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Comfort and performance impact of personal control over thermal environment in summer: Results from a laboratory study

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ABSTRACT

Field studies suggest that the availability of adjustable thermostats, operable windows and other controls has a positive impact on comfort, the incidence of building related symptoms and productivity. This laboratory study was designed to further investigate how having or not having control over the thermal environment affects human responses to the indoor environment.

The study was conducted in summer in a field laboratory that was kept at 28 °C. A total of 23 subjects were exposed twice for about 2.5 h. During the first session (A) subjects were able to fine-tune their local thermal environment at any given time with a personal desk fan with continuous, stepless adjustable control. During the second session (B) subjects still had the desk fans, but this time the fans were controlled from an adjacent room by the researchers who adjusted the individual air speed profiles so they were identical to those recorded during the first session. Thus, each subject was exposed to two customized conditions with identical exposure, only different from a psychological point of view.

During the two sessions identical questionnaires and performance tests were used to evaluate subjects' comfort, SBS symptom incidence and performance. As expected, perceived control over the environment was significantly higher during session A, but there were no differences in perceived comfort and SBS symptom intensity. Both self-assessed and objectively measured performance was significantly better during session B. About two-thirds of the subjects indicated to prefer the situation as during the first session when they themselves controlled the air movement.

1. Introduction

The design of many modern office buildings seems to be based on the assumption that maintaining environmental variables at constant, predefined levels by definition assures comfort and satisfaction of building occupants (Boerstra and Beuker, 2011) [3]; (Boerstra, Loomans and Hensen, 2012) [4]. This assumption implies that people are better off with indoor climates that are centrally controlled within narrow ranges.

But many studies in fact imply that comfort, health and performance are better when occupants are provided with options for control over their indoor climate. For example, Humphreys, Nicol and Raja (2007) [38] and Brager et al. (2004) [35] interpreted field study outcomes and concluded that people are more tolerant of their thermal environment if they can control it. According to Leaman and Bordass (1999) [20] most people are satisfiers not optimizers and want conditions that are 'good enough' while tolerating offsets from the 'ideal' as long as they have adequate opportunities to make indoor climate interventions.

Psychologist Rohles (2007) [37] in this context stated that the ability of the individual to control his or her environment is a rather subtle but important aspect and one that affects our satisfaction with the surroundings to a large extent. Vroon (1990) [30], another psychologist involved in indoor climate research, came to the conclusion that allowing personal control over one's indoor

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environment is a very effective way to limit the negative health effects of stress (including stress induced by exposure to a suboptimal indoor environment).

In a Danish field study in 9 office buildings (5 mechanically ventilated and 4 naturally ventilated) Hummelgaard et al. (2007) [36] found that summer temperatures were higher in the naturally ventilated buildings. Nevertheless occupants in the naturally ventilated buildings were significantly more satisfied with the thermal environment and their perceived level of control over the indoor climate was higher. These findings were in line with those of Hellwig (2007). Hellwig studied indoor climate perceptions in 16 German office buildings (some of them naturally ventilated and others mechanically ventilated) and found a strong correlation between perceived control over temperature and air movement and the incidence of comfort complaints. This correlation was especially strong in the naturally ventilated buildings, and less so in the mechanically ventilated buildings.

Boerstra et al. (2013a) [5] conducted a reanalysis of the European HOPE database (that is further described in Roulet et al., 2006a [25] and Roulet et al., 2006b [26]) and found that availability of effective controls and high perceived levels of control over the indoor climate were positively correlated with occupant satisfaction. Furthermore, several studies showed that SBS symptom prevalence among occupants in naturally ventilated buildings was lower than in mechanically ventilated buildings (e.g. Burge et al., 1987 & Mendell, 1993). Lack of control opportunities in mechanically ventilated and air-conditioned buildings might be one of the explanations for this (Toftum, 2010) [28]. Jaakkola et al. (1989) [17] in this context came to the conclusion that 'individual control of room temperature in office buildings reduces sick building syndrome'.

Laboratory studies that looked at the impact of personal control on comfort, health and performance are scarce. Schweiker et al. (2012) designed a climate chamber study with one façade connected to the outside. During certain episodes people were exposed to relatively high indoor temperatures (>25 °C) while not being allowed to use available thermal controls (operable windows, ceiling fans, sun blinds). At other moments, they were allowed to use these controls at will. Indoor temperatures were slightly lower when subjects were allowed to use the controls (about 1–2 °C). At the same time comfort scores were much better than when control use was prohibited. And the comfort perception offset was much more than was expected just from the 1–2 °C lowered temperature and the locally elevated air speeds. One of the main conclusions of Schweiker et al. was that neither of the comfort models (the traditional model described in Fanger (1970) [8] nor the adaptive comfort model described in de Dear, Brager & Cooper (1997) [7]) was able to explain the much better comfort scores in situations where behavioral interventions were allowed. This led them to the hypothesis that just the permission to interact with the built environment in itself leads to a higher satisfaction and acceptance of (suboptimal) thermal conditions.

Having or not having access to controls also appears to have productivity effects. Kroner (2000) [19] performed field studies with 'environmentally responsive workstations' that offered a high degree of personal control over the thermal conditions and the local air quality at work station level. Productivity measurements showed that the introduction of personal control at workstation level significantly increased measured task performance. Wyon (2000) [32] estimated the task performance impacts of individual control based on the outcomes of several field and laboratory studies. His conclusion was that the provision of individual temperature control (±3 K adjustability around a group average (PMV = 0) neutral temperature) will increase group average performance, while the quantitative effect depends on the nature of the task. The mean performance improvement related to the provision of temperature control that Wyon found was 5.4%. Performance improvements for specific tasks were: thinking +2.7%, typing +7.0%, skilled work +3.4%, and speed +8.6% (Wyon, 2000) [32].

In line with the results of Kroner (2000) [19] and Wyon (2000) [32] also Fisk & Rosenfeld (1997) [11] came to a general conclusion that it is not just temperature in itself that has an impact on the performance of building occupants, but also the availability of adjustable thermostats and other controls. Zweers et al. (1992) [34] conducted a large field study in Dutch office buildings and found that offering adequate options for occupant control over temperature reduced sick leave days.

Some guidelines (e.g. Rehva, 2006 [24]) state that the provision of personal control options has a beneficiary effect on performance and sick leave. Fanger (2001) [9] even argued for a paradigm shift related to the design of building service systems and stated that the provision of adequate personal control over the thermal environment is a key measure to ensure comfort, health and performance of building occupants.

A drawback of many of the studies described above is that is difficult to unravel effects related to physical and physiological aspects on the one hand and psychological aspects on the other hand (with the study of Schweiker et al. (2012) as the possible exception). Therefore, a laboratory study about personal control was designed. The central idea was to compare comfort, health and performance responses in two situations that were the same from a physical and physiological point of view but different from a psychological point of view.

