INVESTIGATING THE EFFECT OF CO_2 CONCENTRATION ON REPORTED THERMAL COMFORT

S. Gauthier[1]; B. Liu[2]; G. Huebner[2]; D. Shipworth[2]

1: University of Southampton, Highfield, Southampton, SO17 1BJ, UK.

2: UCL Energy Institute, Central House, 14 Upper Woburn Place, London, WC1H 0NN, UK.

ABSTRACT

The need to predict occupants' perception of thermal discomfort has become one of the priorities in the quest to reduce energy demand in buildings. Drawn from physical and physiological principles, the current thermal comfort models have long been associated with environmental and personal variables. Research has shown that there is often gap between modelled and perceived thermal comfort sensation. One of the reasons may be additional parameters playing a role which are not currently accounted for in the models. One plausible candidate and causal pathway is elevated CO_2 levels stimulating the human respiratory system resulting in increased metabolic rate and heat exchange with the environment. The hypothesis is that people may feel warmer when indoor CO_2 concentration increases. To investigate this hypothesis, two empirical studies were carried out in London; the first one was undertaken in a climate chamber over the summer of 2014, and the second one in an office setting over the winter of 2015. Findings from the first experiment showed that participants felt on average warmer as CO_2 concentration increased but ambient temperature remained constant. However the relationship between reported comfort and CO_2 concentration was not significant. One may suggest that heating setpoint may be adjusted at lower temperature in winter while keeping CO_2 concentration low enough not to affect cognitive performance. This conjecture initiated the study design of the second experiment. As ambient temperature decreased by 3.1±0.5°C, CO_2 concentration increased by 297±45ppm. In this instance, participants felt slightly colder at the end of the sessions; however a modest relationship between CO_2 was found. Thus future studies may chose to increase the variation in CO_2 concentration, and decrease the variation in operative temperature. To conclude the picture that is emerging from this research shows that there is no significant relationship between reported thermal comfort and CO_2 concentration; although this may be due to the relatively small sample size in the first study, and the relatively small variation in CO_2 concentration in the second study. This finding may support building operation strategies that optimise fresh-air level independently of the provision of thermal comfort.

Keywords: Occupant thermal comfort, Indoor CO_2 concentration, Mixed-methods.

INTRODUCTION

In UK, buildings account for nearly half of the carbon emissions; of which heating, ventilation and air conditioning (HVAC) systems represent the largest part [8]. Thus reducing the demand from these systems while keeping occupants comfortable is considered an important component in the quest to reduce carbon emissions. As described in BS EN 15251:2007 [2], thermal comfort is dependent upon external temperature in the adaptive model, and upon four environmental factors (ambient air temperature (Ta), mean radiant temperature (Tr), mean air velocity (Va) and relative humidity (RH)) and two personal factors (metabolic rate [M] and clothing insulation [Icl]) in the predictive model. Research has shown that there is often a gap between modelled and perceived thermal comfort sensation [1]. One of the reasons may be additional parameters) playing a role, which are not currently accounted for in the models. Persily [9] has shown that indoor CO_2 concentration from 600 ppm to 1000 ppm or higher is linked to occupants' perceptions of stuffiness and discomfort. Results of the study by Kavgic et al. [4] suggests that cold discomfort complaints increased when indoor spaces are over-ventilated with a lower CO_2 concentration level. Additionally, high CO_2 concentrations in internal environments are associated with poor indoor air quality, increased symptoms of health response, poor cognitive performance [7]. Human respiration is one of the important sources of indoor CO_2 [3]. During the respiration process, the human body inhales oxygen (O_2), and exhales CO_2. As metabolic rate increases, the breathing rate increases, and more CO_2 is generated by human respiration [12]. Besides, an increase in indoor CO_2 concentration stimulates the breathing rate [10], and a decrease in indoor CO_2 concentration results in a decrease in breathing rate [11]. Indoor CO_2 concentration stimulates human respiratory system, which will in turn increase human metabolic rate and heat exchange with the surrounding environment. Hence, the hypothesis is that people may feel warmer when indoor CO_2 concentration increases, and people may feel cooler when indoor CO_2 concentration decreases. The two empirical studies presented in this paper aim to test this hypothesis, and to investigate the potential effect of CO_2 concentration on thermal comfort perception.

