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**Control Strategies for Lighting and Ventilation in Offices:
Effects on Energy and Occupants**

Research Article

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ABSTRACT

Participants (N=126) spent a day in a full-scale office laboratory, completing questionnaires and standard office tasks. Some participants experienced typical constant lighting and ventilation conditions, whereas others were given personal control over the dimming of lighting in their workstation and over the flow rate of air from a ceiling-based nozzle in their workstations. Half of the participants, some with personal control and some without, were exposed to environmental changes typical of demand-response load shedding in the afternoon: Workstation illuminance was reduced by 2%/min, and ambient air temperature increased by ~1.5 °C over a 2.5 hour period. Results showed that personal environmental control improved environmental satisfaction. Personal control over lighting led to an average energy reduction of around 10% compared to a typical fixed system; participants with personal control also reduced flow rate compared to the constant condition. Use of each control type averaged 2 – 3 control actions per person per day, which dropped to less than one control action per person per day in a longer-term pilot study (N=5) conducted in the same space. Load shedding had some small negative effects for occupants, but in practice is unlikely to create substantial hardships, and is a reasonable response to peak power emergencies.

Keywords: lighting, ventilation, personal control, load shedding, demand response, comfort, satisfaction, organizational productivity, offices

Introduction

Individual control over environmental conditions offers occupants the possibility to obtain their preferred physical conditions, which may differ substantially from the average recommended conditions expressed in standards. Satisfying individual preferences may have important benefits, for example, creating a state of positive affect (mood) in individuals that can lead to improved environmental satisfaction and work performance [Baron & Thomley, 1994], and increased likelihood of prosocial behaviours [Isen & Baron, 1991].

Surveys consistently indicate that building occupants both desire more control and believe that such control is linked to better health and performance. A survey of office workers [Steelcase, 1999] showed that three out of four people wanted more control over their lighting, and a large majority of workers believed that improved lighting would improve their mood and efficiency. Similarly, questionnaire data from European office buildings revealed that the more control of their environment people perceive they have, the more productive they think they are [Bordass et al., 1993], and that higher perceived control is associated with better comfort and reduced symptom reports [Roulet et al., 2006].

Anecdotally, some facility managers are concerned that environmental control in the hands of office occupants, who are not responsible for utility bills, will lead to increased energy use and higher costs. In fact, laboratory [e.g. Newsham et al., 2004] and field studies [e.g. Moore et al., 2002] suggest the opposite.

We will expand on each of these points in the following literature review of personal control of lighting and ventilation.

Personal Control of Lighting

Veitch and Newsham [2000] conducted an experiment in an open-plan office laboratory in Canada. Participants had dimming control over three ambient lighting circuits, and on-off control over a task light. Forty-seven matched pairs of people participated, occupying the space for a day and completing various simulated office tasks and questionnaires. One of the pair got control of the lighting at the start of the day, with the other participant receiving the same lighting; no further control was permitted. At the end of the day the second participant used the dimmers to express their own preferred lighting conditions. Individual preferred light levels varied widely (mean desktop illuminance, $E_{\text{desk}} = 423$ lx, s.d. 152 lx, min. 83 lx, max 725 lx), but on average choices used 10-15% less power than that recommended by prevailing energy codes [Canadian Codes Centre, 1997]. Newsham and Veitch [2001] performed further post-hoc analyses on the data from participants who made their preferred lighting choice at the end of the day. Participants whose daytime light levels were closest to their own preference had significantly better ratings of mood (pleasure), lighting satisfaction, and environmental satisfaction during the day.

Newsham et al. [2004] conducted a further study in a smaller open-plan office laboratory. One hundred-and-eighteen participants worked for a day under one of four lighting designs. They had no control over the lighting until the latter half of the afternoon, when all participants were offered some form of individual dimming control. During the working day participants performed simulated office tasks and completed questionnaires related to satisfaction and well-being. After lighting control was offered there were significant improvements in mood, room appraisal, lighting satisfaction, glare dissatisfaction, environmental satisfaction, satisfaction with performance, self-assessed productivity, and visual discomfort. Further, participants who made the biggest changes to lighting conditions after they were given control tended to register the biggest improvements. Again, lighting level choices varied considerably between individuals.

Boyce et al. [2000] conducted a study in an office laboratory in the northeastern USA, featuring individual offices with three lighting designs including a typical fixed system of ceiling-recessed parabolic fixtures delivering $E_{\text{desk}} = 490$ lx; identical dimmable fixtures with maximum $E_{\text{desk}} = 680$ lx; and a larger number of fixtures with maximum $E_{\text{desk}} = 1240$ lx. For the lower output dimmable system, the mean chosen illuminance was about 10% lower than for the fixed system, translating into energy savings. Individual preferences for light level varied over a wide range (means <100 lx to >600 lx). Offices with control had higher ratings of lighting quality and comfort, and tasks were rated as less difficult.

In one of a pair of field simulation experiments, Boyce et al. [2006a,b] exposed over 180 people to one of four different lighting conditions for a day in an open-plan office in the northeastern USA. Two of the four conditions had some form of manual control. In one condition (N=33), occupants had three-level switching control over a desk lamp, while ambient lighting from direct/indirect luminaires was fixed. In another condition (N=56), occupants had dimming control over the down portion of a direct/indirect luminaire suspended over the middle of their workstation. For those with dimming control there was a wide difference in illuminance choice between individuals, and the mean E_{desk} was lower than recommended practice, with concomitant energy savings (mean $E_{\text{desk}} = 435$ lx, s.d. 171 lx, min. 243 lx, max 1075 lx). Lighting systems that featured individual control were rated as comfortable by ~90% of participants, compared to ~70% of those without control. In addition, people with dimming

control showed more sustained motivation over the workday, and improved performance on a measure of attention.

The results of these controlled studies have been replicated in the field. Maniccia et al. [1999] collected data from 58 individual offices in a building in Colorado, each with dimming control over recessed parabolic luminaires. Lighting energy savings between 7 and 23% were attributed to the manual lighting controls.

Jennings et al. [2000] focused on the perimeter offices of a large office building in San Francisco. Manual control over recessed parabolic luminaires was available in two forms: bi-level switching of a 3-lamp fixture (N=30), or continuous dimming (N=7). Lighting energy savings of 23% and 9% were attributed to the two manual control options, respectively.