The objective of the study was to investigate how having or not having control over one's thermal environment (under warm summer conditions) affects end-user responses, in particular perceived comfort, the incidence of SBS symptoms and (self-assessed and objectively measured) task performance.

2. Methods

2.1. Overall research design

A conceptual model that envisions control as a moderator variable was the fundament for the present study.

This conceptual model was derived from the general environmental psychology literature (e.g. Bell et al., 2006 [2]) and interactive models developed by other indoor climate researchers (e.g. Paciuk, 1990 [23]). For a further description of these previously developed models see Boerstra & Beuker (2011) [3]; Boerstra et al., 2012 [4].

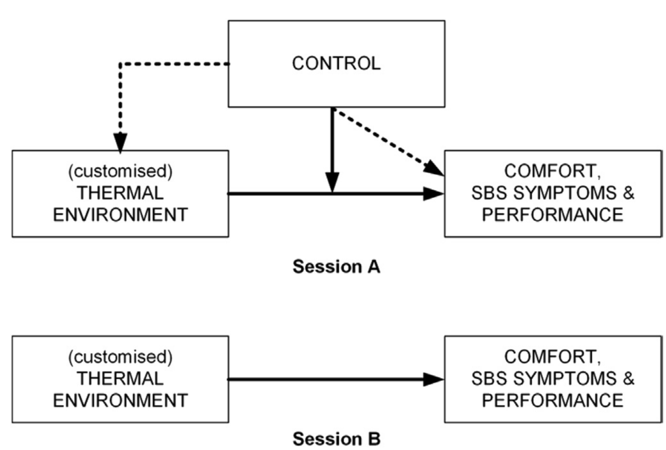

Fig. 1. Schematized research design (with reference to the conceptual 'control as a moderator' model presented in Boerstra et al (2013a) [5].

The core assumption underlying the present conceptual model (that is further explained in Boerstra et al., 2013a [5]) is that human responses to a thermal environment depend at least partly on the amount of control one has (had) over that environment. The hypothesis here is that having or not having control over one's indoor climate influences how environmental parameters like temperature and air speed impact comfort, health and performance. Occupant control in this context is thought of as a moderator or a 'background' variable that affects the strength of the relation between the independent variable indoor environmental condition and the dependent variables health, comfort and performance.

Fig. 1 explains the research design of the laboratory study, with reference to the previously mentioned conceptual model of Boerstra et al. (2013a) [5]. During the first experimental session (A) subjects did have direct control over their thermal environment and during the second experimental session (B) they did not but were exposed to the same, customized thermal environment. The Figure and the overall research procedure are further explained in paragraphs 2.3 and 2.5.

Fig. 3. Field laboratory with 3 of the 6 subjects during one of the experiments.

2.2. Experimental room

The study was carried out at the International Centre for Indoor Environment and Energy (ICIEE) at the Technical University of Denmark. The first sessions (A) took place from the 29th of May through the 1st of June of 2012 and the second sessions (B) took place from the 12th through the 15th of June. The experiments were conducted in a so called 'field laboratory' equipped with a dedicated HVAC system that allowed for very precise conditioning of the room temperature. The experimental room had a Constant Air Volume (CAV) system with supply from two ceiling hung mixing diffusers and extract through two grilles mounted in the upper part of the wall opposite the windows. Floors were covered with hard flooring (low polluting polyolefine).

The floor plan of the experimental room is presented in Fig. 2. A total of 6 workstations were placed in the room. Each included a chair, a table, a desktop computer and an adjustable table fan. The workstations were separated by partitions (see Fig. 3) and (in the middle) a lightweight folding wall. The partitioning between workstations guaranteed that subjects could not feel air movement produced by desk fans other than their own. Daylight entered the room by 2 large windows (of 0.9 m by 1.40 m) and 4 (higher) small windows (of 0.90 by 0.70 m) located in a façade with Western orientation.

To prevent direct sunlight from entering the room during the experiments and to avoid thermal disturbance due to excessive solar heat influx, the experiments purposely were performed in the morning from 9:00 AM till 11:30 AM. The artificial lighting that consisted of ceiling mounted down lighters was kept on at all times during the experiments.

The average outdoor morning temperature (over the period 9.00 AM till 11.30 AM for the 4 days) during the first period (A) was 10.2 °C (SD 0.8 °C) while the outdoor relative humidity was 82% (SD 16%). During the second period (B) the outdoor morning temperature was 13.9 °C (SD 2.6 °C) with an outdoor relative humidity of 74% (SD 14%). During both periods the (morning) sky was mostly cloudy.

The operative temperature of the field laboratory was kept at 28 °C during both experimental sessions. This value of 28 °C is just outside the (category C) comfort range for office work as described in ISO 7730 (2005) [15] and was selected as setpoint to make sure that subjects would be triggered to use their personal fans. Assuming a clo-value of 0.5 clo (0.65 clo chair insulation included), still air and an activity level of 1.2 met an operative temperature of

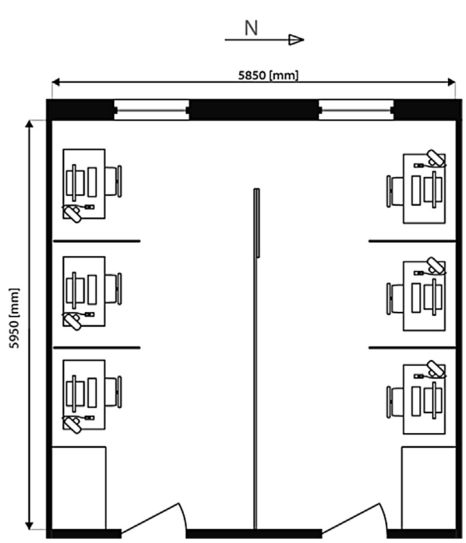

Fig. 2. Floor plan of the DTU field laboratory.

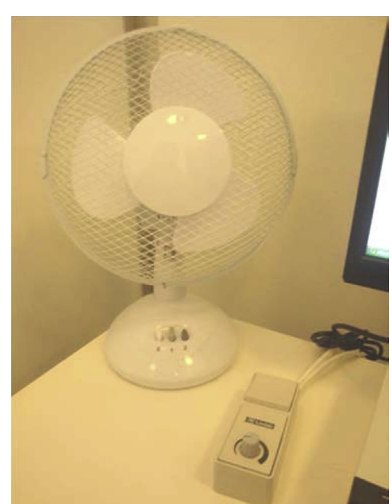

Fig. 4. Fan with control unit (gray unit in lower right, with rotary switch). Note that the regular '0-1-2' button on the fan itself was fixed in the '2' (maximum) position during the experiments.

28 °C (in still air) translates into a Predicted Mean Vote (PMV) value of 1.2 (a bit over 1 = 'slightly warm').

