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# Effects of a Furniture-integrated Breathing-zone Filtration System on Indoor Air Quality, Sick Building Syndrome, and Productivity

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## Abstract

*A field experiment evaluated the effect of a furniture-integrated breathing-zone filtration (BZF) system on indoor air quality, worker comfort, health, and productivity. The BZF system tested filters office air to remove volatile organic compounds and airborne particulates. The BZF system was installed on one floor of a 29 story air-conditioned office building. Another floor of the building served as a control. Comparisons of pre-installation and three month post-installation surveys showed improvements in indoor air quality, sick building syndrome symptoms, and self-reported productivity with the BZF system*

**KEY WORDS:**
Breathing-zone filtration, HEPA filter, Sick building syndrome, Productivity, Particulates, Total volatile organic compounds

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## Introduction

Indoor air quality problems and complaints of the sick building syndrome in office buildings typically result from interactions between inadequate mechanical ventilation, pollutant emissions from localized pollution sources in the office, and exposure of susceptible individuals (Brooks and Davis, 1992). Inadequate mechanical ventilation in offices can arise from the interplay of several factors:

- poor ventilation rate, i.e. the mechanical system may deliver an insufficient volume of outdoor air to the office
- poor ventilation efficiency i.e. the "fresh" supply air inadequately mixes with the "stale" office air
- contaminated outdoor air
- contaminated mechanical ventilation system which contaminates supply air

Consequently, progressively increasing the ventilation rate above 71 $sec^{-1}$ in an office frequently does not resolve worker complaints about climate conditions and health, or reduce levels of indoor air pollutants (Jaakkola et al., 1991; Menzies et al., 1992).

Localized pollutant sources in offices are diverse, including office technologies, such as photocopiers and computers, correction fluids, furniture, building materials, cigarettes, and perfumes. Many of these sources release volatile organic compounds into indoor air, and these are associated with mucous membrane irritation symptoms of the sick building syndrome. Other sources, such as ceiling tiles and moveable office partitions, release airborne particulates and mineral fibers. Sick building syndrome complaints correlate with total particulates (Armstrong et al., 1989) and with settled mineral fibers (Hedge et al., 1993). Thorough cleaning of office interiors reduces the incidence of sick building syndrome symptoms by about 50% (Leinster et al., 1990), and better filtration of office air has been suggested as a remedy for many sick building syndrome complaints (Armstrong et al., 1989).

Several personal risk factors may change a worker's susceptibility and propensity to report sick building syndrome symptoms. These factors typically include gender, daily hours of computer use, and levels of job stress (Hedge et al., 1992; Zweers et al., 1992). Research on stress shows that negative effects can be reduced when individuals are given personal control over their work situation (Steptoe and Appels, 1989). Lack of personal control of environmental conditions is associated with increased symptom reports (Hedge et al., 1989).

Recently, a number of personally controllable localized air distribution and air filtration technologies have become commercially available. These products range from small air cleaner units to larger furniture-integrated air cleaning systems. A typical product contains a fan which circulates air through one or more filters. Domestic use of a room air cleaner, which contained a HEPA (high efficiency particular air) filter to remove airborne particulates, resulted in a 70% decrease in airborne particles $>=$ 0.3 μm, and significantly lowered the occurrence of allergic respiratory symptoms among people with perennial rhinitis and/or asthma (Reisman et al., 1990). Retrofitting a fan/filter system, comprised of a HEPA filter and an activated carbon filter, into existing office furniture in a building with widespread indoor air quality and sick building syndrome complaints produced some significant improvements in indoor air quality, and in worker reports of indoor air quality, ventilation, thermal comfort, and several sick building syndrome symptoms after two months use (Hedge et al., 1991).

The use of localized air distribution and air filtration products theoretically should improve ventilation efficiency and mitigate against emissions from localized sources in the office, thereby reducing exposure risks, and allowing workers to control these units may help to lower their susceptibility. This study tested the effects of a furniture-integrated BZF system on indoor air quality and worker comfort, health and productivity in a large government office.

