs to be done proactively to effectively keep the CO_2 levels low e. g. opening the windows sooner before the CO_2 levels can rise up.

Technological development could improve indoors conditions significantly in the upcoming years. The cost of micro-controllers dropped rapidly in the past few years and the whole infrastructure around it improved which decreases the development time of many devices. The cost of various sensors decreased as well. This technological evolution could lead to lower costs and higher diversity of various "smart building" technologies. (Maksimović *et* al 2014).

Summary

We have monitored 8 lecture rooms during two semesters in 2014/15 and 2015/16 academic years. Microclimate changed significantly in all lecture halls and smaller lecture rooms throughout the year and even throughout the day. Best environmental conditions were generally in large lecture halls with lower occupancy. Large lecture halls have more window surface area, bigger volume of air and lights are more likely to be turned on. We have not measured any extreme critical values.

Temperature, relative humidity and CO_2 levels were generally within acceptable ranges and a lot of lectures had optimal conditions. Light levels were very likely to be often suboptimal especially in March and September but it is hard to prove that, since the sensor we used did not properly measure indirect light.

There were no lectures that had CO_2 levels over 5000 ppm, which is a maximum allowed limit introduced by ASHRAE. On the other hand, 3 out of 14 lectures in summer semester and 26 out of 39 lectures in winter semester had median CO_2 level above 1000 ppm which is, according to ASHRAE, an indicator for inadequate ventilation.

The median temperature for 34 winter lectures was 22.2 °C, while for summer semester it was 23.2 °C. In summer semester, the median temperature exceeded 24 °C in 9 out of 29 lectures. In winter semester it was 4 out of 34 lectures and 2 lectures had median temperature below 19 °C. That implies that 52 out of 63 lectures had sufficient thermal conditions (between 30 – 70%).

Relative humidity tended to be lower in summer semester. Based on OSHREP guidelines, in summer semester 21 out of 29 did not meet the sufficient recommended values because the humidity was too low and only 3 out of 29 fell into the optimal recommended range (40 – 60%). In winter, all lectures had sufficient relative humidity and 22 out of 34 lectures had optimal humidity levels. We did not record any lecture that would exceed 70% RH.

Correlation of 0.52 was found between occupancy and CO_2 levels (for lectures that had windows and doors closed) and correlation of 0.50 between indoor and outdoor RH, when the windows were opened. Window opening plays an important role on indoor microclimate, but it mostly seems that it is a reactive behavior, not proactive one. Occupants tend to open windows when the CO_2 level or indoor temperature is already quite high. A habit of opening windows before or at the beginning lectures would very likely be more efficient, especially if the lecture room is very crowded. Light levels could be significantly improved if less window blinds would be closed but this will not likely happen

because projected presentations that are being used on vast majority of lectures may be badly visible if there was a lot of indirect light. For this reason, it might be useful to turn the lights on more often, especially in March and September. Lights turned on generally interfere less with the projected presentation as they are emitting light more directly to the lecture room floor. So even though we did not measure any extreme values, there is still room for improvement. If mechanical ventilation would be introduced both CO2 levels and RH levels would very likely stay much closer to the optimal range.