2.3. Adjustable fans

All workstations were equipped with an adjustable desk fan, see Fig. 4. The fans were connected to a separate control unit (lower right on the photo) that allowed for stepless adjustable, continuous control over the local air velocity between 0.1 and 2.5 m/s. The fans did not have swivel capacities.

During the first experimental session (A) the control units were left on the tables and subjects were told that they were allowed to adjust the control units at will throughout the experiment. The control units of the fans were connected to voltmeters placed in an adjacent room. This allowed the research team to record fan settings during the course of experimental session A without disturbing the subjects. During the second session (B) control units were still connected to the fans but had been moved to an adjacent room. In this second session the control units were operated by the research team (with remote control) to recreate the customized air velocity profiles and provide an identical thermal exposure (different for each individual) as during session A. See Fig. 1.

Before session A and after session B local air velocities at the seating positions with different control unit settings were measured with a calibrated B&K 1213 Indoor Climate Analyzer. At the start of the overall experiment the control unit voltages were measured at the different control unit settings. This allowed to derive a voltage-air velocity correlation for each fan. As an example, Fig. 5 presents such a correlation for one of the fans. It was these output voltage-air velocity correlations that enabled the research team to recreate the individual air velocity profiles during session B from the adjacent room.

Verification measurements were done to make sure that air velocity profiles during session B and session A were congruent. Fig. 6 shows an example for 1 subject that used fan no. 1. It can be seen that the reproduced air velocity profile as created during session B was very much in line with the air velocity profile as created by the subject during session A. Verification measurements for the other subjects and other fans showed similar congruity.

Note that during session B too brisk air velocity adjustments were flattened out by a maximum air velocity/acceleration of 0.01 m/s^2. This was done so subjects would not feel too sudden air velocity changes when air velocities were adjusted by the researchers from the adjacent room.

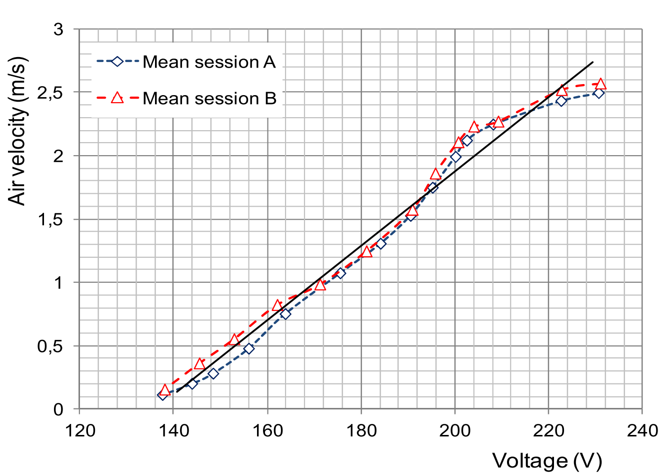

Fig. 5. Measured output voltage air velocity correlation (example for fan no. 1 only).

2.4. Subjects

Twenty-three subjects participated in the experiment. Originally, a sample size of twenty-four subjects was planed (six subjects per day times four research days), but during the experiments one subject dropped out, leaving twenty-three subjects at the end. The subjects were randomly selected from an existing ICIEE database with subjects that had been involved in earlier laboratory experiments. They signed a consent form beforehand and were paid for their participation. Before the experiments started subjects were told that the recorded data would be used in a way that safeguarded confidentiality.

The subjects were students, 12 male and 11 female aged between 20 and 35 years. Table 1 shows additional characteristics of the subjects. The Body Mass Indices presented in Table 1 were calculated based on height and weight data as provided by the subjects themselves (questionnaire). The subjects were of different nationalities, but all were born in Europe.

2.5. Experimental procedure

The subjects came three times to the laboratory facilities: first for a pilot (training) session, then for experimental session A (the 'with-control-situation') and (2 weeks later) for session B (the 'no-control-situation').

During the pilot session subjects first received an oral explanation about the experiments as a follow up on the written instructions they had received by email. Subjects were introduced to the field laboratory and the workstations and were invited to try out the table fans and their control units (rotary switches). Subjects also had to do some practice performance tests on the desktop computers and were introduced to the online questionnaires. The aim of the pilot sessions that lasted 1 h was to get the subjects acquainted with the experimental facilities *before* the actual experiments started. No actual output data were gathered during the pilot sessions.

Prior to session A the subjects received another email with instructions. This email told them that they were not allowed to drink alcohol the day before the experiment. Also drinking strong tea or coffee the hour before the experiment was prohibited. Subjects were also instructed to wear the same clothes during both experimental sessions and it was recommended not to wear shorts, a short skirt or a warm sweater or vest. Furthermore, they were instructed to use the same mode of transport for getting to the laboratory during both experimental sessions. The latter in order to make sure that pre-experiment metabolism was more or less the same for session A and B.

The subjects were divided into four groups of six persons each. Each group was assigned to a specific day of the week. The two experimental sessions were organized in such a way that groups had to come twice (apart from the pilot session) on the same day of the week, with two weeks in between. All four groups had both male and female subjects in them.

The procedure during session A (the with-control situation) was as follows: subjects entered the room and were seated at the same workstation as during the pilot session. At the start they were allowed only to make small changes to their clothing to acclimatize to the temperature. Subjects were invited to adjust the air velocity to their preferred (start) level. Then they were told that they were allowed to adjust their fan and local air velocity at any time during the experiment, as practiced during the pilot session the week before. They were requested to fill in a short form (on their computer) every time they readjusted the table fan. This form asked whether the subject decreased or increased the air velocity; also

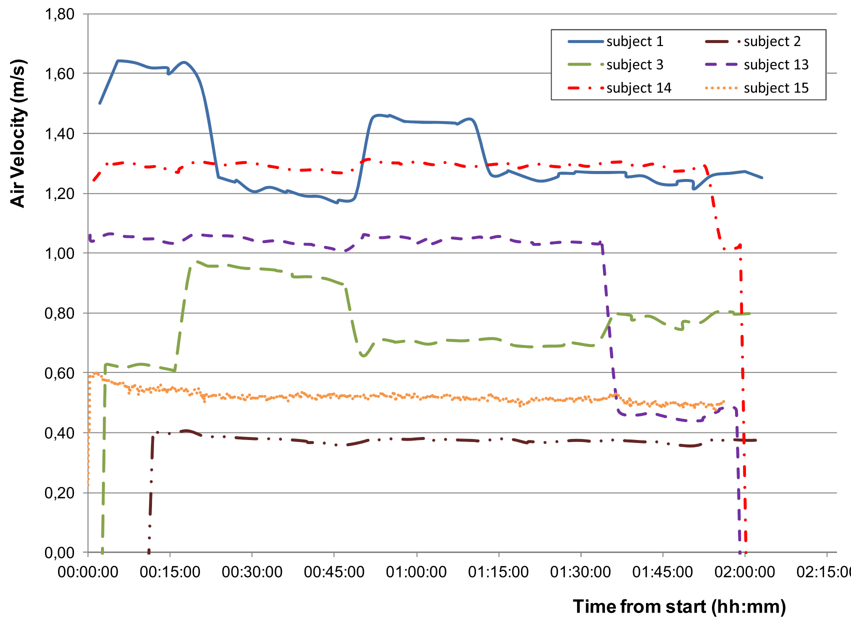

Fig. 6. Verification measurement outcomes for one subject that used fan no. 1: comparing the air velocity profile of this subject for session B (created by the research team) with that of session A (original velocity profile as created by this subject).

