Atze Boerstra promotion was at the Eindhoven University of Technology as first promotor Prof.dr.ir Jan Hensen chaired by Prof. ir. Elphi Nelissen of the Eindhoven University of Technology and as second promotor Prof. Bjarne Olesen of the Danish Technical University, Lyngby/Copenhagen and co-promotor dr.ir. Marcel Loomans.

Summary of the PhD Thesis of Atze Boerstra

Atze Boerstra, Vice President of REHVA, defended on September 8th 2016 with great success his thesis "Personal Control over Indoor Climate, Impact on Comfort, Health and Productivity".

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How does having or not having control over one's indoor climate affect office workers? It was this question that triggered Atze's PhD study. The central aim of the study was to investigate the mechanisms behind availability and (objective and perceived) quality of indoor climate control devices, and to explore the impact of control on comfort, health and performance of office building users. A first result of the study, was a conceptual model that describes the core variables at hand and their interrelationships. The central assumption that underlies the model is that human responses to sensory stimuli are modified when those exposed have control over these stimuli. This implies that it is not just the objectively measured indoor climate that affects whether people feel warm or cold, or experience olfactory discomfort. Instead the idea is that personal control (availability of adaptive opportunities) also has an impact and in fact acts as a moderator.

Background

Office workers often have no or limited possibilities at their workplace to control their indoor climate. They nowadays frequently are exposed to environments deprived of operable windows, adjustable thermostats and other opportunities to fine-tune their local air quality and personal thermal environment according to momentary needs. When office buildings are (re) designed personal control over indoor climate and adjustability of facades and HVAC systems are apparently not always high on the agenda. This probably is due to a lack of knowledge in terms of personal control related mechanisms amongst relevant decision makers (principals, architects, consultants etc.) and amongst building scientists in general.

Study objectives

How does having or not having control over one's indoor climate affect the average office worker? What is the impact of perceived and exercised control on general satisfaction with the work environment and, for example, thermal and olfactory comfort? To what extent can the incidence of building related (sick building) symptoms be influenced by introduction of optimal control options? And how is individual task perfor-

mance affected by adjustable and responsive heating, cooling and ventilation systems? It was these kind of questions that triggered the PhD study presented in this thesis.

The primary aim of the study was to investigate the mechanisms behind availability and (objective and perceived) quality of indoor climate control devices and the impact of control on comfort, health and task performance of office building users.

The core research objectives were as follows:

1. to examine relationships between availability and quality of HVAC/building related control devices in office buildings and perceived control over the indoor climate;
2. to examine relationships between perceived control over the indoor climate and comfort and satisfaction of office workers;
3. to examine relationships between perceived control over the indoor climate and health of building occupants, specifically the incidence of building related symptoms (SBS);
4. to examine relationships between perceived control over the indoor climate and (self-assessed and objectively measured) performance and (self-assessed) sick leave of office workers.

An additional objective was to compile an inventory of available, exercised and perceived indoor climate control in modern Dutch office buildings.

Conceptual model

A first result of this study was a conceptual model that describes the core variables at hand and their interrelationships (see **Figure 1**). The core assumption is that it is not just the objectively measurable indoor climate that affects whether people feel warm or cold, or are dissatisfied with indoor air quality. Instead the central idea is that personal control (availability of adaptive opportunities) also has an impact and in fact acts as an interactive variable. Human responses to sensory stimuli like elevated temperatures or suboptimal indoor air are assumed to be modified when those exposed have control over these stimuli.