## Method

### Office Building

Two office floors, each $-1{,}200$ m$^2$, in a 29 story Canadian government office building were surveyed. One floor served as a control floor, the other as a test floor. These floors were 12 stories apart and were accessed by different elevators. Both floors were occupied by workers performing comparable activities, and were served by the same ventilation system. Space standards were identical for each floor, an average of $\sim 10$ m$^2$ per workstation, but because of a difference in the amount of storage space on the two floors there were more workstations on the control floor ($n=84$) than on the test floor ($n=63$). The post-installation arrangement of the control and test floors is shown in Figures 1 and 2.

### BZF System

The BZF system which was tested consists of three parts. A fan capable of moving air at a continuous rate of at least 50 l s$^{-1}$. A cylindrical filter made of polymer fibre and activated carbon, which removes volatile organic compounds (30% efficient) and larger particulates. The polymer/carbon filter is wrapped around a cylindrical HEPA filter (99.97% efficient at 0.3 μm), which removes small particles. The BZF system draws aged office air into the filtration system at worksurface height, and supplies filtered air above head level at an adjustable rate. The BZF system is integrated into the corner of a systems furniture office workstation and it works completely independently of the ventilation system. The BZF system has been tested using pulse injection of sulfur hexafluoride tracer gas and controlled emissions of environmental tobacco smoke (McCarthy et al., 1993). Results show that the BZF system markedly increases the homogenization of office air and increases the rate of contamination removal to effectively create a canopy of filtered air for each furniture workstation module (Figure 3).

### Pre-installation Survey

The pre-installation survey was conducted in June, 1992, prior to installation of the BZF system on the test floor. Concentrations of carbon monoxide, carbon dioxide, and total volatile organic compounds were measured continuously for a 48 hour period with a multi-point multi-gas analysis system (Brüel & Kjaer model 9652). Real-time measurement of respirable particulate levels (0.1 to 0.4 μm) were made at different workstations for each of four days with a laser particle counter (LPC-101 Micro-Laser Particle Counter), which was placed inside furniture modules with and without the air filtration system. A series of 19 sulfur hexafluoride ($SF_6$)