Table 1
Subjects' characteristics (mean values and standard deviation).

Gender	Age [years]	BMI	Number of subjects
Males	24.9 ± 2.4	22.9 ± 1.6	12
Females	24.4 ± 3.8	22.3 ± 4.8	11
All	24.7 ± 3.1	22.6 ± 3.5	23

they were invited to describe (in their own words, open question) the reason for their adjustment.

After an acclimatization period of 15 minutes the experiment started. At predefined times subjects had to do different performance tests or were asked to fill in questionnaires. Custom software automated most of the data collection and controlled the duration of each task. The experimental procedure is further explained in Table 2. The experiment was divided into four different time intervals that all lasted around 30 minutes. In all cases, for both sessions and all subjects, the order of the tests was the same (pre-arranged, order as indicated in Table 2).

Table 2
Experimental procedure for both experimental session A and B.

Approximate time	Interval no.	Event	Duration (minutes)
9:00 AM	–	Acclimatization, welcome & instructions	15
9:15 AM	1	Questionnaire A – Introduction	1
		Questionnaire B – Comfort	1
		Questionnaire D – SBS symptoms	1
		Tsai-Parrington numbers test	3
		Word processing task	14
		Questionnaire C – Performance	1
		Calculation task/Addition	12
9:48 AM	2	Questionnaire D – SBS	1
		Calculation task/Multiplication	12
		Questionnaire B – Comfort	1
		Calculation task/Addition	10
10:12 AM	3	Questionnaire C – Performance	1
		Word processing task	14
		Questionnaire D – SBS	1
		Calculation task/Multiplication	12
		Questionnaire B – Comfort	1
10:41 AM	4	Word processing task	12
		Questionnaire C – Performance	1
		Tsai-Parrington numbers test	3
		Calculation task/Addition	12
		Questionnaire B – Comfort	1
		Questionnaire E – Perceived control	2
		Questionnaire X – Clothing & General comments	1
11:13 AM	–	End	–

At the start of session B subjects were assigned to the same workstation as during session A. During the acclimatization period the research assistant checked verbally and visually whether individual clothing insulation was comparable with that during the first session (reference: clo -values as described in ISO 7730 (2005) [15]). This was further verified at a later stage by comparing the clothing questionnaire results from both experimental sessions. Other than that, the procedure during session B was the same as during session A (see again Table 2).

At the start of session B subjects were told that this time they would not have control over the fans and that they would be exposed to a predefined air velocity setting as decided upon by the research team. So the subjects were not aware of the fact that during session B they were exposed to the same air velocity profile as during session A. They also did not know that they were all exposed to different (customized) air velocities.

Normally with an experiment that investigates how two different conditions affect subjects one would choose to expose half of the subjects first to condition A and then to B and the other half first to B and then to A (randomize the subjects over the conditions). In this specific case this was simply not possible as one needs the session A results (the individual air velocity profiles) to be able to create the session B conditions.

2.6. Questionnaire and performance tests

During both experimental sessions subjects had to answer online questions and conduct performance tests. The questionnaire consisted of eight different sections that were filled in at different times during the experiments. The different sections dealt with issues like occupants' overall assessment of the indoor environment, perceived air quality, thermal comfort, satisfaction with the

Table 3
Indoor climate conditions during the two experimental sessions and their 4 time intervals.

Experimental session	Time interval no.	Operative temperature [°C]	Relative humidity [%]	CO_2 concentration [ppm]
A (with-control situation)	1	27.9 ± 0.13	33.0 ± 1.59	465 ± 32
	2	27.9 ± 0.21	31.7 ± 0.82	476 ± 39
	3	28.0 ± 0.08	23.1 ± 1.12	442 ± 29
	4	28.0 ± 0.13	25.3 ± 1.18	454 ± 37
B (no-control situation)	1	27.9 ± 0.11	31.3 ± 0.47	434 ± 36
	2	28.0 ± 0.06	33.1 ± 0.93	470 ± 40
	3	28.0 ± 0.06	28.9 ± 0.51	437 ± 25
	4	28.0 ± 0.10	24.1 ± 0.44	433 ± 30

environment, self-assessed performance, perceived control over different environmental aspects and prevalence of building related (SBS) symptoms.

The questionnaire was developed using the recommendations in ISO 10551 (1995) [16] and elements from a previous field study questionnaire that also dealt with indoor climate and personal control (Boerstra, Loomans and Hensen, 2013b) [6]. In most cases 7-point Likert scales were used. See column 1 and 2 of Tables 4 and 5 for a further (indirect) description of the questions and response categories.

During both sessions subjects had to execute computerized performance tests. The tests involved addition, multiplication, Tsai-Parrington numbers tests and text typing. During the addition test subjects had to add five 2-digit numbers without the use of a calculator. Also the use of paper and pen or pencil was prohibited. The multiplication test involved multiplying 1-digit numbers with 2-digit numbers. The Tsai-Parrington numbers test meant that subjects had to connect numbered dots presented on their computer screen. The dots were randomly divided over the screen and not all numbers of a continuous row were present (think of a string with 3, 6, 8, 11, 15, 16, 22, etc.). The text typing task involved copy-typing text from science magazines.

For the addition and multiplication tests the number of correct answers per minute was used as a performance indicator. For the Tsai-Parrington numbers test this was the total amount of correct dot connections between successive numbers. For text typing the total numbers of errors and the number of characters typed per minute were used as indicators.

2.7. Data analysis

The overall experiment asked for a two-level repeated measures within-subject design. In this case we dealt with two related samples and paired intrapersonal comparison; the results of one subject as obtained during session B (no-control situation) were compared with the results of that same subject during session A (with-control situation).

Results were analyzed (in accordance with the requirements in e.g. Baarda, et al. (2004) [1] and Field (2005) [10]) with the Wilcoxon signed-rank test (W) and the McNemar chi-square test (M). Non-parametric tests were chosen as the sample size was limited ($n < 25$) and because the data were not really normally distributed.

The Wilcoxon test is a non-parametric test that can be used to analyze differences between two related samples. The Wilcoxon signed rank test was used for the binominal and ordinal variables. The McNemar chi-square test is a statistical test used on paired nominal data that can be applied to 2 × 2 contingency tables with matched pairs of subjects (in this case same-subject comparison). The McNemar test was used for the dichotomous variables. For more background information on the two tests described, see e.g. Field (2005) [10].