Moore et al. [2002] studied the use of individual lighting controls in 14 UK office buildings with recessed parabolic luminaires, three of which offered dimming control at the individual level. Data showed that mean chosen illuminance in winter, without daylight, was below 500 lx in all 3 buildings. The mean power use of the lighting systems was ~50-60% of the maximum available.

A study in French office buildings with manual controls [Escuyer & Fontoynt, 2001] revealed similar findings. Preferences for light levels varied (E_{desk} 20 to 580 lx across 33 occupants in three buildings), individuals often chose light levels according to tasks or daylight availability, and manual dimming was reported as being a desirable control feature.

Personal Control of Ventilation

Grivel and Candas [1991] studied the thermal preferences of sedentary young adults (N=48) in a climate chamber in France. Measurements showed a wide range of chosen temperatures across individuals (mean air temperature, $T_{\text{air}} = 26.6^{\circ}\text{C}$, s.d. 2.6°C , min. 19.7°C , max 32.1°C). This suggests that the provision of personal control of a ventilation system permitting manipulation of local temperature and air velocity would be likely to improve individual thermal comfort.

Akimoto et al. [1996] conducted a pilot study in a California office that featured eight cubicle workstations with desktop-mounted supply air units. Each desktop held two supply units, each capable of delivering $20\text{-}70\text{ l s}^{-1}$ of air at approximately 18°C . The supply units were part of a larger Personal Environment System (PES) that included a dimmable task light, masking noise generator, and foot-level radiant panel. In tests where the average room temperature was high ($26\text{-}27.5^{\circ}\text{C}$) the desktop supply units were able to maintain the local air temperature $1\text{-}2^{\circ}\text{C}$ below ambient, whereas a traditional ceiling-based diffuser system achieved only 1°C below ambient. Occupants also had higher levels of comfort with the local supply system, although there were wide differences between individuals in the fan speeds chosen. An earlier study in the same office [Bauman et al., 1993] demonstrated that neighbouring offices with very different heat loads could achieve similar calculated thermal comfort conditions by modifying the local air flow rate.

Bauman et al. [1998] conducted a field study on the implementation of a desktop PES in a financial institution in San Francisco. Pre-post data (March and July) were gathered from a group who received the system [N=28], and from a control group [N=25]. Change scores in occupant satisfaction were analyzed, and there were significant improvements in thermal quality for the group receiving the PES. Occupants with the PES system were better able to maintain

comfortable conditions over a wider range of temperatures. There were wide differences between individuals in their choices of settings of the various controls.

Kaczmarczyk et al. [2004] studied five alternative desktop-based personal ventilation systems in an office laboratory with no panels between workstations. Participants (N=30, in Denmark) were able to control the direction and flow rate (up to 15 ls^{-1}) for each system, which supplied 100% outdoor air at 20 °C. Participants were able to maintain thermal neutrality in general room air temperatures up to 26 °C, though there was a wide variety in flow rates chosen between individuals. However, the exposure time to each system was only 25 minutes.

Kaczmarczyk et al. [2002] assessed the effect of a personally-controlled flexible arm system delivering air to the breathing zone. Compared to a conventional system delivering the same amount of outdoor air, or a personal system delivering recirculated air, participants (N=30, in Denmark) experiencing the personal system delivering 100% outdoor air perceived better quality air and reported fewer sick building syndrome (SBS) symptoms. Participants in the latter conditions rated their own task performance higher, but there was no effect on objective measured performance. Hayashi et al. [2003] and Kroner et al. [1994] reported performance improvements of the order of 2% through the use of PES, in a laboratory study and a field study respectively. However, in neither study were appropriate statistics used to demonstrate the significance of these effects.

Local control can also be provided by floor-based (FB) systems, which draw air from a raised-floor plenum; individual control of air flow direction and rate is offered. Hedge et al. [1993] studied installations in six buildings in the USA, collecting data from the facility managers of all buildings, and office workers in three of the buildings (N=151). Two-thirds of occupants said the FB system provided more satisfactory thermal and ventilation conditions compared to traditional ventilation systems they had experienced. This was despite the fact that a third of workers reported never adjusting the controls, and fewer than 10% reported making daily adjustments. All facility managers reported a reduction in complaints associated with thermal comfort and air quality.

Bauman et al. [1994] conducted a field study of FB systems in an open-plan office in Arizona. In general, occupants (N=79) reported feeling too cold, and more than 75% of the fans in the FB systems had been switched off. As a consequence, the use of the controls was limited, with 80% adjusting the controls less frequently than once per week. Nevertheless, a substantial majority rated the FB system as better for air movement, air quality, and thermal comfort than traditional ventilation systems they had experienced.

Faulkner et al. [1993] showed improvements in ventilation efficiency and pollutant removal for a PES, but only in specific circumstances. Tracer gas measurements made in an open-plan office laboratory showed that the age of air in the breathing zone was reduced by 30% compared to a perfectly mixed room when 40 ls^{-1} of outdoor air was delivered through nozzles aimed directly at the occupant. Other, more typical, supply conditions produced little effect on age of air measures. Similar tests done on an FB system yielded similar results [Fisk et al., 1991]. Faulkner et al. [1999] and Sekhar et al. [2003] found similar improvements in ventilation effectiveness for desk-based systems with lower local flow rates (7 to 15 ls^{-1} per occupant) provided the local flow was 100% outdoor air, the flow was directed towards the occupant, and there was an ambient system to provide additional space cooling.

The potential energy effects of personal ventilation systems have also been explored through simulation. Energy effects can accrue through effects on electricity for cooling and for fans (central and local); for a PES the associated task lighting and radiant panel also have

electricity requirements. The local zoning of such equipment also allows for manual or automatic switching off of equipment when the space is vacated.

Bauman et al. [1994] conducted whole building energy simulations for a standard office building on two sites in California, and compared both a FB system and a PES to a traditional variable-air-volume (VAV) system. The energy effects ranged from substantial savings to substantial penalties depending on the building operating assumptions. In Fresno, allowing an increased thermostat throttling range and stratification on the assumption that local control can compensate resulted in reductions in overall cooling energy of 10%, for fans of 15%, and peak demand of 9%, for a FB system. In San Jose, the same system was less successful: Overall cooling energy went down by 6%, fans energy increased by 34% (due to the extra layer of local fans in the FB system), and peak demand went down by 2%. However, a PES in San Jose, with the additional measure of occupancy sensors, yielded substantial savings: Overall cooling energy went down by 18%, fan energy by 18%, and peak demand went down by 7%.