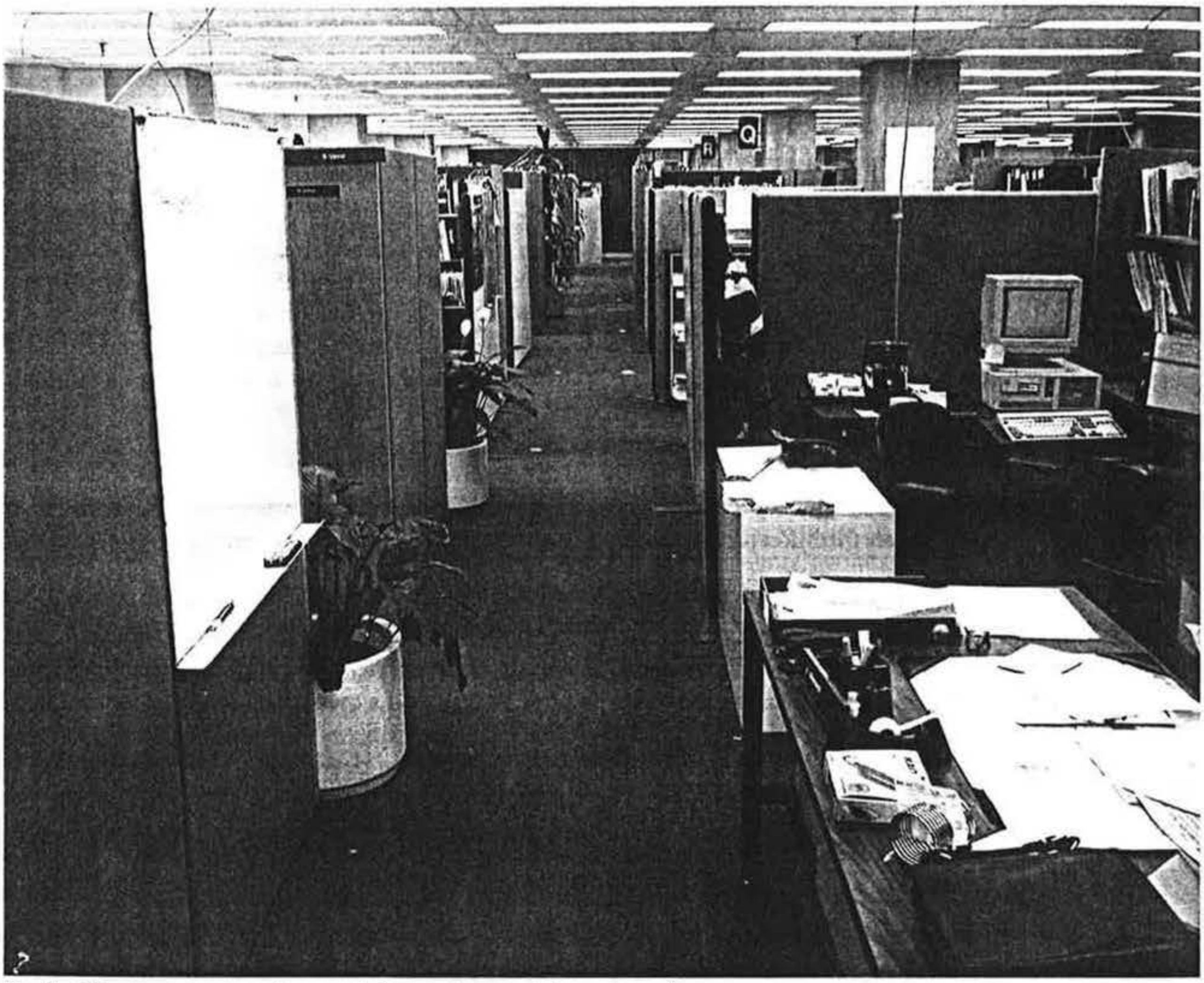

Fig. 1 Office environment on the control floor at the time of the post-installation survey

tracer gas tests was conducted to evaluate air exchange rates, and horizontal and vertical air mixing. These tests assessed ventilation effectiveness as indicated by the quality of air mixing in the office space. Areas were screened for $SF_6$ prior to testing. Tracer gas was released into an inlet diffuser and levels were monitored at an air outlet and at selected sites in the office space. Horizontal air dispersion was assessed by injecting $SF_6$ inside one module and measuring the buildup and decay of $SF_6$ in neighboring modules. Vertical air dispersion was assessed by injecting $SF_6$ inside one module at a 1.07 m level and measuring the buildup and decay of $SF_6$ at the air return. $SF_6$ levels were monitored with a multi-point multi-gas analysis system (Brüel & Kjaer model 9652). To ensure that the concentration of $SF_6$ reaching each monitoring point would be quantifiable, the total volume of tracer gas to be released in each test was separately determined. While these tests were being performed the outdoor air dampers were set to the "minimum outdoor air position" for the system.

Concurrent with the indoor air quality monitoring, a questionnaire survey was conducted on the test and control floors. Questionnaires were manually distributed to and collected from all workstations on each floor. The survey questionnaire was comprised of 131 questions which collected information on work patterns, job characteristics, perceived ambient environment conditions and their impact on productivity, sick building syndrome symptoms and their impact on productivity, furniture workstation characteristics, and personal details. Sixty-three completed questionnaires were returned from the control floor (75% return) and 49 completed questionnaires were returned from the test floor (78% return).


Fig. 2 Office environment on the test floor at the time of the post-installation survey

### Post-installation Survey

Immediately following the pre-installation survey, the test floor was re-carpeted, and new furniture with the BZF system was installed (18 filtration units). One quadrant of the test floor served as a placebo condition, and all filters were removed from 6 BZF units, the fans remaining operational. The experimenters and the workers were blind to this area.