Statistical analyses were performed with SPSS 20 (IBM, 2011) [14]. The selected significance level was $p = 0.05$.

3. Results

3.1. Background conditions

It was essential for the overall experiment that the environmental background conditions in the test room were the same during session B (no control situation) as during session A (with

Table 4
Perceived control related outcomes and their paired comparison correlations; significant differences are marked with an asterisk.

Variable	Legend	Session A (with-control)	Session B (no-control)	Difference (B vs. A)		p-value[a]	Stat. Test used[b]	Signed-ranks		
		Mean	Mean	Abs. (B-A)	% (B-A)/A			Pos.	Neg.	Ties
Perceived control over temperature	1 = no control at all; 7 = full control	4.39	1.17	−3.22	–	<0.001*	W	0	21	2
Amount of subjects satisfied with control over temperature		15 out of 23	4 out of 23	–	−73%	0.001*	M	0	11	12
Perceived control over air movement	1 = no control at all; 7 = full control	5.74	1.17	−4.57	–	<0.001*	W	0	23	0
Amount of subjects satisfied with control over air movement		19 out of 23	6 out of 23	–	−68%	<0.001*	M	0	13	10
Perceived control over ventilation	1 = no control at all; 7 = full control	3.74	1.00	−2.74	–	<0.001*	W	0	17	6
Amount of subjects satisfied with control over ventilation		16 out of 23	7 out of 23	–	−56%	0.012*	M	1	10	12
Perceived control over lighting	1 = no control at all; 7 = full control	1.04	1.00	−0.04	–	0.317	W	0	1	22
Perceived control over noise	1 = no control at all; 7 = full control	1.87	1.26	−0.61	–	0.015*	W	2	10	11

[a] An asterisk(*) indicates a significant difference, with $p < 0.05$.
[b] W = Wilcoxon signed rank test, M = McNemar's chi-square test.

Table 5
Comfort and SBS symptoms related outcomes and their paired comparison correlations; significant differences are marked with an asterisk.

	Variable	Legend	Session A (with-control)	Session B (no-control)	Difference (B-A)		p-value[a]	Stat. Test used[b]	Signed ranks		
			Mean	Mean	Abs. (B−A)	% (B−A)/A			Pos.	Neg.	Ties
Comfort	Thermal sensation	−3 cold > +3 hot	0.52	0.42	−0.10	–	0.294	W	10	13	0
	Amount of subjects satisfied with thermal environment	(no unsatisfactory score during either of the 4 intervals)	9 out of 23	13 out of 23	–	+44%	0.298	M	6	2	15
	Thermal preference	1 cooler; 2 same; 3 warmer	1.52	1.55	+0.03	–	0.567	W	7	7	9
	Thermal acceptance	0 clearly acceptable; 100 clearly not acceptable	28.8	28.0	−0.8	–	0.855	W	10	13	0
	Air movement sensation	0 no, 1 a little, 2 moderate 3 strong	1.27	1.53	+0.26	–	0.013*	W	14	4	5
	Amount of subjects satisfied with air movement	(no unsatisfactory score during either of the 4 intervals)	13 out of 23	9 out of 23	–	−31%	0.344	M	3	7	13
	Air movement preference	1 less; 2 no change; 3 more	1.89	1.90	+0.01	–	0.865	W	7	10	6
	Air movement acceptance	0 clearly acceptable; 100 clearly acceptable	26.1	28.5	+2.4	–	0.465	W	13	9	1
	Air Quality sensation	1 very stuffy; 7 very fresh	3.64	3.82	+0.18	–	0.118	W	12	6	5
	Amount of subjects satisfied with Air Quality	(no unsatisfactory score during either of the 4 intervals)	11 out of 23	14 out of 23	–	+27%	0.375	M	4	1	18
	Air Quality acceptance	0 clearly acceptable; 100 clearly not acceptable	32.1	29.6	−1.5	–	0.523	W	13	10	0
SBS symptoms (during interval 4)	SBS Head	Headache	1 out of 23	3 out of 23	–	+200%	0.625	M	3	1	19
	SBS Nose	Nose blocked	0 out of 23	0 out of 23	–	+0%	1.000	M	0	0	23
	SBS Throat	Dry throat	3 out of 23	4 out of 23	–	+33%	1.000	M	4	3	16
	SBS Fatigue	Fatigued	5 out of 23	2 out of 23	–	−60%	0.250	M	0	3	20
	SBS Eyes	Irritated eyes	7 out of 23	2 out of 23	–	−71%	0.180	M	2	7	14
	Personal Symptom Index (5)	0 = no symptoms; 5 = all 5 symptoms	0.70	0.48	−0.22	−31%	0.260	W	4	9	10

[a] An asterisk(*) indicates a significant difference, with $p < 0.05$.
[b] W = Wilcoxon signed rank test, M = McNemar's chi-square test.

control situation). This was verified by continuous measurement of operative temperature, humidity and CO_2 concentration at 1-min intervals. The operative temperature was measured with a calibrated Vivo temperature sensor (20T32), humidity was evaluated with a calibrated Vivo humidity transducer (20T33) and CO_2 was measured with a calibrated HOBO data logger. The equipment was positioned in the middle of the experimental room at a height of about 600 mm. The subjects were not allowed to walk around during the experiments so this central location of the measurement devices was such that disturbance of the subjects (and their tasks) was avoided. The outcomes of the indoor climate measurements are presented in Table 3. The table shows that the differences between the background conditions during experimental sessions B and A are negligible (difference was not statistically significant).

Illumination levels were measured (horizontally) at the workstations and background sound pressure levels (mainly due to installation noise) were measured in the centre of the room. This was done with handheld equipment immediately before and after the two sessions. Illumination levels were measured with a Hagner digital EC 1 luxmeter and sound pressure levels with an Extech sound level meter. Also no statistically significant differences were found between the illumination and sound pressure levels of session A and B. Mean illumination level for session A was 272 lux (SD 84 lux); for session B this was 283 lux (SD 72 lux). Mean sound pressure level for session A was 45.7 dB(A) (SD 1.3 dB(A)); for session B this was 45.5 dB(A) (SD 0.9 dB(A)).

3.2. Perceived control

Perceived control was objectified by asking the subjects, during the last half hour of the two experimental sessions (interval 4), about the amount of control they perceived to have over different indoor environmental aspects (measured on a 7-point Likert scale, varying from 1 = no control at all to 7 = full control). Subjects also were asked to indicate (yes/no) whether they were satisfied with the amount of control that was provided to them.

Table 4 presents the perceived and exercised control related results for the two sessions and compares the within-subject outcomes. Significant differences (with $p < 0.05$) are marked with asterisks. Also the signed ranks scores are presented in Table 4. The scores describe how many subjects scored higher during session B than during A (see under ‘signed ranks/pos.’), how many scored lower during session B (see under ‘neg.’) and how many scored the same during both sessions (see under ‘ties’).