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Supplementary material

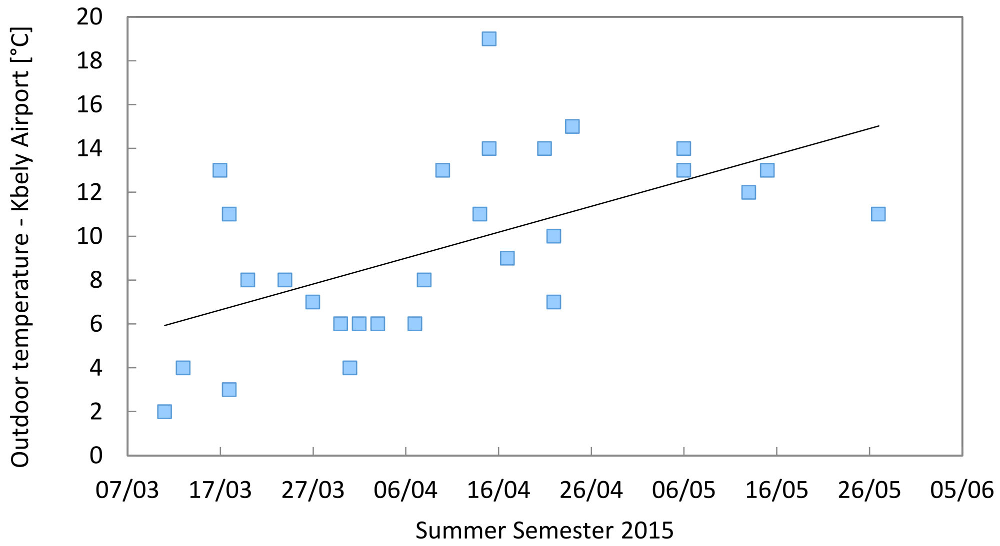

Figure 10.temperature at Kbely Airport weather station in spring and summer 2015

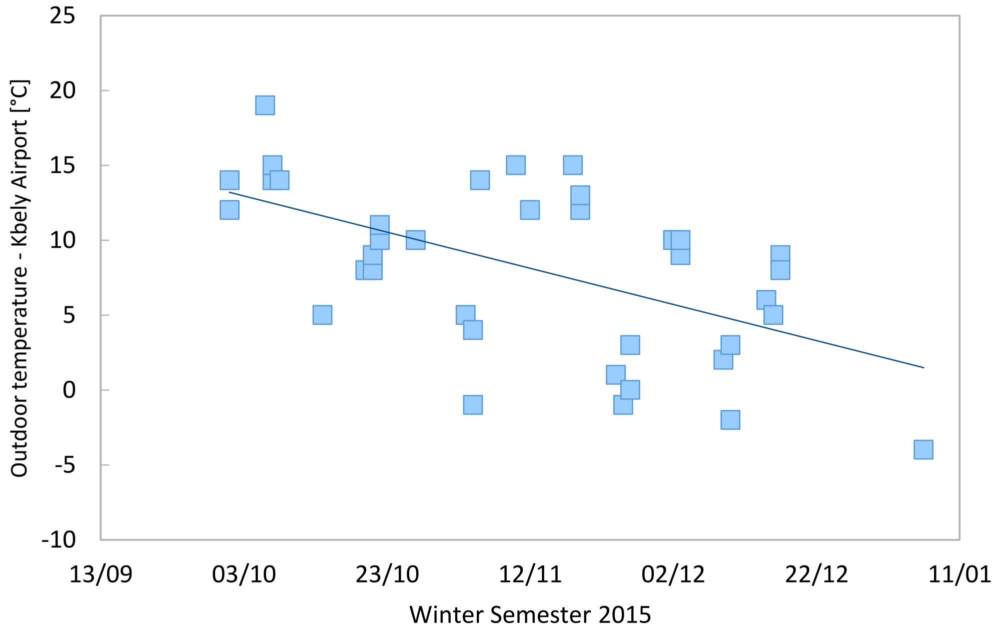

Figure 11 temperature at Kbely Airtport weather station in autumn and winter 2015