Seem and Braun's [1992] simulations, for the climate of Madison, Wisconsin, indicated that a typical PES would use 9.5% more electricity than a conventional VAV system: the additional requirements of the local fans and radiant panel offset the occupancy sensor savings. However, they also demonstrated that a PES in which radiant panels were not used during periods of cooling, and local fans were not necessary for air circulation, could result in a 6% saving.

All of the above studies dealt with either a floor-based or desktop-based system. A third system type uses a nozzle in the ceiling that draws mixed supply air from a conventional duct system. The nozzle may be manually rotated for directional control, and a damper behind each nozzle may be controlled from the occupant's computer. Such a system has been deployed by Public Works and Government Services Canada (PWGSC). A comparison of one Ontario site with several hundred of these systems to other similar offices in the same city with conventional ventilation revealed a 61% reduction in complaint calls. PWGSC valued this improvement at CDN\$112,950/year using standardized costs per complaint call [Pero, 2006].

Demand-Responsive Load Shedding

It has been suggested that during periods of peak demand for electricity, when grid stability may be endangered, that buildings could automatically reduce their demand for electricity [Watson et al., 2006]. The two most likely strategies are reducing ("ramping down") cooling and lighting loads. Such strategies degrade indoor environment conditions compared to recommended practice, and risk compromising occupant satisfaction and performance. We have performed a substantial literature review of this topic [Newsham et al., 2006], which we will not repeat in this paper, for succinctness.

Hypotheses

The ceiling-based personal control system described by Pero [2006], combined with personal control of a direct-indirect luminaire, was used in the laboratory study described in the remainder of this paper. As well as offering personal control to some participants, we also imposed changes in temperature and light levels (ramps) typical of demand-responsive load shedding on other participants. Specifically, our hypotheses were:

1. Participants with personal control have better environmental satisfaction, mood, and task performance, compared to those without such control.
2. Participants with personal control use these controls to create individualized microclimates.
3. The use of personal controls reduces energy use of building services.
4. Participants exposed to ramps in environmental conditions will experience negative effects on environmental satisfaction, mood, and task performance.
5. Participants with personal control exposed to ramps will be less negatively affected by the ramps than those without personal control.

Methods & Procedures

Setting

The experimental space was 12.2 m x 7.3 m x 2.7 m, with two small windows facing west; Venetian blinds were drawn and closed over the upper two-thirds of these windows. The space contained six typical cubicle offices of 2.83 m x 2.22 m, panel height 1.68 m. The space had a dedicated HVAC system and air was delivered via 10 nozzles in the ceiling (one in each corner, and one per cubicle). Electric lighting was fluorescent with two components: 14 2-lamp prismatic lens luminaires on the perimeter; and 6 pairs (one pair per cubicle) of 3-lamp suspended direct-indirect luminaires, with one lamp (up-light) mounted above the other two lamps (down-light); the downlight utilized a parabolic louver. All lamps were 32W T8 3500K (CRI=82). Figure 1 shows a photograph of the space. Table 1 shows the measured reflectances of the major surfaces [Houser et al., 1999].

Table 1. Measured reflectances of major surfaces

Room Surface	Material	Colour	Reflectance
Ceiling	acoustical ceiling tile	matte white	89.0
Desktop	formica	low gloss off-white	50.3
Floor	carpet	matte multi-colored	12.2
Furniture Panel	fabric	matte off-white	46.0
External Wall	painted wallboard	light neutral gray	62.7

Figure 1. Photograph of the experimental space.

Participants

Participants were recruited from a local temporary-employment agency. Up to six people participated on a testing day, between 9 am and 4 pm. On each day, one of four experimental conditions prevailed: no control (NC), control (C), no control with ramping (R-NC), and control with ramping (R-C), each of which are described below. Table 2 shows the characteristics of the participants, by group. The participants self-reported having normal or corrected-to-normal vision and hearing, and had no physical impairments that might have affected their task performance.

Table 2. Characteristics of the participants.

Group	N	Gender		Age*				
		Male	Female	18-29	30-39	40-49	50-59	60+
NC	31	17	14	10	10	6	3	2
C	33	16	17	23	0	7	3	0
R-NC	31	16	15	18	9	2	2	0
R-C	31	16	15	12	7	9	1	0

* sum of age counts does not equal N for R-C condition because some participants did not report age.

Experimental Conditions

During the day participants undertook a variety of satisfaction questionnaires and simulated office tasks, which are described below. The day was divided into four sessions: T1, between morning arrival and mid-morning break; T2, between mid-morning break and lunch; T3, between lunch and mid-afternoon break; and T4, between mid-afternoon break and the end

of the afternoon. Session T1 included on-screen instructions, questionnaires and practice tasks; the remaining sessions had very similar content, featuring the questionnaires and tasks practiced in T1.

In the NC condition, the perimeter and indirect lighting were fixed and delivered ~100 lx on the desktops, and the direct component of the direct-indirect luminaire was fixed so that total mean E_{desk} was ~500 lx. The windows contributed up to 60 lx to the desktop illuminance in the two workstations closest to the windows; however, this was dependent on weather and time of day, and the overall effect was minimal. The corner air supply nozzles were fully open, and the other nozzles were at ~half flow (total flow rate ~350 ls^{-1} , ~25% outdoor air). Supply air temperature was 18°C, resulting in a room temperature of ~22.5°C. The workstation nozzles were aimed towards the head of the seated occupant. The flow rate for each of these nozzles was 16 ls^{-1} , resulting in an air velocity measured at the head position of ~0.15 ms^{-1} . These conditions were maintained throughout the experimental day, and the participant had no personal control.