METHOD

Experiment in climate chamber

The first empirical study was carried out in a climate chamber over the summer of 2014. While the six independent variables of the predictive thermal comfort model were kept constant, eighteen participants were each exposed to three consecutive conditions: an increase (Stage 1), then a decrease (Stage 2), and finally a constant exposure (Stage 3) in CO_2 concentration. Six experimental sessions were carried out with three participants taking part in each session. This was a convenience sample, participants were recruited through a call for participation sent out to friends and colleagues. The age range was 22 to 25 years old. The sample consisted of N = 18 participants, only four were male. During Stage 1, the participants were exposed to a gradual increase in CO_2 concentration for a period of 30-minutes. The source of CO_2 was the product of four occupants' respiration (including the researcher) in the fully closed climate chamber. During the next stage (Stage 2), participants were exposed a gradual decrease in CO_2 concentration by partly opening two vents and the chamber's door, for a period of 30-minutes. Finally during Stage 3, participants were exposed to constant and low level of CO_2 concentration by fully opening two vents and the climate chamber door, for a period of 30-minutes. In the climate chamber (Ta) was set at 24°C, and (RH) at 50% [3]. Upon arrival, the participants were given information sheets, a consent form, and had to fill in a background survey about their age, gender, clothing, activity prior to testing, etc. This pre-testing period of about 15 minutes ensured a somewhat comparable rate of metabolic activity, i.e. 15 minutes of sitting still. During the experiment all participants remained seated. Using ISO 7730:2005 Annex B [6], participants' activity level was estimated as 1 met or 58 W/m^2, and constant throughout the experiment. With regards to (Icl), participants were asked not to change their clothing insulation level during the experiment. Using ISO 7730:2005 Annex C [6], (Icl) was estimated at 0.78 ±0.2 clo.

During the experiment, four Eltek datalogger GD-47 were used to monitor (Ta), (RH) and CO_2 concentration at 1-min interval. Three datalogger were located in the climate chamber at the height of 1.2 m, which is regarded as the breathing zone height of seated participants. The fourth datalogger was located outside the climate chamber. Additionally, an anemometer was placed inside the chamber to monitor (Va) during the experiments. Concurrently to the environmental monitoring, participants were required to complete thermal comfort surveys at

10-minutes interval. These aimed to assess participants' thermal perception or actual mean vote (AMV); which was evaluated using the 7-points scale, from -3 ("cold") to +3 ("hot") [2].

Experiment in office setting

To follow the experiments in the controlled environment, a second study was carried out in an office setting over the winter of 2015. While ambient air temperature was decreasing, participants were exposed to an increase in CO_2 concentration for a period of 40-minutes. CO_2 concentration increased due to breathing of the participant and the research assistant in a relatively small space of about 8m^2. Participants were recruited through the online subject data pool of the University College London (UCL). The age range was limited to 18 to 35 years. The sample consisted of N = 30 participants, only two were male. For the purpose of a separate research question, participants had been split up into a control (N = 12) and an intervention group (N=18), with the only difference that in the intervention group participants had control over the light setting in the room. To reflect any potential impacts of this manipulation, group membership (control = 0; intervention = 1) was included as a dummy predictor in subsequent analysis. During recruitment, participants were told what to wear during the experimental session in order to keep the (Icl) identical across participants. This was specified as '*a long-sleeve top, long trousers, shoes and socks*', resulting in (Icl) of about at 0.7 clo [6]. Similar to the first experiment, a pre-testing period of about 15 minutes ensured comparable rate of metabolic activity. During the experiment participants remained seated, with an estimated (M) of 1 met or 58 W/m^2.

During the experiment, one Eltek datalogger GD-47 was used to monitor CO_2 concentration, one anemometer monitored (Va), and four HOBO datalogger U12-012 were used to monitor (Ta) and (RH) at four heights - 0.1m, 0.6m, 1.1 and 1.7m [5]. The sampling rate was set at 1-min interval. Concurrently, participants were asked to complete thermal comfort surveys at 10-minutes intervals, these were similar to the one used in Experiment 1.