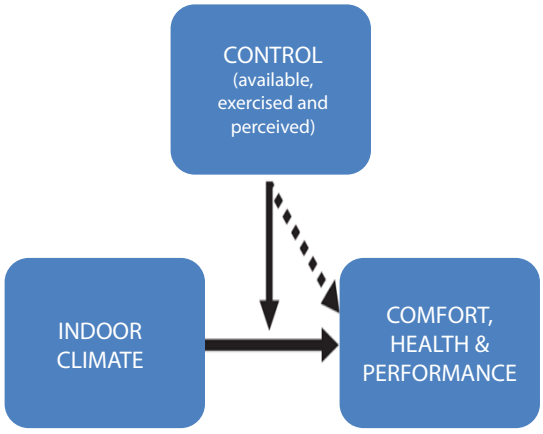

Figure 1. Variables & relations studied

This model was constructed after an analysis of existing related models as found in the literature. Specifically models that acknowledge man-environment interactions, occupant behaviour and adaptation were evaluated.

Methodology

The conceptual model was further explored through:

- a (re)analysis of a historical database;
- a field study in 9 Dutch office buildings, and:
- a laboratory-intervention study (conducted in cooperation with the Danish Technical University).

The database research step involved analysing data from 1612 occupants working in 21 Dutch office buildings (BBA database). This database was selected as it contained information on building characteristics, questionnaire data related to available and perceived control, comfort perceptions and SBS symptom incidence. The data were explored using a multilevel modelling strategy with occupants nested within buildings. In four separate models it was tested whether personal control scores were related to comfort, symptom incidence, productivity and sick leave scores (the 4 outcome parameters studied).

The database analyses outcomes were used to design a field study. The field study was performed during the winter of 2011/2012 in 9 modern Dutch office buildings and involved inspection of relevant building and building service system characteristics (including presence of operable windows, adjustable thermostats and other controls) and indoor climate measurements. In these 9 buildings, a total of 236 office workers agreed to participate in a questionnaire and a subgroup of 161 were also interviewed. The questionnaire contained general questions related to respondents' thermal and olfactory comfort and also asked about building related symptoms, comfort perceptions, self-assessed productivity and self-reported sick leave. Furthermore, people were asked about perceived control and control use (exercised control). The indoor climate measurements included thermostat effectiveness measurements with

control adjustments done by the research team, that helped to objectify how 'fast' the available temperature controls are during the heating season. First, standard tests were used to explore relations between available, exercised and perceived control. Next the field study data were analysed using a multilevel strategy to find out what building, installation and organizational factors determine perceived control over one indoor climate.

Multilevel analysis techniques too were used to investigate correlations between combined perceived control over temperature and ventilation on the one hand and comfort-, satisfaction-, building symptom and productivity-indices on the other hand. Next a laboratory study was conducted to further investigate how having or not having control, specifically over the thermal environment, affects human responses to the indoor environment. This study was conducted during summer in a field laboratory that was kept at a constant temperature of 28°C. During the first session of 2.5 hours (A) subjects were able to fine-tune their local thermal environment at any given time with a personal desk fan with continuous, 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 researchers who adjusted the individual air velocity 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 task performance.

Database & field study results

The database analysis revealed a significant association between personal control (an aggregated 5-point control index) and 4 outcome parameters (in all cases with a p-value of 0.001 or lower). Higher control scores were systematically associated with higher comfort scores, lower symptom incidence, higher productivity scores and lower sick leave effects. The results imply that when building occupants are provided with effective operable windows and effective adjustable thermostats, they generally will be more comfortable and more productive (at least according to their own estimations). They will also experience less sick building symptoms and will report in sick less often due to an inadequate indoor climate.

The field study results implied that just about 1 out of 3 Dutch office workers are satisfied with the amount of indoor climate control at their workplace. Mean score for perceived control over temperature in winter, over temperature in summer and over ventilation (in general) was around 3 on a 7-point scale (with 1 = no control at all, 7 = full control). The scores were considerably lower than those for perceived control over sun penetration and perceived control over light. The number of colleagues one shares the workplace with has a considerable effect: more officemates means a lower level of perceived control over one's indoor climate. Also men and those with workstations further away from the facade have a significantly lower level of perceived control.