In the C condition participants were given personal control over the airflow rate (but not direction) from the nozzle in their cubicles, and over the output of the down-lights in their cubicles; initial settings were the same as in the NC condition. This control was exercised through an interface on the computer monitor that was always available. The position of the nozzle damper in each cubicle had a minimal effect (~0.5 °C) on mean air temperature in the cubicle, because of good air mixing in the larger space. However, control of the nozzle damper could vary the local air velocity from ~0 to 0.3 ms^{-1} . Although Fanger & Christensen [1986] demonstrated susceptibility to draught from air directed on the neck, this was the only flow direction that could create a substantial effect on local cooling sensation. Participants could choose a down-light output from 20 to 100%, resulting in a desktop illuminance of ~200 to 700 lx. The maximum effect of one person's lighting choice on their neighbour was about 20 lx, and there was no effect of personal airflow choice on neighbouring cubicles. The design of the HVAC system was such that reducing the flow through the individual cubicle nozzles tended to increase the flow through the nozzles in the corners, thus maintaining an appropriate overall airflow rate.

The R-NC condition simulated the ramping of lighting and temperature conditions characteristic of demand-responsive load shedding. During the morning, the conditions were the same as in the NC condition. However, at the beginning of session T3, ramping was initiated. The direct component of the direct-indirect luminaire was reduced by 2% of full output per minute, to a minimum 20% output. To simulate the effect of reduced chiller operation, the supply air setpoint was raised from 18°C to 24°C in a single step; the supply air temperature reached 24 °C ~30 minutes later. The air temperature in the test space increased by ~1.5°C over the following 2.5 hours.

The R-C condition was created to explore the use and benefits of personal controls to combat indoor environment stressors such as ramping. In the R-C condition participants had access to personal controls throughout the day, as in the C condition, but they were exposed to an afternoon ramp, as in the R-NC condition.

Dependent Variables

The dependent variables consisted of occupant responses to questionnaires, their performance on various simulated office tasks, and their use of available controls and the physical conditions thus created.

Questionnaires and Tasks

The questionnaires and tasks are described briefly below, in the order in which they appeared within a session or during the day.

Typing Performance. Participants re-typed a set text, printed in high-contrast 12-point type on white paper into a simple word-processor [Newsham et al., 1995]. Performance was scored for speed and accuracy. We also recorded the time spent on the instruction screen prior to the typing task beginning, as a measure of participant-regulated Rest Breaks [Boyce & Eklund, 1996].

Rating Resumes. Participants read fictional resumes for a fictional job opening, and rated applicants on skills, competence, intelligence (0=Very Poor to 4=Excellent), and assigned a starting salary. The measures were the ratings themselves, and the time taken to complete the ratings after reading the resumes [based on a task in Veitch & Newsham, 1998]. The ratings are measures of pro-social behaviour.

Creativity. Participants were presented with a picture of an everyday object and asked to suggest novel uses for that object. The measure of performance was the number of uses suggested. This task has been used previously in lighting research [Veitch & Gifford, 1996], where it was sensitive to the degree of control participants had.

Serial Recall Memory. Eight digits were presented to participants on-screen one at a time, after 10 seconds they attempted to type back the sequence [Banbury et al. 2001]. We recorded the number of correct digits, and the time taken to recall them.

Anagram Solving. Participants were asked to solve five-letter anagrams [based on Aspinwall & Richter 1999; Sandelands et al., 1988], some of which were impossible. We recorded the time taken to solve the solvable anagrams, and the time before giving up on the impossible anagrams; the latter served as a measure of Motivation.

Magazine Article Rating. Participants read short magazine articles, and rated the article on whether it was interesting, grammatically correct, well-written, and biased (0=Unfavourable to 4=Favourable). The measures were the ratings themselves, and the time taken to complete the ratings [based on a task in Boyce et al. 2006a]. The ratings are measures of pro-social behaviour.

Environmental Satisfaction. This was assessed using a version of the questionnaire implemented during a large field study of cubicle offices [Charles et al., 2004]. Nineteen items produced three subscales on lighting, privacy & acoustics, and ventilation (including temperature and air quality), as well as overall satisfaction (0=very unsatisfactory to 7=very satisfactory).

Mood. The participant placed a mark in one square of a 9 x 9 matrix (Affect Grid) on which one axis indicated pleasure and the other arousal [Russell et al., 1989].

Visual Discomfort. Measured using a modification of the scale developed by Wibom and Carlsson [1987], with which they demonstrated that high luminance ratios between paper and a computer screen tended to reduce visual comfort. The measure was the total of the intensity ratings for eight symptoms. Physical Discomfort was the total of the intensity ratings for nine symptoms, adapted from Hedge et al. [1992]. Veitch & Newsham [1998] and Newsham et al. [2004] found these measures to be sensitive to lighting conditions.

Thermal Comfort. Rated using a thermal sensation scale (0=cold to 99=hot) and the McIntyre thermal preference scale (-1=prefer cooler to +1=prefer warmer), based on measures that are standard for thermal comfort research [Schiller et al., 1988].

Strain. Assessed using a modified version of the questionnaire used by Hedge, Erickson & Rubin [1992] (0=low strain, 4=high strain).

Changes in Environment. Participants were asked if they noticed any changes in the lighting, temperature, air quality or noise since the last break (0=No, 1=Yes small changes, 2=Yes large changes), and if they were distracted by these changes (0=No, 1=Yes a little, 2=Yes a lot).

Incidental Learning. During early questionnaire practice sessions participants were asked to review a list of options and select responses. At the end of the day, with no prior expectation of doing so, participants were asked to indicate which items appeared on that earlier list. We recorded the accuracy of the response.

Semantic Memory. At the end of the day, with no prior expectation of doing so, participants were asked multiple-choice questions on the content of the magazine articles they had rated earlier. Both speed and accuracy were recorded.

Satisfaction with Performance during the day. The mean of four questions (0=low satisfaction to 4=high satisfaction) [see Boyce et al. 2006a].

Willingness to Volunteer. At the end of the day, participants were asked how much time they would be willing to spend completing questionnaires on environmental issues, at home, on a scale ranging from zero to ten hours, and how willing they would be to spend another day like they had just completed. This is a measure of pro-social behaviour.

Vigilance. At various times during the day, an on-screen icon similar to e-mail arriving appeared. Participants were instructed to click on the icon as soon as it appeared, the measure was the time taken [see Boyce et al. 2006a].