Three months after installation of the BZF system, in October 1992, a post-installation survey was conducted. The indoor air quality monitoring followed an identical protocol to that of the pre-installation survey. A post-installation survey questionnaire comprising 161 questions similar to the pre-installation questionnaire, was distributed to and collected from occupied workstations, because at the time of this survey not all workstations on the test and control floors were occupied. On the test floor 37 questionnaires were returned from the 43 occupied workstations with the BZF system (86% return), and 6 questionnaires were returned from the placebo area (46% return). On the control floor 46 questionnaires were returned from the 64 occupied workstations (72% return).

### Questionnaire Design

Both the pre-installation and post-installation survey questionnaires contained a common core of questions. Those of greatest interest include the 19 items on office environmental conditions: poor indoor air quality; insufficient ventilation; too little air movement; stale air; air too dusty; air too dry; unpleasant odors in air; too warm; too cold; temperature too variable; uncomfortable drafts, electrostatic shocks; lighting too dim; lighting causes glare

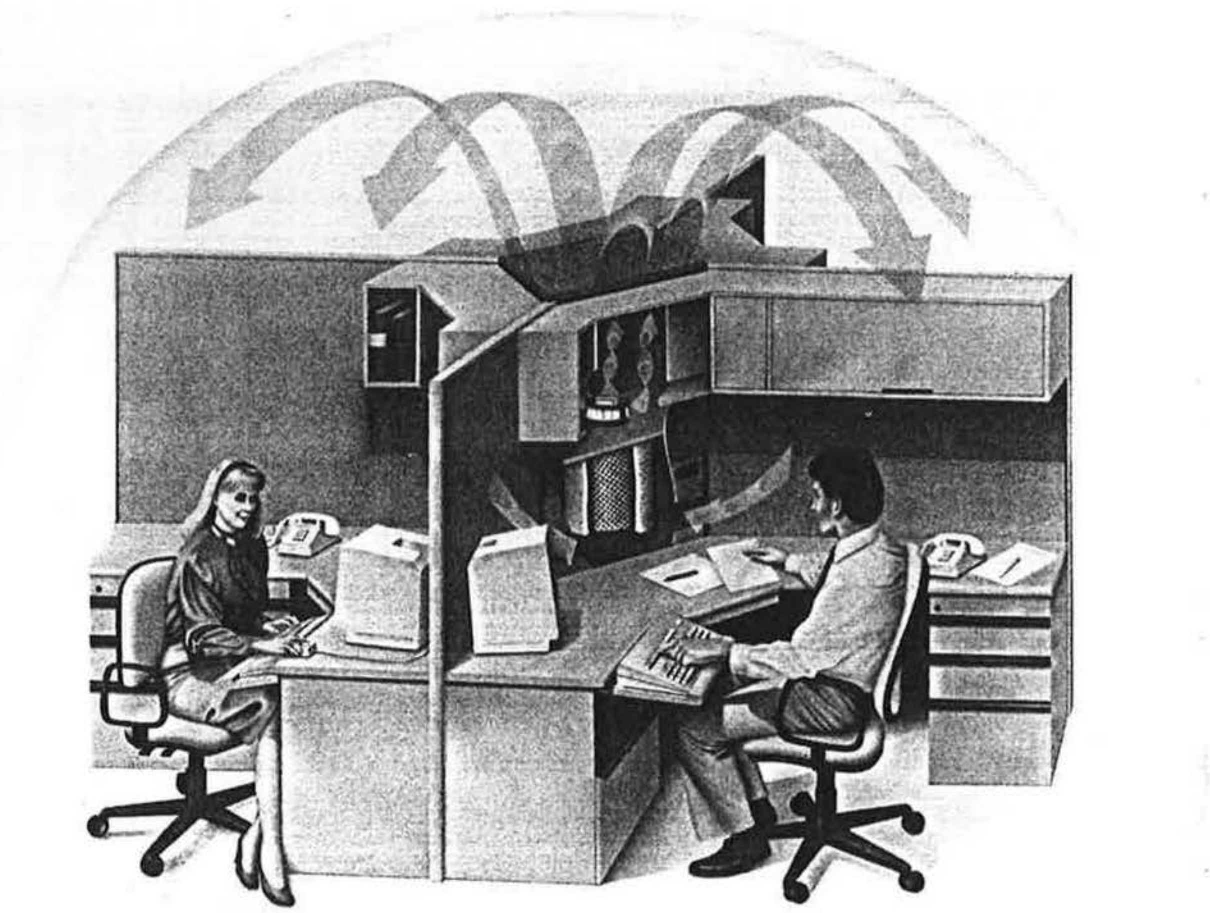

**Fig. 3** Diagram of the pattern of air circulation with a furniture-integrated BZF system.
NOTE: Arrows indicate the movement of air. Air is drawn into the filtration system at worksurface height. The air passes through the polymer/carbon pre-filter, then the HEPA filter. Clean air is supplied from the top of the unit above seated head height. The constant circulation of air in this way effectively creats a microenvironmental umbrella of filtered air over the workstation.

problems; poor visual privacy; poor speech privacy; and distracting office noise. Respondents were asked to rate how often they had experienced each of these conditions in the month prior to each survey on a four point rating scale: never, 1 to 3 times a month, 1 to 3 times a week; almost every or every day. They were then asked whether they were experiencing each of these conditions at the time of the survey (Yes or No), and how each of these conditions affected their productivity during the month prior to each survey on a five point rating scale: substantially decreased; slightly decreased; no effect; slightly increased; substantially increased. Also of interest are the 14 sick building syndrome items: dry eyes; irritated, sore eyes; sore throat; hoarseness; stuffy nose; runny nose; lethargy; nervousness; headache; wheeze; nausea; dizziness, dry skin; skin irritation, rashes. There were 2 musculoskeletal symptoms: aching hands, wrists; aching neck, shoulders, and 1 eyestrain symptom: tired, strained eyes. Respondents were asked to rate how often they had experienced each of these symptoms in the month prior to each survey on a four point rating scale: never; 1 to 3 