The majority of the Dutch respondents turned out to have access to both an adjustable thermostat and an operable window. And more than 80% of the respondents indicated not to take energy use effects into account when using their controls. As far as exercised control is concerned, according to the office workers themselves, the use of adjustable thermostats is less frequent than that of operable windows, especially in winter. Also, winter adaptation by clothing adjustment turned out to be more popular than thermostat use. Frequency of use of controls showed to be linked to perceived control over indoor climate. For example, those respondents that used their adjustable thermostats less frequently than monthly, or never, score significantly lower on perceived control over temperature in winter than those that used them monthly, or more often.

The results of the thermostat effectiveness measurements in the 9 buildings allowed for a quantitative estimation of available control over temperature during the heating season. The different buildings and their heating systems showed large variation in thermostat effectiveness. Measured average of speed' differed between buildings from +0.2 to +2.5 K/h for upward interventions. Upward adjustments of thermostats in winter were found to be more effective than downward adjustments in winter. A strong correlation was found between measured thermostat speed in heating mode and average thermostat speed as perceived by the occupants during winter.

The field study analysis revealed that access to operable windows and not experiencing organisational bans on use of controls (use of thermostats, operable windows etc.) are two factors that have a positive and significant effect on perceived control over the indoor climate. Further analysis of the field study data showed positive and significant associations between perceived control and comfort perception, overall satisfaction with the indoor climate and self-assessed productivity (in all 3 cases with p-values of 0.001 or lower). No correlation was found between perceived control and the incidence

of building related symptoms. The field study results imply that perceived control over indoor climate in office buildings can be elevated by providing access to operable windows and by not banning building occupants from control use. The results furthermore imply that buildings that are designed for a high amount of perceived control over the indoor climate will have more comfortable and more satisfied occupants. They furthermore will have occupants that estimate themselves to be more productive.

Lab study results

Then, as far as the laboratory study is concerned: perceived control over temperature, air velocity, ventilation etc. was significantly higher during session A (the with-control situation), but there were no differences in perceived comfort and SBS symptom intensity. About two-thirds of the subjects indicated a preference for the situation as during the first session when they themselves controlled the air movement. Surprisingly, self-assessed performance during session B (the no-control situation) was significantly higher than during session A. 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. Also objectively measured performance was significantly higher during session B, specifically for number addition and multiplication tests (performance differences were respectively 10.4%-point and 8.2%-point). A further analysis indicated that this task performance effect probably can be explained with the cognitive load theory. This theory assumes that the working memory of the human brain has limited capacity and can be overloaded when involved in too many (complex) tasks.

Conclusions

The combined outcomes of the database analysis, the field study and the laboratory study support the hypothesis that control (having or not having control) over one indoor climate alters one's reactions to that indoor climate. The mechanism involved was not totally explained but, overall, the combined studies imply that investing in effective and usable indoor climate controls will enhance perceived control over the indoor climate. Enhanced perceived control also improves office workers' satisfaction with their thermal environment and the indoor air quality at their workplace. It also increases overall comfort perceptions. The results related to the productivity effects (both self-assessed and objectively measured productivity effects) were rather inconclusive. Also the results in relation to the incidence of building related (SBS) symptoms were somewhat inconclusive.

As modern office buildings become more and more open plan offices of the future, where workers may not have a fixed designated work station, in many instances, will ask for more than just standard controls like operable windows and adjustable thermostats. Recent developments in the form of personal ventilation systems and local climate control systems integrated in office furniture seem to open up promising alternative routes towards better adjustable indoor climates in offices.

This PhD study revealed that personal control over indoor climate is a complex phenomenon that involves many aspects. The conceptual model was partly validated but some mechanism-related questions remain unanswered. To better understand how office workers use controls and to understand how building occupants' perceptions about their indoor climate are influenced by the presence and use of these controls, it is necessary to look beyond the traditional borders of building science and indoor climate research. Further research is needed in close cooperation with environmental psychologists and other social scientists to explore in more detail how control over one's indoor climate affects comfort, health and task performance. ■