RESULTS

Experiment in climate chamber

This study in controlled environment intended to keep the six predicted factors associated with thermal comfort constant. Clothing insulation and metabolic rate were controlled for. With regard to the environmental variables, (Ta) varied slightly with a mean of 22.9±0.4°C, (RH) also varied slightly with a mean of 60±3%. From the output of the anemometer, (Va) was maintained at 0.05 m/s during the six sessions. As this result is lower than 0.15 m/s,

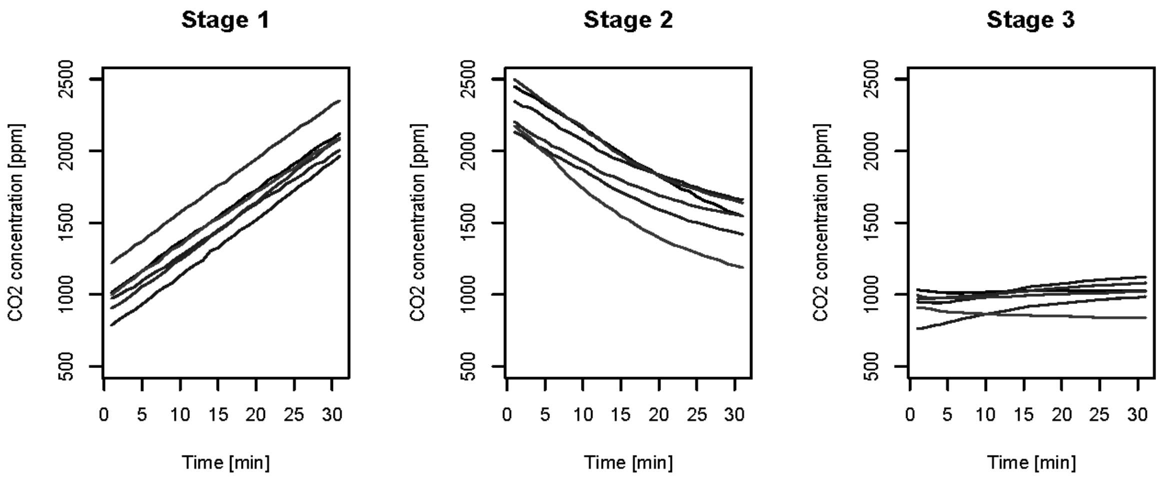

Figure 1: Variation in CO_2 concentration, during Stage 1 to 3, for the six experiments.

(Tr) was regarded as equal to (Ta) (ISO 7726:2001, Table 3 [5]). With regards to variation in CO_2 concentration, results are illustrated in Figure 1. During Stage 1, CO_2 concentration increased on average by 1,118 ±55 ppm; during Stage 2, it decreased on average by 799 ±135 ppm; and during Stage 3, it remained relatively constant with an average of 78 ±113 ppm.

With regards to thermal perception, the mean AMV for the eighteen participants at each survey time is shown in Figure 2. The results show that AMV varied slightly around the "*Neutral*" rating. During Stage 1, AMV increased on average by 0.23 points; during Stage 2 it decreased on average by 0.22 points; and during Stage 3 it remained relatively constant with an average decrease of 0.06 points.