The table shows that perceived control over temperature, perceived control over air movement and perceived control over ventilation was significantly higher during session A than during session B (Wilcoxon signed-ranks test; $p = 0.001$, <0.001 and 0.012). Group average scores on the 7-point perceived control scale for these 3 indoor climate related aspects were 2.7 till 4.6 points lower during session B (the no-control situation).

This perceived control difference is also reflected in the amount of subjects that indicated to be satisfied with their control over temperature, air movement and ventilation. During session B the amount of subjects satisfied with these three control aspects decreased by 56% till 73%. The difference was statistically significant for all three indoor climate aspects (McNemar chi-square test; $p < 0.05$), see Table 4.

As expected, during session A perceived control over temperature, air movement and ventilation was significantly higher than perceived control over lighting and noise. During session B perceived control scores for all 5 aspects were at the very low end of the 7-point scale (1.0 or close to 1.0).

For perceived control over lighting and noise no statistically significant differences were found between the two sessions.

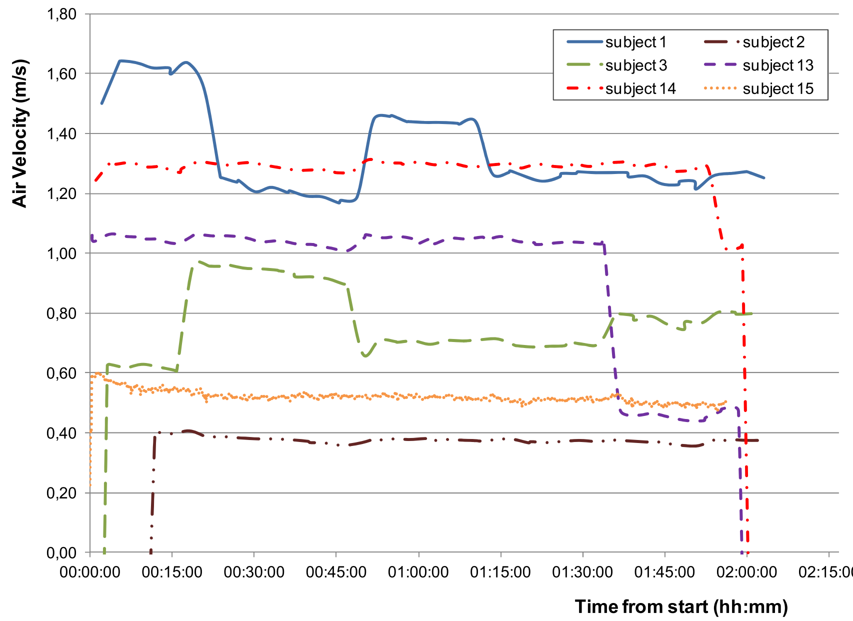

Fig. 7. Air velocity profiles during session A of the 6 subjects from the Tuesday group.

The conclusion concerning perceived control was that, as expected, indoor climate related scores were higher (better) during session A.

3.3. Exercised control

Fig. 7 as an example, presents the air velocity profiles as chosen during Session A by the six subjects in the 'Tuesday group'. The graph shows that there were large individual differences in fan operation: one subject (s15) choose one setting at the start and then kept it that way during the whole experiment. Others (e.g. s1 and s3) readjusted their fans several times during the experiment.

The maximum air velocity value of the Tuesday group was slightly higher than 1.6 m/s, the minimum value 0 m/s. The interpersonal differences within the other 3 groups were comparable with those of the Tuesday group. The time-weighted mean value for the air velocity as selected by all 23 subjects was 0.76 m/s; the mean minimum air velocity was 0.51 m/s and the mean maximum air velocity was 0.97 m/s. On average, subjects made close to 2 adjustments in total during the 120 min lasting core session (apart from the fine-tuning of the fan at the start). The individual frequency varied between 0 and 4 adjustments.

Whenever subjects made adjustments to the air velocity at their workstation, they described why they choose to make an adjustment. The main reasons for increasing the air velocity during session A were: 'the environment being too warm' or 'the air being too stuffy'. The main reason for decreasing the air velocity was: 'the air being too irritating to eyes and/or throat'.

As far as exercised control is concerned the conclusion was that there were large individual differences in fan use and preferred local air velocities.

3.4. Comfort & SBS symptoms

Table 5 presents the comfort and Sick Building Syndrome (SBS) symptom related responses as determined during the two experimental sessions. It also describes the differences between the results of session B and session A. Statistically significant differences are marked with asterisks.

The comfort scores presented in Table 5 are based on individual scores averaged over all four experimental intervals (see Table 2). For the building related (SBS) symptoms only responses recorded during the last interval (no. 4) were used in the analyses. We made this exception as SBS symptoms are expected to develop over time during an experiment. Based on the individual scores (yes/no) for the incidence of the SBS symptoms (headache, nose symptoms, dry throat, irritated eyes and fatigue) we also calculated the Personal Symptom Index (PSI, 5) of each subject. This is a number between 0 and 5 that communicates how many of the 5 standard SBS symptoms a subject had.

Neither comfort nor SBS symptom scores differed significantly between session A and B. For example, the averaged thermal sensation during session A was +0.52 on the 7-point ASHRAE scale while the thermal sensation during session B was slightly (but not significantly) lower at +0.42. As a reference: 0 on the ASHRAE scale refers to a 'neutral' thermal sensation and +1 refers to a 'slightly warm' sensation. The number of persons that were satisfied with their thermal environment was higher during session B, but again the difference was not statistically significant (McNemar chi-square test; $p = 0.298$). At the same time the number of persons satisfied with the air movement was higher during session A, but again the difference was not significant (McNemar chi-square test; $p = 0.344$). The only significant difference that we found was the one between air movement sensation during session B and A (Wilcoxon signed-ranks test; $p = 0.013$). During session B more subjects indicated to feel a moderate or strong amount of air movement.

SBS symptom incidence was comparable at the end of session A and B, see the lower part of Table 4. Slightly more subjects had headache and a dry throat at the end of session B; but at the same time more subjects had irritated eyes or were fatigued at the end of session A. For none of the SBS symptoms the difference was statistically significant. The Personal Symptom Index (PSI, 5) was slightly higher at the end of session A (0.70 vs. 0.48) but again the difference was not significant (Wilcoxon signed-ranks test; $p = 0.260$).

The conclusion concerning comfort aspects and the incidence of SBS symptoms was that there were no real differences between the no-control situation of session B and the with-control situation of session A.

Table 6
Performance related outcomes and their paired comparison correlations; significant differences are marked with an asterisk.