Physical Measures

Lighting. Illuminance on the desk (E_{desk}), and the dimmer setting of the direct component of the direct-indirect luminaire, were recorded in each workstation every two minutes. Panel illuminance, other representative illuminances in the experimental space, and exterior vertical illuminance were also recorded on the same schedule. Spot luminance measurements were made at representative locations prior to the experiment beginning.

Ventilation. Flow rate was measured just after the motorized damper behind each nozzle, and air temperature was measured close to a panel wall in each workstation; both of these measures were recorded every two minutes. Additional representative temperatures in the space, as well as HVAC system internal temperatures, humidity, flow rates, and external temperature were also recorded on the same schedule. Air velocity and temperature at the vicinity of the occupant were made prior to the experiment beginning.

Figure 2 shows a scale drawing of a single cubicle indicating the locations of the principal sensors, office furnishings, luminaires and air nozzle.

Figure 2. Scale diagram of a single experimental workstation, showing luminaire, air nozzle, and sensor location (units are cm).

Results

Illuminance and Ventilation Choices

Table 3 shows the measured conditions for the NC and C groups; those from the C group reflect their personal choices. These numbers were derived from the mean values for each participant at the end of sessions T2, T3 and T4; averaging values over three times provides reliability, and T1 was excluded because the conditions were still novel and the session content was different. Table 3 shows that dimmer level choice and E_{desk} were significantly lower for participants with control, compared to the NC condition. This corresponds to an energy saving of about 10%, and agrees with energy savings due to individual control found by Veitch and Newsham [2000]. However, some people chose higher levels, as illustrated by Figure 3. The mean E_{desk} chosen and its distribution, 452 lx (s.d. 125 lx), is remarkably similar to other similar studies with different luminaire types. Newsham et al. [2004] found a mean preference of 452 lx (s.d. 241 lx), and Veitch and Newsham [2000] reported a mean preference of 445 lx (s.d. 147 lx) and 400 lx (s.d. 155 lx) for participants at the start and end of a work day, respectively. This is also consistent with recommendations for office lighting [ANSI/IESNA, 2004].

Table 3 also shows that flow rate choice was significantly lower for participants with control. There was no difference between the C and NC conditions for air temperature, suggesting that the main effect on thermal sensation was via air movement. Typically, a lower flow rate would correspond to a lower energy use for the HVAC system, although the system

design did not allow a direct measurement for the equipment we used. However, one must interpret this result carefully. Responses to the questionnaires indicated that participants were generally cool (mean thermal sensation for NC group 40.0 (s.d. 13.5), on a scale from 0-99), and therefore they may have reduced the flow rate to combat this. A different personal diffuser design, or a different ambient air temperature, might have produced very different flow rate choices. In a system where ambient and task ventilation are separated, allowing ambient temperature at the upper end of the thermal comfort range, while promoting higher local flow rates to offset this, may also reduce energy use [e.g. Bauman et al., 1994]. Nevertheless, there was a wide range of chosen flow rates, as illustrated by Figure 3.

Table 3. Mean (s.d.) conditions for two of the experimental groups.

	NC	C	Difference Significant?
E _{desk} (lx)	506 (33)	452 (125)	$F_{1,118}=5.99^*$, $\eta^2_{\text{partial}}=0.048$
Dimmer (%)	75	64 (23)	$F_{1,118}=8.49^{**}$, $\eta^2_{\text{partial}}=0.067$
Flow Rate (ls ⁻¹)	16.3 (0.4)	12.3 (8.3)	$F_{1,118}=4.46^*$, $\eta^2_{\text{partial}}=0.036$
Air Temperature (°C)	22.7 (0.5)	22.7 (0.5)	n.s.
			Multivariate test:
			$F_{4,115}=3.22^*$, $\eta^2_{\text{partial}}=0.101$

* = $p<0.05$, ** = $p<0.01$, n.s. = not significant.

Figure 3. Distribution of chosen desktop illuminance and flow rate, for data at the end of the T4 session.

We also examined how frequently the controls were used in the C and R-C conditions, as shown in Table 4. The average use of each control was 2 to 3 times per person over the day, with a general trend of declining use over the day, presumably as participants settled on a preferred condition and the novelty of the controls declined. The obvious exception to this was the use of the lighting dimmer to increase light levels during T3 for the R-C group; this was clearly a response to the imposed ramp down in light levels, and is analyzed in detail in Newsham and Mancini [2006]. The difference in the frequency of dimmer use to increase electric light level at T3 between the C and R-C groups is statistically significant ($t_{39} = -2.26$, $p=0.03$, assuming unequal variances); however there is no significant difference between these

groups on control use over all times, or at T3 over all control types. Kaczmarczyk et al. [2004] observed that participants with personal control tended to choose higher air flows when the prevailing room temperature was higher. The chosen flow rate at T4 for the R-C group was slightly higher than for the C group (12.4 ls^{-1} s.d. 10.4 vs. 11.7 ls^{-1} s.d. 9.9), but this difference was not statistically significant. This may be because the room air temperature difference between the conditions was about half the difference in Kaczmarczyk et al. [2004], and because our supply air temperature was lower.

Table 4. Mean frequency of control use, by session, and daily total.

	C				R-C			
	T1	T2	T3	T4	T1	T2	T3	T4
Dimmer Up	0.3	0.2	0.4	0.2	0.2	0.1	1.2	0.5
Dimmer Down	0.6	0.3	0.2	0.1	0.6	0.3	0.0	0.1
Dimmer Total				2.4				3.0
Flow Rate Up	0.5	0.1	0.2	0.3	0.4	0.1	0.3	0.3
Flow Rate Down	0.8	0.5	0.2	0.3	0.9	0.5	0.1	0.1
Flow Rate Total				2.9				2.6

Questionnaire and Tasks

Analysis Strategy

Most outcomes were measured at three times, and the general experimental design was a $2 \times 2 \times 3$ (Control x Ramping x Time) factorial; Control and Ramping were between-subject effects, and Time was a within-subject effect. However, some outcomes were measured at T2 and T4 only, in which case the experimental design was a $2 \times 2 \times 2$ (Control x Ramping x Time) factorial. Further, some outcomes were measured at the end of T4 only, and the experimental design for analysis was a 2×2 (Control x Ramping) factorial. Dependent variables were grouped for analysis if they were related conceptually and if they were measured the same number of times. When there was more than one dependent variable in a group, the analysis was a multivariate analysis of variance (MANOVA), which yields an overall test of significance for all dependent variables and individual, univariate significance tests. The univariate effects on individual measurements were interpreted only if the multivariate test was significant. This practice limits the possibility of Type I statistical errors. If the group had only one dependent variable, univariate analysis of variance was used (ANOVA). For outcomes measured at three times, we tested both the linear and quadratic contrasts.