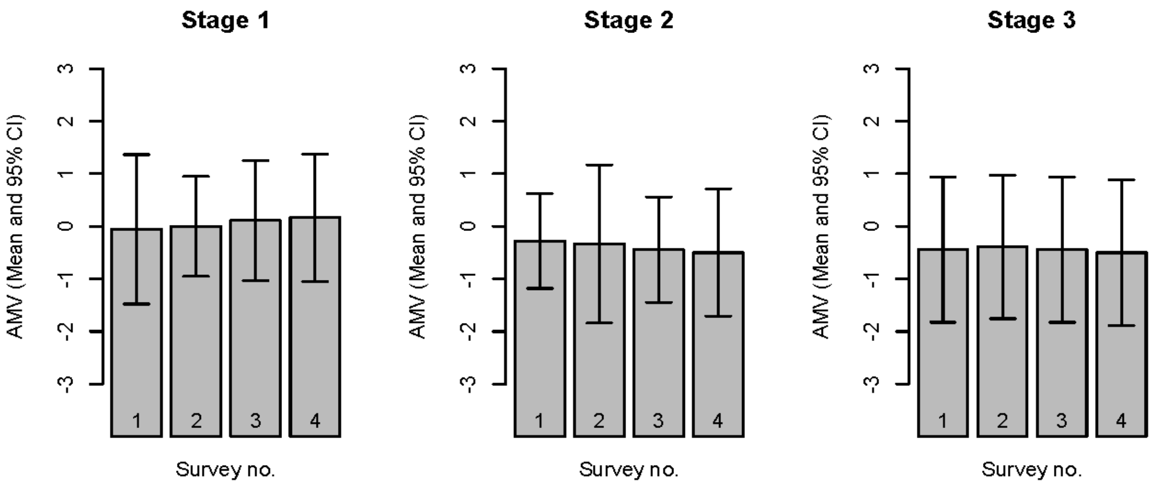

Figure 2: Variation in AMV, during Stage 1 to 3, for the eighteen participants.

To investigate the relationship between CO_2 concentration and thermal perception, repeated measures ANOVA for each Stage were carried out. Although participants felt warmer on average when CO_2 concentration increased, there was no statistically significant effect of CO_2 concentration on AMV, $F(1, 68) = 0.51$, $p = 0.479$. In Stage 2, participants felt on average colder when CO_2 concentration decreased, but there was no statistically significant effect of CO_2 concentration on AMV, $F(1, 68) = 0.01$, $p = 0.921$. Finally, participants' individual AMV was compared at the start and the end of Stage 3 using Wilcoxon paired test. Results showed that AMV is not significantly different at the start and the end of the experiment ($Z = 0.33$, $p = 1$), therefore participants' thermal perception did not change when CO_2 concentration remained constant.

Experiment in office setting

This study in office environment intended to keep five predicted factors associated with predictive thermal comfort constant. Clothing insulation and metabolic rate were controlled for. With regard to the environmental variables, (RH) varied slightly with a mean of 35±3%, and (Va) was maintained below 0.1 m/s. As this result is lower than 0.15 m/s, (Tr) was regarded as equal to (Ta) [5]. With regards to (Ta), a review of the monitoring output using z-score revealed three outliers, where (Ta) did not varied significantly during the course of the session, and where (Ta) level was set at a significantly higher level at the start of the session. These three outliers were not included in the subsequent analysis. With regards to variation in (Ta) and CO_2 concentration, results are illustrated in Figure 3. During the course of the 27-sessions, (Ta) decreased on average by 3.1±0.5°C, and CO_2 concentration increased on average by 297±45ppm.