	Variable	Legend	Session A (with-control)	Session B (no-control)	Difference (B-A)		Significant? ($p < 0.05$)	p-value[a]	Stat. Test used[b]	Signed-ranks		
			Mean	Mean	Abs. (B−A)	% (B−A)/A				Pos.	Neg.	Ties
Performance	Self-assessed Performance	1 = −30%; 4 = 0%; 7 = +30%	3.78	4.20	+0.42	–	Yes	0.034*	W	12	5	6
	Ditto, recalculated into % outcomes	percentage between −30% and +30%	−2.2%	+2.0%	+4.2%	–	–	–	–		–	–
	Additions correct p/min	–	2.24	2.47	+0.23	+10.4%	Yes	0.012*	W	16	7	0
	Multiplications correct p/min	–	4.12	4.46	+0.34	+8.2%	Yes	0.010*	W	18	5	0
	Errors Text typing total no.	–	25.1	23.1	–	–	No	0.677	W	10	11	2
	Characters p/min	–	158.8	167.3	+8.51	+5.4%	Yes	0.006*	W	17	5	1
	Tsai P correct total no.	–	29.2	29.0	–	–	No	0.672	W	10	12	1

[a] An asterisk(*) indicates a significant difference, with $p < 0.05$.
[b] W = Wilcoxon signed rank test, M = McNemar's chi-square test.

3.5. Task performance

The task performance results are presented in Table 6. Again, statistically significant differences are marked with asterisks. The performance scores that are presented in Table 6 are based on individual scores averaged over the test results from all 4 intervals (see Table 2). Some tests were only conducted during 2 or 3 of the 4 intervals (e.g. multiplication only during interval 2 and 3); in those cases the averaged values of only those (2 or 3) intervals were used.

Self-assessed performance during session B was significantly higher than during session A (Wilcoxon signed-ranks test; $p = 0.034$). On the applied 7-point scale that went from 1 = −30% to 7 = +30%, self-estimated performance increased by 4.2%-points from session A to B.

Objectively measured performance was significantly higher during session B for the addition and the multiplication tests (Wilcoxon signed-ranks test; $p = 0.012$ and 0.010). Session B resulted in a performance increase of 10.4% and 8.2% for the two mathematical tests.

Also the rate of characters typed during the text typing test was higher during session B (Wilcoxon signed-ranks test; $p = 0.006$). The increase was +5.4% compared to session A. No statistically significant differences were found for the number of errors made during text typing or for the Tsai Parrington numbers test results.

The conclusion was that both self-assessed and objectively measured performance were significantly higher in the no-control situation of session B. Averaged out over the 5 types of performance indicators (assuming 0% effect for text typing errors and the Tsai Parrington numbers test) the outcomes translate into an average overall performance effect of +4.8%.

3.6. Other results

At the end of session B, all subjects were asked to guess what the overall experiment was about. This was done to doublecheck whether the research team managed to obscure the study's core characteristics from the subjects. The majority of the subjects, 18 in total, thought it was about how indoor climate and air velocity influence productivity in office environments. One subject thought it was about the impact of fans and fan use on thermal perception. Another subject thought it was about general control over air movement and perhaps temperature. Only two subjects rightly guessed the overall purpose (in the words of one of them: 'finding out whether the ability to control one's environment would improve performance and other outcomes'). So overall the experiment can be regarded as a single blind study.

One week after the experiments, the following question was asked by email to all subjects:

'Which of the two situations would you prefer at your own workplace or study place?'. Subjects could choose from: 1) a situation like during session A, and 2) a situation like during session B, and 3) no preference. A total of 20 out of 23 subjects answered this question: 12 preferred the with-control situation, 7 the no-control situation and 1 had no preference. So slightly less than two-thirds of the subjects preferred a session A type situation (with control) at their work place or study place.

Subjects that choose a session A type situation as their favorite had several reasons for this: 'I like to be able to adjust the air velocity myself', or 'I prefer to have control over the situation and to be able to adjust the indoor climate according to my momentary feelings and needs'. One person explicitly mentioned that it is not just about using controls: 'Although I did not use the fan much, it is always good to know you are in control of something regarding the environment.' The seven subjects that preferred a session B type situation explained this as follows: 'I just felt more comfortable during the 2nd session' or: 'The no-control situation somehow was more appropriate as the wind flow was more satisfactory'. Two of the seven subjects referred to assumed performance effects: 'I was more focused on my work during session B while not being in control', 'I felt better and more concentrated on my work when the fan was in automatic mode'.

4. Discussion

No significant differences were found between the comfort scores and SBS symptom incidences of session A and B. On the other hand, contrary to expectations, self-assessed performance was significantly higher (+4.2%) during session B. Also, 3 of the 5 objective performance tests showed significantly better performance during session B: +10.4% for the addition test, +8.2% for the multiplication test and +5.4% for the text typing test (amount of characters typed per minute).

At first sight, these task performance findings are not congruent with those of others. For example Wyon (2000) [32] and Kroner (2000) [19] concluded that the provision of control leads to a substantial *increase* in task performance, not a decrease as implied by the present study. See also the Introduction. One important methodological difference however between the present study and those of Wyon and Kroner is the no-control reference situation. During this study, when subjects did not have control, the 'automated' climate they were exposed to was customized and adapted to individual requirements (based on the session A results). While in the two earlier studies the no-control reference situation consisted of a group average optimum climate.

One possible explanation for the unexpected performance findings might lie in learning effects. The basic idea then is that

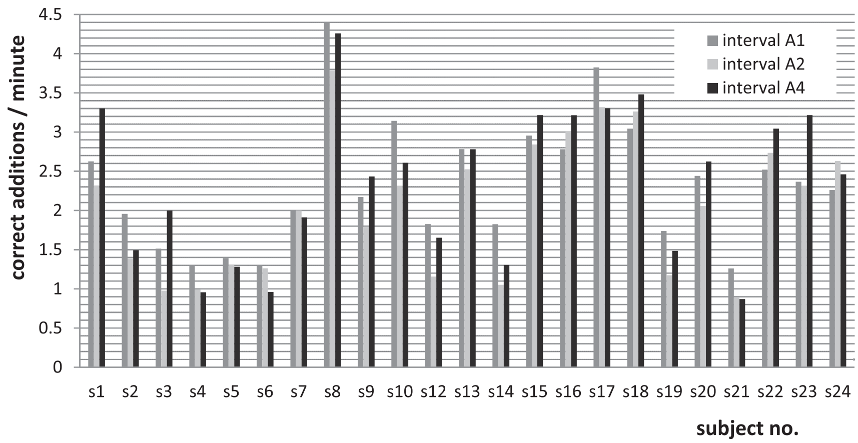

Fig. 8. Individual outcomes for the addition test during session A; the figure illustrates that there is no within-session learning effect for the addition test during session A.

subjects over time become more efficient at conducting the addition, multiplication and text typing tests. If this assumption holds then one would expect to see a learning curve not just when comparing the average session B results with the session A results but also over the course of the two sessions themselves. Such a within-session learning effect however is not really supported by the data. Fig. 8 as an example presents the individual addition test outcomes as gathered during session A. For 9 of the 23 subjects the addition score during the last interval was highest; while for 10 of the 23 the first score was highest. For the other 4 subjects the score during the middle interval was highest or there was no difference between the first interval and last interval score. This implies that there was no learning effect for the addition test during session A. Had there been a clear learning effect then for the large majority of the subjects the last interval score should have been higher than the first interval score, especially during the first session (A). Note that only interval 1, 2 and 4 included an addition test, which explains why no values are presented in Fig. 8 for interval A3. Duration for the 3 addition test episodes were respectively 12, 10 and 12 minutes for A1, A2 and A4.