We decided not to test for window effects for several reasons. First, the physical data indicated no overall difference in average desktop illuminance between the workstations. Second, closed blinds covered two-thirds of the window area, and participants sat with their backs to the windows, leaving little opportunity for a meaningful view. Third, adding a fourth factor to the experimental design would have resulted in small group sizes, limiting the overall power of the analysis.

Results

Table 5 shows the statistically significant effects related to Control and Ramping. Main effects of Time reflected common learning, post-lunch, and fatigue effects; these effects are not the primary concern of this paper, and are not described or shown in Table 5 for succinctness. Effects where Time interacts with Control or Ramping are shown; linear effects of Time

compare T2 to T4, therefore when showing the means for linear effects, values for T2 and T4 only are shown, even if the variable was measured for T3 also.

As Table 5 shows, there were no Control x Ramping effects, therefore the following discussion will address effects related to Control first, followed by effects related to Ramping. There were three-way effects related to pro-social behaviour; these are shown in Table 5 for completeness but are not discussed below because, as is common with three-way effects, interpretation is complex and does not help in drawing straightforward conclusions for practice. Further, the accumulation of missing cases in this analysis resulted in a relatively low sample size.

There were main effects of Control related to Environmental Satisfaction and Changes in Environment. As shown by the means for the NC groups, environmental satisfaction was generally quite high. Participants with personal control expressed significantly higher satisfaction on all sub-scales, as expected: participants could directly manipulate lighting and ventilation, and the privacy sub-scale included an item related to the ability to change the environment. The relatively large effect on overall environmental satisfaction likely reflects these benefits in aggregate.

Participants with personal control expressed significantly lower distraction from changes in temperature and acoustic conditions. Control of ventilation may have helped to moderate prevailing changes in temperature, but there is no obvious mechanism for the acoustics effect. Note also that levels of distraction were relatively low overall.

There was a Time-Quadratic x Control effect on Vigilance. In general, response time decreased over the day, a typical practice effect. However, for the NC groups the decrease was similar from T2 to T3 to T4, whereas for the C groups there was little change from T2 to T3, and a large change from T3 to T4. Further measurements over a longer exposure would be required to decide if this was indicative of better performance associated with control in the long term.

There were main effects of Ramping on both visual and physical discomfort. There was a small but significant increase in discomfort for the R groups, although overall, discomfort levels were very low.

Participants exposed to ramping were significantly more likely to notice changes in lighting, and to report being distracted by these changes. However, there was no effect for temperature changes. Note also that levels of detection and distraction were relatively low overall.

Because ramping was only in operation in the afternoon, Time x Ramping interaction effects are more convincing indicators of the effect of imposed changes in lighting and temperature than simple main effects. There was a Time-Linear x Ramping effect on Arousal. Whereas arousal stayed relatively constant from T2 to T4 for the NR groups, it dropped noticeably for the R groups. This might be expected given that the temperature was higher and the light levels lower for the R groups at T4.

There was also a Time-Linear x Ramping effect on Thermal Sensation and Preference. Initial mean values at T2 show that the environment was perceived as slightly cool, and participants had a preference for a higher temperature. By T4 for the NR groups there was a small shift towards thermal neutrality, consistent with the small increase in temperature over the day associated with internal heat gains. However, for the R groups the change to thermal neutrality was complete, on average, due to the larger change in temperature imposed by ramping. Therefore, because of the relatively cool initial temperatures ramping was beneficial

for thermal comfort; this is likely not typical of most real workplaces, although it might apply in situations where pre-cooling is practiced as a load shedding strategy [Xu et al, 2004].

Finally, there were Time-Quadratic x Ramping effects for pro-social behaviour, related to rating the magazine articles as interesting and well-written. The overall time pattern shows higher mean ratings at T2 and T4, with a lower rating at T3; this is typical of a “post-lunch dip” effect, but may also reflect an inherent difference in the article set rated at each time. In all cases the drop from T2 to T3 was lower for the R groups, but the increase from T3 to T4 was also lower. Further measurements over a longer exposure would be required to better discriminate between the two groups.

Table 5. Significant Effects from Analyses of Task and Questionnaire Outcomes.
Effects related to Control & Ramping