times a month; 1 to 3 times a week, almost every or every day. They were asked how each of these symptoms was affected on days when away from work on a 3 point scale: got better; no effect; got worse. Respondents were asked whether they were experiencing each of these symptoms at the time of the survey (Yes or No), and then asked how each of these symptoms in turn affected their self-assessed productivity during the month prior to each survey on a five point rating scale: substantially decreased; slightly decreased; no effect; slightly increased; substantially increased.

### Data Analysis

All comparisons of responses to individual questions were made using Chi-square tests. Responses on self-reported productivity items were separately summed for those indicating slight or substantially decreased productivity and for slight or substantially increased productivity. In keeping with previous studies (Hedge et al., 1992; 1993), work-related health symptoms were defined as those symptoms that had occurred at least once in the month prior to a survey and which got better on days away from work. The number of work-related sick building symptoms each worker reported was summed to give a person symptom index (PSI). The minimum PSI value per worker was 0 and the maximum was 14. Seven environmental conditions items were used to construct a perceived indoor air quality scale: poor indoor air quality; insufficient ventilation; too little air movement; stale, stagnant air; air too dusty; air too dry, and unpleasant odor in air. The number of questions answered positively (i.e. each problem condition had been experienced at least once in the month prior to and including the day of survey) was counted to create the index of perceived indoor air quality (PIAQ). The minimum PIAQ value per worker was 0 and the maximum was 7. To preserve confidentiality and anonymity, individual workers were not tracked between surveys. Pre- and post-installation comparisons of the PIAQ and PSi were performed using independent groups t-tests. The placebo group was small and questionnaire responses for individual questions could not be tested. However, because tests of the PIAQ and PSI data were based on group means, the responses of the placebo group were included in these analyses.

## Results

Over half of the workers surveyed had worked in the building for 6 or more years (control floor = 51.1%; test floor = 54.1%). A majority of workers worked 5 days per week in the building (control floor = 95.4%; test floor = 86.5%). All workers worked 7 or more hours per day in the building. A majority of workers were aged between 30 to 49 years (control floor = 72.1%; test floor = 78.4%). There were significantly more women respondents on the test floor (83.3%) than on the control floor (60.5%: $\chi^2 = 5.279$, $p = 0.022$). There were no significant differences between the floors in the prevalence of migraine, asthma, eczema, hayfever, other allergies, or smoking status.