During session B, the addition test outcomes also did not implicate a within-session learning effect. The same is true — for both session A and B — for the multiplication test results. Only for the text writing test we found a slight learning curve specifically for the amount of characters produced per minute. During session A 13 of the 23 subjects had their highest text writing score during the last interval; while only 8 subjects scored highest during their first interval. Overall, the reanalysis of the within-session test results did not support the hypothesis that the unexpected performance differences between session B and A can be explained by learning effects.

In this context it is important to mention that measures were taken right at the start of the experiments to avoid disturbances due to learning effects. Subjects had to take part in an obligatory training (pilot) session a week before the actual experiments started (see under 'Methods', par. 2.5). Amongst other things this enabled them to get acquainted with the performance test beforehand.

A second and more likely explanation for the unexpected performance results might be found within the cognitive load theory as described by Paas, Renkel & Sweller (2004) [22]. This theory contends that during complex activities the amount of information and interactions that can be processed in the human brain is finite. During session A subjects had control over their thermal environment and were free to adjust their fans at any time. Possibly this situation occupied part of the working memory of their brains thus slightly limiting the brain capacity left over for the performance tasks. More research, in cooperation with environmental psychologists or other social scientists, is needed to test this second, cognitive load explanation further.

The unexpected performance findings of this study are in line with the conclusions of Veitch & Gifford (1996) [29]. These researchers studied the effect of decisional control over lighting in a laboratory environment. They came to the conclusion that subjects that had been given choice over lighting performed more poorly and more slowly than subjects that had not been given choice. Interesting detail here is that Veitch & Gifford especially found significant ($p<0.05$) performance effects with tests that involved creativity. Subjects that were not given control over their lighting situation needed 15% less time (per idea) to come up with novel uses of common objects in comparison with subjects that did have control over their lighting situation.

In this context, Wineman (1982) [31] has argued that in some circumstances the provision of control may contribute to unwanted performance effects especially when controls offer end-users choices that they do not want.

Then, as far as practical implications are concerned:

Some might interpret the present performance results as if generally, when (re)designing buildings and their building service systems, it is better *not* to design for occupant control options and to avoid adjustable thermostats, fans and/or personal climatization systems all together. We would like to warn against such a misinterpretation of the study's outcomes. More research is needed that takes aspects like expectations, user behavior and robustness into account (see e.g. Fountain et al., 1996 [12]; Haldi and Robinson, 2008 [13]; Karjalainen & Koistinen, 2007 [18] and Leyten et al., 2014 [21]) before final conclusions can be drawn related to customized personal control and productivity effects. But the preliminary interpretation of the present study's outcomes is that occupants might be more productive when *not* in control over their thermal environment only *under the condition that an 'automatic system' manages to tune in exactly with individual preferences and differences*. Which is something, by the way, that no building management system in real world settings is capable of yet, especially not at workstation level. With as the possible only exception the 'human in the loop' system as developed by Zeiler et al. (2014) [33] that for now is still in the prototype stage. This involves remote, infrared skin temperature registrations that allow for sensor-automated but customized provision of thermal comfort at the workstation level.

The study has a few limitations that one should take into account when further interpreting the results:

- All subjects first were exposed to the with-control-situation (session A) and after that to the no-control-situation (session B). Methodologically seen it would have been better to randomize the subjects over two different start-conditions and to expose half of the subjects first to the with-control situation and the other half first to the no-control situation. Unfortunately this was not possible as it was necessary to know the individual air velocity profiles (as generated during session A) to create the no-control-situation (the exposure during session B). In the week that the session B experiments were performed the morning outdoor temperature was about 3.5 °C higher than during the session A week. Ideally experiments should have been conducted under identical outdoor climate conditions to exclude the impact of weather adaptation (see e.g. de Dear, Brager & Cooper, 1997 [7]). The data analysis showed no statistically significant difference between comfort perceptions during session A and B, which implies that this 3.5 °C difference in fact had little effect.
- A combination of math, text and creativity tests was used during the experiments to evaluate how indoor climate and having or not having control affects task performance. Real office work involves a complexity of tasks that cannot all be simulated easily during a laboratory experiment (see also Wyon, 2000 [32]). So the performance results presented in this paper should be interpreted with care when used to estimate how performance in real world settings is affected.
- During both session A and B subjects' exposure only lasted about 2.5 h. While in normal office buildings office workers spend 8 h a day, 5 days a week in their work environment. Needless to say that some of the effects that were measured during the present experiment, for example the incidence of SBS symptoms, are more likely to arise when people are exposed (much) longer than 2.5 h. Also performance results might differ when people are exposed 8 in stead of 2.5 h. Tanabe, Nishihara & Haneda (2007) [27] showed that fatigue affects task performance especially during relative long exposure periods. On the other hand: beneficial effects of decisional control over the thermal environment (as provided during session A of the experiment) on comfort and overall wellbeing probably accrue over time (Veitch & Gifford, 1996) [29].

5. Conclusions

The objective of the study was to investigate how having or not having control over one's thermal environment (under warm summer conditions) affects end-user responses. As expected perceived control over temperature, air movement and ventilation was significantly higher during session A (the with-control situation). Comfort scores during session A and B were similar (with an exception for air movement sensation and satisfaction). Also the incidence of SBS symptoms did not differ significantly between the two sessions.

Contrary to expectations, self-assessed performance was significantly higher (4.2%) during session B (the no-control situation). Also 3 of the 5 objective performance tests showed significantly higher performance during session B. The average performance improvement for the 5 combined tests parameters was 4.8%. Learning effect might explain the difference. However, a more likely explanation is that of some cognitive over-load when subjects had control over their thermal environment and at the same time were involved in performance tasks.

The study revealed large interpersonal differences in terms of preferred air velocities. There were also substantial differences in fan use frequency. Subjects furthermore differed when it comes to preferences for automatic vs. manual climate control: about two-thirds of the subjects preferred a session A type situation (with manual control) over a situation B type situation (with 'automatic control').

More research is needed, preferably in close cooperation with environmental psychologists, before the present study outcomes can be translated into concrete implications for real live work environments and future building service system solutions.

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