Effect/Outcome	F-test	η^2_{partial}	Scale	Means (s.d.)	
MOOD					
Time-L x Ramping	F _{2,119} =3.81*	0.060			
Arousal	F _{1,120} =7.67**	0.060	0 to 8	T2/NR: 3.75 (1.77) T4/NR: 3.89 (1.94)	T2/R: 4.25 (1.69) T4/R: 3.45 (1.84)
ENVIRONMENTAL SATISFACTION					
Control	F _{4,115} =2.45*	0.078			
Lighting	F _{1,100} =4.71*	0.045	0 to 6	NC: 3.80 (0.96)	C: 4.17 (0.75)
Ventilation	F _{1,100} =8.98**	0.082	0 to 6	NC: 3.96 (1.02)	C: 4.53 (0.94)
Privacy	F _{1,100} =8.67**	0.080	0 to 6	NC: 3.95 (0.95)	C: 4.46 (0.87)
Overall	F _{1,100} =20.6**	0.171	0 to 6	NC: 3.60 (1.00)	C: 4.44 (0.88)
THERMAL AND VISUAL COMFORT					
Ramping	F _{3,118} =3.42*	0.080			
Visual Discomf.	F _{1,120} =4.69*	0.038	0 to 32	NR: 1.80 (2.01)	R: 2.84 (3.34)
Time-L x Ramping	F _{3,118} =27.9**	0.188			
Thermal Sensation	F _{1,120} =21.8**	0.154	0 to 100	T2/NR: 36.3 (15.4) T4/NR: 40.8 (13.3)	T2/R: 34.0 (14.4) T4/R: 50.4 (13.7)
Thermal Pref.	F _{1,120} =18.1**	0.131	-1 to 1	T2/NR: 0.52 (0.56) T4/NR: 0.34 (0.60)	T2/R: 0.67 (0.48) T4/R: 0.03 (0.64)
PHYSICAL COMFORT					
Ramping					
Physical Discomf.	F _{1,113} =3.99*	0.034	0 to 36	NR: 2.31 (2.40)	R: 3.42 (3.40)
CHANGES IN ENVIRONMENT					
Control	F _{6,102} =3.08**	0.153			
Temp. Distraction	F _{1,107} =8.43**	0.073	0 to 2	NC: 0.47 (0.46)	C: 0.26 (0.30)
Acoust. Distraction	F _{1,107} =5.27*	0.047	0 to 2	NC: 0.25 (0.35)	C: 0.12 (0.27)
Ramping	F _{6,102} =2.23*	0.116			
Lighting Change	F _{1,107} =7.30**	0.064	0 to 2	NR: 0.37 (0.39)	R: 0.58 (0.43)
Light. Distraction	F _{1,107} =7.14**	0.063	0 to 2	NR: 0.09 (0.23)	R: 0.24 (0.36)
PRO-SOCIAL BEHAVIOUR					
Time-Q x Ramping	F _{10,46} =2.04*	0.308			
Interesting	F _{1,55} =4.09*	0.069	0 to 4	T2/NR: 2.52 (0.44) T3/NR: 1.96 (0.62) T4/NR: 2.84 (0.47)	T2/R: 2.35 (0.66) T3/R: 2.03 (0.69) T4/R: 2.69 (0.76)
Well Written	F _{1,55} =7.33**	0.118	0 to 4	T2/NR: 2.66 (0.37) T3/NR: 2.31 (0.49) T4/NR: 2.89 (0.33)	T2/R: 2.68 (0.49) T3/R: 2.46 (0.55) T4/R: 2.73 (0.53)

Time-L x Ramping x Control	$F_{10,46}=2.24^*$	0.328					
Grammatical	$F_{1,55}=4.28^*$	0.072	0 to 4	T2/NC/NR: 3.00 (0.58) T4/NC/NR: 3.18 (0.48)	T2/NC/R: 2.89 (0.34) T4/NC/R: 2.91 (0.34)	T2/C/NR: 2.92 (0.41) T4/C/NR: 2.92 (0.36)	T2/C/R: 2.85 (0.63) T4/C/R: 3.09 (0.42)
Resume Time	$F_{1,55}=8.57^{**}$	0.135	seconds	T2/NC/NR: 26.5 (12.2) T4/NC/NR: 26.1 (11.3)	T2/NC/R: 42.0 (17.3) T4/NC/R: 30.2 (10.3)	T2/C/NR: 24.2 (11.4) T4/C/NR: 20.5 (6.8)	T2/C/R: 30.2 (15.4) T4/C/R: 29.6 (15.4)
VIGILANCE							
Time-Q x Control							
Vigilance	$F_{1,84}=11.5^{**}$	0.120	seconds	T2/NC: 26.6 (10.4) T3/NC: 18.9 (7.4) T4/NC: 12.0 (7.3)		T2/C: 22.5 (8.7) T3/C: 21.6 (9.7) T4/C: 10.1 (6.7)	

* = $p \leq 0.05$, ** = $p \leq 0.01$.

Discussion

Although the list of effects in Table 5 appears quite long, most outcomes we tested were not affected by control or ramping. Nevertheless, the effects that were significant showed consistent and logical trends. Provision of personal environmental control was beneficial, particularly for the important outcomes of environmental satisfaction (discussed further below). This is consistent with the previous research described in the Introduction section of this paper.

On the other hand, the effects of ramping, were generally negative, as would be expected from the imposed deviation from prevailing environmental conditions. However, these negative effects were relatively small. It is also important to note the outcomes that were not affected by ramping: there was no effect on environmental satisfaction, or on any of the many task performance outcomes (typing, memory, creativity, anagram solving, vigilance). Newsham et al. [2006], using a less comprehensive analysis of these experimental data, concluded that the kind of ramping we practiced here was unlikely to create substantial hardships for occupants, in the context of a peak power emergency; the analysis in this paper does not contradict this conclusion. Nevertheless, more extreme changes in light levels or temperature, or ramping practiced more frequently, might exaggerate the relatively minor negative effects observed in this experiment.

In conclusion, with reference to the specific hypotheses at the start of the paper:

1. *Participants with personal control have better environmental satisfaction, mood, and task performance, compared to those without such control.*
We observed benefits for environmental satisfaction, but not for the other outcomes. The effects for environmental satisfaction were medium-sized in terms of explained variance.
2. *Participants with personal control use these controls to create individualized microclimates.*
There were large differences in chosen light levels and ventilation flow rates between individuals.
3. *The use of personal controls reduces energy use of building services.*
On average, light levels and ventilation flow rates were significantly reduced.

This was associated with a ~10% reduction in lighting energy; HVAC energy effects depend greatly on the larger system design and operation.

4. *Participants exposed to ramps in environmental conditions will experience negative effects on environmental satisfaction, mood, and task performance.* We observed small negative effects on comfort and arousal, but environmental satisfaction and task performance were not affected.
5. *Participants with personal control exposed to ramps will be less negatively affected by the ramps than those without personal control.* There were no significant interaction effects, and therefore this hypothesis was not supported.

Longer-Term Pilot Study

Exposure to conditions in the above experiment lasted one working day. It is reasonable to ask whether occupant behaviour would differ over longer exposures. We had the opportunity to study this issue. After the completion of the above experiment, the laboratory space was occupied for several months by five visiting staff (all young males, aged 18-29). We collected data on environmental conditions and control use. We periodically initiated unannounced afternoon ramps in lighting and temperature, as in the above experiment, to create additional environmental stressors. We also collected questionnaire data on Environmental Satisfaction and Change in Environment, as described above, at several times during occupancy, and administered a questionnaire on the space and control system at the end of occupancy.

Results

Given the small sample size, we applied descriptive statistics only to the data, with only qualitative interpretation. Therefore, we consider this element of the research a pilot study only.