Indoor air results showed that both before and after installation of the BZF system, the pollutants measured were consistently well below current standards on both the control and test floors. Tracer tests showed that the air supply and return were reasonably well balanced and the air distribution was fairly uniform on both floors during the June and October surveys. However, there were consistent seasonal differences in the operation of the HVAC system. In June, there were around 4 outdoor air changes per hour on the test floor and 3 outdoor air changes per hour on the control floor. In October, there were about 0.6 outdoor air changes per hour on the test floor and 1 outdoor air change per hour on the control floor. In June, the measured ventilation efficiency (degree of mixing of supply air with aged room air) was 54% on the test floor and 47% on the control floor. In October, this was 53% on the test floor and 50% on the control floor. No significant differences in horizontal dispersion of tracer gas between workstation modules on the test and control floors was found for either survey. However, tracer test results for vertical dispersion (floor to ceiling), which estimates relative exposures from a contaminant source, showed an improvement in vertical air mixing following installation of the BZF system.

There was no difference in TVOC levels on the control floor for the pre-installation ($1.27 \pm 0.06$ ppm) and post-installation surveys ($1.17 \pm 0.11$ ppm). There was a 48% decrease in TVOCs on the test floor between the pre-installation ($1.67 \pm 0.72$ ppm) and post-installation ($0.87 \pm 0.06$ ppm) surveys which approached significance ($t = -1.918$, $df = 5$, $p < 0.06$ one-tail). Counts of the submicronic particulates ($<= 0.25$ μm) were reduced by the BZF system (Table 1). There had been over a five-

**Table 1** Effects of the BZF system on airborne particle counts (particles $cc^{-1}$) in the 0.1 μm and 0.2 μm ranges

| Office Area | Pre-installation | | Post-installation | |
|---|---|---|---|---|
| | 0.05–0.15 μm | 0.15–0.25 μm | 0.05–0.15 μm | 0.15–0.25 μm |
| Control | $21 \pm 10$ | $23 \pm 14$ | $110 \pm 32$ | $38 \pm 16$ |
| Test† | $19 \pm 7$ | $9 \pm 4$ | $73 \pm 9$ | $26 \pm 4$ |
| BZF | | | $13 \pm 6$ | $4 \pm 2$ |

† Pre-installation the test floor included the placebo area. Post-installation particle counts are for the placebo area.

fold increase in particulates on the control floor, and a three-fold increase in the placebo area between the June and October surveys. Compared with the placebo area, however, there was over an 80% decrease in submicronic particles in the BZF area. This reduction in particles may partly explain the significant improvement in workers' perception of the general cleanliness of their workspace area with the BZF system, from 72% rating this as dusty in June to no-one rating this as dusty in October ($\chi^2 = 47.36$, $p = 0.000$), whereas there was no difference in perceived dustiness on the control floor (from 58% rating this as dusty in June to 65% rating this as dusty in October).

Pre- and post-installation differences in perceived environmental conditions for the month prior to each survey were not significant for the control floor. However, the impact of the BZF system on perceived environmental conditions on the test floor was dramatic (Table 2). The mean PIAQ was significantly lower for both the test and placebo areas (Table 3). Because the fans were operational in the placebo units and workers could control these this result may indicate a general benefit of increasing air movement in the breathing zone for workers with these units. Also, since there was no barrier between the test and placebo areas there was some mixing of the filtered air from the test space with that in placebo space, as confirmed by the particulate measurements, which also may partly explain the results.