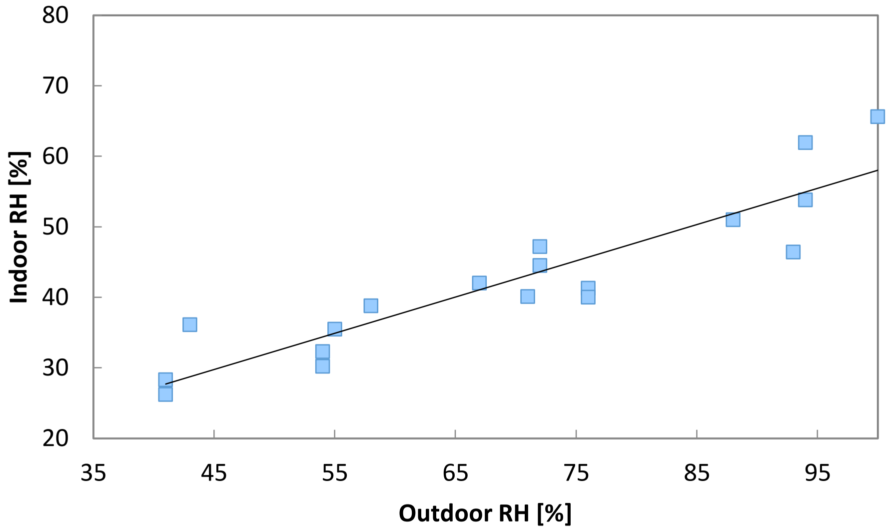

Figure 12. Indoor/Outdoor RH correlation on lectures with opened windows

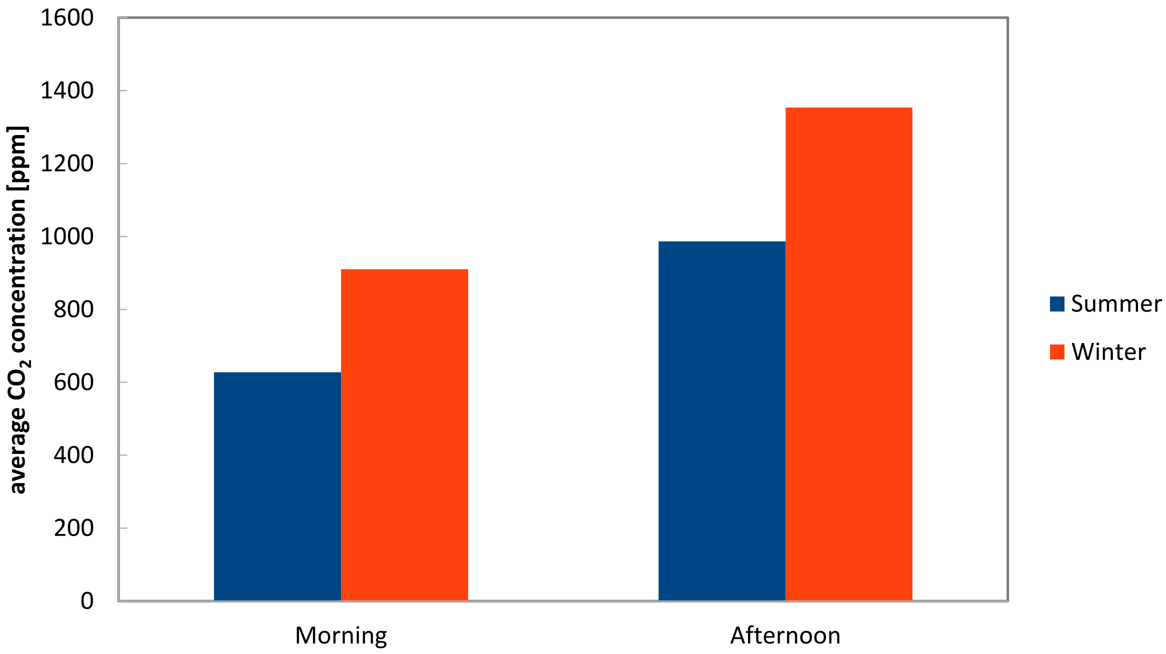

Figure 13 Comparison of CO_2 concentrations on morning and afternoon lectures

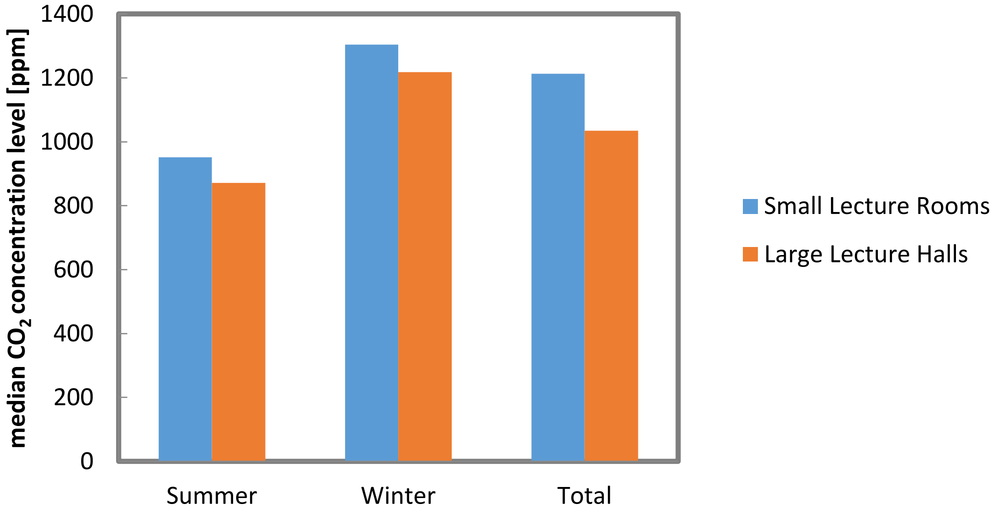

Figure 14– Comparison of CO_2 concentrations in small and large lecture halls