Table 6 shows the frequency of control use, on days with no ramping and days with afternoon ramping. To assess the novelty effect, the data for no-ramping days are separated to look at control use in the first week of occupancy vs. use in later weeks. Because of a malfunction in the control software, the first three ramping days had temperature-only ramps, whereas the following four included both ramp types. Therefore the data for ramping days are further separated by ramping type. Note that because of differences in arrival and departure dates, and in work schedules and absenteeism, the first weeks differed between participants, as did the number of days in each condition; the number of days of data contributing to each dataset is shown in the final row of Table 6.

Table 6. Upper section of table shows mean (and range of) frequency of control use by ramping condition. Lower section of table shows number of days each person experienced each condition

	Mean (and range of) changes/person/day			
	No-Ramping Days		Ramping Days	
	First Week	Later Weeks	Temp. Only	Temp. + Light.*
Dimmer	1.7 (0.0 – 4.0)	0.5 (0.1 – 0.7)	0.2 (0.0 – 0.5)	0.9 (0.0 – 2.0)
Flow Rate	1.3 (0.3 – 2.5)	0.7 (0.0 – 1.5)	2.4 (0.0 – 4.0)	0.8 (0.0 – 1.5)
	Mean (and range of) days in condition/person			
	2.8 (1 – 4)	45.4 (29 – 63)	1.8 (1 – 3)	2.0 (0 – 4)

* N=4 for this combination

Table 6 does suggest a novelty effect; control use is higher in the first week compared to later weeks. This suggests a continuing decline in use beyond the decline we saw over a single day in Table 3. Nevertheless, the control use did not drop to zero, and was higher than the on-going use self-reported in Hedge et al. [1993] and Bauman et al. [1994].

Data on environmental satisfaction were obtained on three afternoons, the first two on no-ramping days, and the third during a temperature and lighting ramp. The mean responses are shown in Table 7. Satisfaction on the sub-scales is above the mid-point (3) of the scale, and is comparable to the values expressed during the one-day experiment (see Table 5). However, overall environmental satisfaction is substantially lower than in the one-day experiment. One item on this scale referred to the effect of the physical environment on self-rated productivity, and the participants provided particularly low ratings on this item. We speculate that this was because the participants were university students unused to working as individuals in a generally quiet cubicle setting.

The mean environmental satisfaction ratings during ramping are slightly lower than on the no-ramping days. Data from the Change in Environment questionnaire showed that no-one reported noticing changes in environmental conditions on the final no-ramping day, whereas two of five participants reported noticing and being a little distracted by changes in electric lighting, temperature, and air quality on the ramping day. Again, there is not enough data from which to draw firm conclusions.

Table 7. Mean Environmental Satisfaction (in longer-term pilot study)

	No Ramping (N=5)	No Ramping (N=4)	Ramping (N=5)
Lighting	4.2	4.2	4.0
Ventilation	3.7	4.3	3.7
Privacy & Acoustics	4.2	4.2	4.2
Overall	2.9	3.0	2.5

At the end of the occupancy period, participants completed an additional questionnaire. First, they were asked to rate the space compared to other offices where they had worked on items related to lighting, ventilation, and support for work and well-being. Mean responses were ~5.5 on a scale of 1 (Much Worse) – 7 (Much Better). In this longer-term study, participants were allowed to manually adjust the direction of the air nozzle using a stick to reach the ceiling; the modal estimate of change frequency was “once per month”. The following questions asked for ratings of ease of use and responsiveness of the environmental controls. Changing the nozzle direction was rated 5 on a scale of 1 (Very Difficult) – 7 (Very Easy); the control of lighting and

flow rate through the computer interface both received a mean rating of 6.6. Responses on the speed of response to control actions followed expectations, the mean rating for lighting was 6.8, and temperature 4.6, on a scale of 1 (Very Slow) – 7 (Very Fast). Finally, agreement with statements “I was able to change the lighting (or temperature, or air direction) to my preferred conditions”, all received mean ratings of 5.8 on a scale of 1 (Very Strongly Disagree) – 7 (Very Strongly Agree). Overall, responses indicated a high degree of satisfaction with the control system and its contribution to creating a highly satisfactory environment.

General Discussion

This experiment found that having personal control over lighting and ventilation had clear benefits for environmental satisfaction, and hinted at a possible effect on work performance (via vigilance). The results are broadly consistent with other investigations [Boyce et al., 2006a; Newsham et al., 2004]. The overall pattern of results suggests that there may be economic benefits for organizations that install personal controls. For example, the reduction in complaint calls observed by Pero [2006], presumably due to increased environmental satisfaction, improves an organization’s bottom line, as does a reduction in energy bills. Further, research has demonstrated a positive correlation between environmental satisfaction and job satisfaction [Charles et al, 2004; Carlopio, 1996]. This is important because job satisfaction is major predictor of behaviours of consequence to organizational performance such as organizational citizenship (promoting the organization internally and externally) [Podsakoff et al., 2000], employee turnover [Allen et al., 2005; Harter et al., 2002], and customer satisfaction [Harter et al., 2002].

The afternoon ramping had medium statistical effect sizes for effects on physical and visual comfort and on prosocial behaviours; however, it showed no effects on environmental satisfaction or the pleasure component of mood, which one might expect to see. Control had few mitigating effects on the response to ramping (there were few interaction effects of control x ramping). Overall, the pattern for the short-term and long-term data suggests that the modest ramps in physical conditions experienced here are not preferred, but neither are they intolerable. Further research is needed to determine the limits of both ramp speed and environmental conditions that should be attempted in response to peak load conditions.

Conclusions

As with all research, the results of this study must be interpreted with due consideration for the context in which it was done. Nevertheless, our results do accord with those in other published studies, which increases our confidence in the following conclusions:

- Personal environmental control over lighting and air flow rate in an open plan office improved occupant environmental satisfaction.
- Personal control over lighting led to an average energy reduction of around 10%, compared to a typical fixed system. The energy use of personal ventilation control is highly dependent on the overall HVAC system design and operation.
- Over the long-term, occupant use of such controls averaged less than one control action per person per day.

- Such control systems are perceived as being easy to use, and to provide a valuable utility compared to conventional offices.
- Reducing light level and increasing temperature in a way typical of a demand-responsive load shed did have small negative effects on arousal and comfort. However, such effects are unlikely to create major hardships in the context of a response to a peak power emergency.

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