The BZF system significantly reduced complaints about disruptions to productivity caused by office environment conditions (Table 4), whereas apart from response to the item "insufficient ventilation" ($\chi^2 = 4.20$, $p = 0.040$), these pre- and post-installation differences were not significant for the control floor. The BZF system also significantly decreased reports of work-related sick building syndrome symptoms by over 50%, from an average of $3.84 \pm 0.46$ symptoms per employee in June, to an average of $2.05 \pm 0.59$ symptoms per employee by October ($t = -2.53$, $p = 0.013$), whereas symptom reports did not change significantly on the control floor (June = $3.22 \pm 0.33$ symptoms per worker; October = $3.60 \pm 0.51$ symptoms per worker). In the placebo area, where workers received some benefit from the overall space cleaning effects of the BZF

**Table 2** Effects of the BZF system on perceived indoor climate conditions for the month before each survey.

| Environmental Condition | Control floor | | BZF floor | | Pre-post BZF P value |
|---|---|---|---|---|---|
| | % Pre- | % Post- | % Pre- | % Post- | |
| Poor indoor air quality | 88.1 | 83.7 | 97.9 | 21.2 | 0.000 |
| Too little air movement | 83.4 | 73.8 | 95.8 | 21.2 | 0.000 |
| Insufficient ventilation | 88.5 | 87.2 | 93.6 | 18.2 | 0.000 |
| Stale air | 78.3 | 74.4 | 76.1 | 19.4 | 0.000 |
| Air too dusty | 61.3 | 65.0 | 89.6 | 37.1 | 0.000 |
| Air too dry | 62.7 | 61.0 | 80.0 | 40.0 | 0.000 |
| Unpleasant odors | 36.6 | 48.3 | 55.6 | 17.1 | 0.000 |
| Chemical smells in air | 17.5 | 21.7 | 34.1 | 17.1 | ns |
| Air too humid | 17.5 | 34.4 | 31.0 | 14.3 | ns |

**Table 3** Effects of the BZF system on mean ratings of perceived indoor air quality (PIAQ)

| Office Area | Pre-installation | Post-installation |
|---|---|---|
| Control | $4.87 \pm 0.24$ | $4.63 \pm 0.32$* |
| BZF | $5.61 \pm 0.23$ | $1.62 \pm 0.33$† |
| Placebo | | $2.00 \pm 1.23$ |

† Pre-BZF vs. post-BZF, $t = -10.41$, $p = 0.000$
* Post-control vs. post-BZF, $t = 6.51$, $p = 0.000$
Post-BZF, vs. placebo, ns.

**Table 4** Effects of the BZF system on disruptions to productivity

| Environmental Condition | Control floor | | BZF floor | | Pre-post BZF P value |
|---|---|---|---|---|---|
| | % Pre- | % Post- | % Pre- | % Post- | |
| Productivity disrupted by: | | | | | |
| Poor indoor air quality | 56.1 | 52.8 | 60.0 | 9.3 | 0.000 |
| Insufficient ventilation | 68.4 | 47.4 | 52.2 | 9.4 | 0.000 |
| Too little air movement | 58.5 | 39.5 | 50.0 | 9.7 | 0.000 |
| State air | 46.4 | 29.0 | 35.6 | 6.3 | 0.003 |
| Air too dry | 38.5 | 35.3 | 33.3 | 9.4 | 0.014 |

**Table 5** Changes in worker reactions between the pre-installation and post-installation surveys

| Office Conditions | Control floor | | BZF floor | |
|---|---|---|---|---|
| | % worse | % better | % worse | % better |
| Office air quality | 17.9 | 3.6 | 0.0 | 94.1 |
| Office ventilation | 10.7 | 3.6 | 0.0 | 94.1 |
| Cleanliness of worksurface | 10.7 | 3.6 | 0.0 | 93.9 |
| Air movement | 7.1 | 0.0 | 0.0 | 91.2 |
| Dust in air | 14.3 | 0.0 | 0.0 | 91.2 |
| Office layout | 14.3 | 7.1 | 5.9 | 91.2 |
| Satisfaction with office conditions | 14.3 | 7.1 | 2.9 | 79.4 |
| Dust on computer screen | 14.8 | 3.7 | 0.0 | 73.5 |
| Office noise level | 14.3 | 14.3 | 14.7 | 55.9 |
| Work productivity | 10.7 | 0.0 | 3.0 | 45.5 |
| Nose and throat symptoms | 3.6 | 0.0 | 0.0 | 45.5 |
| Eye symptoms | 7.1 | 0.0 | 3.0 | 45.5 |

system, an average of $3.00 \pm 1.50$ symptoms was reported.