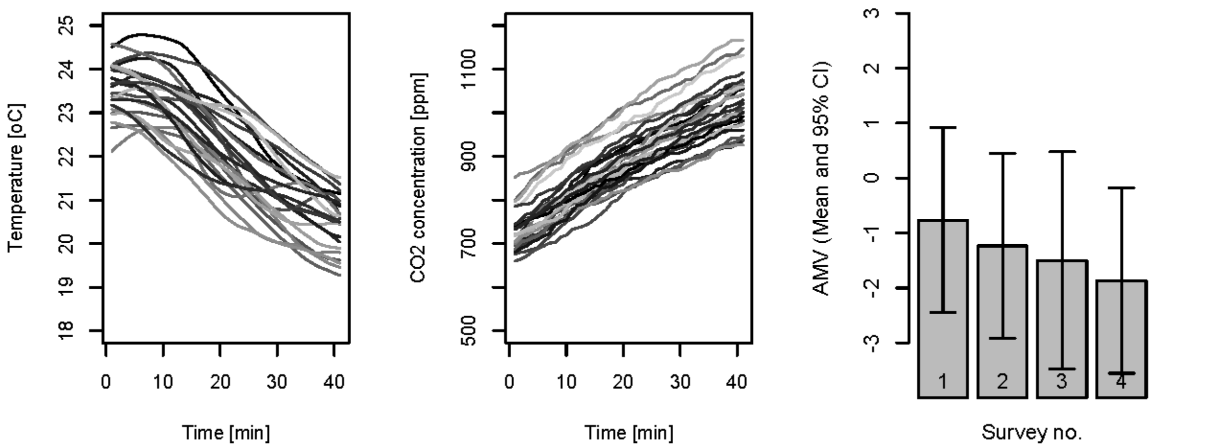

Figure 3: Experiment 2 - variation in (Ta), CO_2 concentration and AMV.

With regards to thermal perception, the mean AMV for the twenty-seven participants at each survey time is shown in Figure 3. The results show that AMV decreased on average by 1.1 points; on average participants felt slightly colder at the end of the session.

To investigate the relationship between CO_2 concentration and thermal perception, cross-sectional regression analysis between mean AMV and mean CO_2 concentration at each survey time were carried out, with AMV as dependent variable and CO_2 and condition as predictors. Results showed weak relationships, with Survey 1 (Adj. R^2=0.08, p=0.08, β=-0.33), Survey 2 (Adj. R^2=0.02, p=0.55, β=-0.11), Survey 3 (Adj. R^2=0.04, p=0.91, β=0.02) and Survey 4 (Adj. R^2=0.03, p=0.82, β=-0.04). Further analysis need to take the longitudinal character of the study into account, building a hierarchical model with the repeated measures of comfort as dependent variable; and with time-varying covariates (CO_2, Ta) and time-constant predictors (e.g. Body-Mass-Index) as predictors.

DISCUSSION

With regards to the first study, the sample size was relatively small, with N=18. Using the results of the experiment to determine the expected effect size, a power calculation was undertaken to determine how many participants you be required to obtain a significant numerical difference. The desired statistical power was assumed to be 80% and alpha level was set at 5%. Results show that for Stage 1, 75 participants would be required, and for Stage 2, 50 participants would be required. Future research may also consider varying the sequencing of the exposure to CO_2 concentration, as there might be a 'lag' in thermal sensation between stages. This will require the use of a climate chamber with control over fresh-air intake, and rising CO_2 concentration using gas bottle. Ethical consideration should be reviewed. With regards to internal validity and study design, one limitation of the second study might be the CO_2 concentration range considered, which was relatively low. A larger effect on AMV may be observed when increasing CO_2 concentration further. Finally, the analysis methods considered AMV as a continuous variable, however studies using the adaptive approach have considered AMV as a discrete variable [1]. Further analysis may employ logistic regression to review the monitoring results.

CONCLUSION

Our study used two experimental designs to investigate the relationship between indoor CO_2 concentration and reported thermal comfort. Results of the first experiment in climate chamber show that when reviewing the mean comfort vote at each survey time, participants felt warmer when CO_2 concentration increased, colder when it decreased, and reported no change when it remained constant. However the results were not satistically significant. A post-hoc sample size calculation has shown, that the study would have required substantially larger number of participants (75) to reveal a satistically significant effect. To follow from this study, a second experiment in office environment was carried out. As operative temperature decreased, CO_2 concentration increased. Results of this experiment showed that participants felt slightly colder at the end of the session. This may be due to the fact that (Ta) may have a greater impact on AMV than CO_2 concentration. In addition the variation in CO_2 concentration was relatively modest compare to the first experiment, with a mean decrease of 297±45ppm. Thus future studies may chose to increase the variation in CO_2 concentration, while minimising the impact on cognitive performance. To conclude this paper shows that there is no significant relationship between reported thermal comfort and CO_2 concentration, therefore there is no basis for concern when controlling for CO_2 concentration having adverse effect on occupants' perception of thermal comfort. In winter, heating and ventilation systems should provide fresh-air and thermally comfortable environments. This will be a challenge; as thriving for energy conservation, buildings are becoming more airtight with lower infiltration rate and fine-tuning of fresh air intake.

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