Analysis of individual symptoms showed no significant changes on the control floor, whereas on the test floor complaints of lethargy fell from 82.2% to 41.7% ($\chi^2 = 14.31$, $p = 0.000$), dry skin from 72.7% to 41.7% ($\chi^2 = 7.88$, $p = 0.005$), and headache from 80.9% to 55.6% ($\chi^2 = 6.20$, $p = 0.013$). All other sick building syndrome complaints were lower following installation of the BZF system, but these changes failed significance at the 5% level. On the test floor disruptions to productivity caused by lethargy fell by 37.7% ($\chi^2 = 10.00$, $p = 0.002$), tired eyes by 33.1% ($\chi^2 = 8.14$, $p = 0.004$), and irritated eyes by 22.4% ($\chi^2 = 4.51$, $p = 0.034$). There were no significant changes on the control floor.

Ratings of how office conditions had changed for better or for worse between the June and October surveys were consistently better for the test floor than for the control floor (Table 5).

## Discussion

Previous work has shown that installing a BZF system into a building with widespread reports of the sick building syndrome improves indoor air quality and worker comfort and health (Hedge et al., 1991). Unlike previous work, the present study was conducted in a building that did not have known indoor air problems, and this was confirmed by the results of the indoor air surveys. However, the results of the worker surveys showed widespread concerns about indoor climate conditions on the control and test floors, and many workers also reported sick building syndrome symptoms in the pre-installation survey. Installation of the BZF system on the test floor did not affect the performance of the building ventilation system. Air exchange rates and horizontal dispersion remained comparable between floors, and therefore the significant survey results cannot be attributed to changes in ventilation system performance. The BZF system improved vertical dispersion and substantially decreased airborne submicronic particles. The BZF system significantly improved reports of indoor air quality, some sick building syndrome symptoms, and productivity.

Results showed improvements in the responses of workers in the placebo area, which questions the degree to which the present findings might be explained by a Hawthorne effect, where workers respond positively to any change in their environment irrespective of this change. Unfortunately, the placebo area did not work as well as intended because, as shown by the particulate count data, there was some mixing of air in the test and placebo areas of the office. Also, workers in the placebo area had real controls to adjust fan speed to improve air movement. Recent research on the effects of using a "personalized environments" system, which also delivers filtered air to workers shows that workers quickly realize when they are using dummy controls and they readily register complaints about this (Kroner et al., 1992). No such comments were made by workers in the present study. Given this, and the three month period covered by the study, we think it unlikely that the improvements reported in the test area can be attributed solely to either a placebo effect, or to a Hawthorne effect. However, a longer-term follow-up study of this space is being designed which will further investigate this issue.

It is not clear why there should have been such a large increase in submicronic particles between the June and October surveys, but the results clearly show that the BZF system substantially reduced airborne submicronic particles. The BZF system also can remove any volatile organic contaminants, and although concentrations of total volatile organic compounds were low in these offices, 3 months after installation of the BZF system TVOC levels had fallen 48% on the test floor. The BZF system lowered airborne particulate counts on the test floor, worker's perceived an improvement in the general cleanliness of their workspace.

Symptoms of headache, lethargy, and dry skin fell significantly on the test floor, and the levels of other sick building syndrome symptoms also were generally lower after installation of the BZF system. There was a reduction in self-reported productivity losses because of symptoms on the test floor. The BZF system also significantly reduced complaints about poor ventilation, and indoor air quality, and reduced self-reported productivity loss because of these conditions. Although the BZF system which was tested in this study is integrated into the furniture other types of systems are commercially available, including free-standing and ceiling-recessed air cleaning systems. Given the benefits of breathing-zone filtration which this study has shown, this choice of systems gives considerable flexibility for designing an optimal local air cleaning system for any office space, and breathing-zone filtration technology gives design professionals an additional cost-effective technology to better mitigate against poor indoor air quality in offices.

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