IMPACT OF VENTILATION RATE, OZONE AND LIMONENE ON PERCEIVED AIR QUALITY IN OFFICES

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ABSTRACT
The objective was to clarify to what extent ozone (O_3) and O_3/limonene, in interaction with surface materials, have an impact on the perceived air quality in typical low-polluting offices at realistic outdoor air change rates. Three offices furnished with similar materials and ventilated with charcoal filtered outdoor air were investigated. Eight environmental conditions with different realistic combinations of air change rate, O_3 level and limonene were studied. A sensory panel entered the offices and immediately assessed the acceptability of the air. Decreasing the air change rate from 1.0 to 0.3 h^{-1} deteriorated the perceived air quality considerably, most pronounced in the presence of O_3. Adding more polluting materials to the offices with a low air change rate kept at 0.3 h^{-1} deteriorated the perceived air quality, most pronounced in the presence of O_3 and O_3/limonene. The results confirm the importance of maintaining sufficient ventilation even for low-polluting offices in order to ensure good perceived air quality.

INDEX TERMS
Perceived air quality, Indoor air chemistry, Ozone, Limonene, Ventilation.

INTRODUCTION
It is well established that the perceived air quality indoors is affected by the ventilation rate and the pollution load on the air. Building materials have been identified to be an important source of pollution indoors as emitters of volatile organic compounds (VOCs). Other factors may affect the perceived air quality, e.g. O_3 and limonene.

Usually most indoor O_3 originates from outdoor O_3 brought indoors by ventilation. Typical indoor/outdoor concentration ratios range from about 0.2 to 0.7. The main reason that the O_3 concentration is lower indoors than outdoors is the interaction between highly reactive O_3 and indoor surfaces (i.e. heterogeneous reactions and deposition) and homogeneous gas phase reactions with chemically reactive VOCs (Weschler, 2000, Morrison et al., 1999). These reactions with O_3 may result in emissions of new chemical substances that are odorous, e.g. aliphatic and unsaturated aldehydes. The chemical composition of VOCs in indoor air may therefore change when the concentration of O_3 changes and consequently change the perceived air quality. It has been demonstrated that O_3 induces changes in emissions from some materials, which affect the perceived air quality (Knudsen et al., 2000).

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Terpenes, e.g. limonene, are often found in indoor air. In its natural form limonene is found in orange and citrus fruits and it is used as an odorant in many household products. Recently, the irritative effects caused by terpenes have been considered due to complaints of the working environment. Wolkoff et al. (1999) have reported irritative effects in mice exposed to combined O_3 and terpenes. Weschler and Shields (2000) have reported chemical effects in indoor environments when O_3 and limonene were present. O_3 reacts with unsaturated chemical compounds and generates new chemical compounds, which may affect the perceived air quality.

The present investigation is part of a large study, with the objective to investigate to what extent O_3, in interaction with surface materials, affects the air quality in buildings. The present paper focuses on the influence of O_3 and O_3/limonene on the perceived air quality in typical low-polluting offices at different, but realistic, ventilation rates.

METHODS

The experiments were carried out in three similar adjacent offices, A, B and C, located at the end of a corridor in a mechanically ventilated office building selected to represent typical Swedish offices. The offices were connected directly with a larger room, that served the sensory panel as a place for refreshing their olfactory sense between air quality assessments. The “refreshing” room was ventilated by charcoal filtered outdoor air to obtain an O_3 concentration below 2 ppb at an air change rate kept at approximately 10 h^{-1}. The temperature and relative humidity were kept at the same level as in the offices. The volume of the offices A, B and C were 29.5, 34.0 and 34.2 m^3, respectively. All office floors were covered with linoleum and walls and ceilings were painted with water-based paint. These surface materials were at least two years old. Each office was furnished with a desk, a chair and a shelf, all at least ten years old. A non-smoking policy had been in force in the building for over a decade. Thus, the offices investigated represented low-polluting offices without strong indoor sources of air pollution.

The original supply and exhaust air devices in the three offices and the “refreshing” room were disconnected. Instead, the offices were ventilated with the use of a specially designed ventilation system constructed for the explicit purpose of the present study. The supply air was filtered using both a coarse particle filter and an activated carbon filter for removal of outdoor pollutants including O_3. O_3 was added to the supply air of offices A and B by means of two O_3 generators of the brand Ozone Technology, model 2000. The O_3 concentration was measured continuously by an UV-photometer of the brand Environics, series 300 connected to a computer that was used for automatic control of the O_3 concentration in the offices. According to the manufacturer, the detection limit of O_3 for this instrument is 1 ppb.

The air temperature and relative humidity in the three offices deviated typically less than 0.6 ºC and 2 % RH, respectively, during days when sensory assessments were carried out. The air temperature varied from day to day within the interval 19-22 ºC. The corresponding interval for the relative humidity was 20-34 % RH.

Eight experiments were carried out, one per week, according to the plan shown in Table 1. Prior to each experiment the offices were conditioned at the new environmental conditions for a one-week period. The offices were operated at the same air change rate during a specific experiment. In office C, the O_3 concentration was kept at a low concentration throughout the investigation, while O_3 was supplied to offices A and B during all experiments except experiments 1 and 7. Experiment 1 should verify whether the three offices were similar initially and experiment 7 was conducted to investigate if the air quality in the offices was perceived to be equal after the various treatments with O_3 and O_3/limonene. Experiments 2, 3 and 4 were carried out to study the effect of O_3 on perceived air quality at different ventilation rates. During experiments 5 and 6 the effect of O_3/limonene were studied at different ventilation rates. Offices B and C were cleaned four times a week with limonene-scented tap water (0.2 – 0.5 ml of limonene, in 5 l of water). The last cleaning activity took place the evening before the panel assessments. Experiment 8 was conducted to compare offices, that were more polluted due to addition of a 1 m^2 rug and 1 m of stacked printed paper and 0.5 m of new paper, with the low-pollution conditions in experiment 5.

Table 1. Experimental plan, where ACR means air change rate

	Office A			*Office B*			*Office C*			
Experiment No.	ACR	Ozone conc.*	Limonene	ACR	Ozone conc.*	Limonene	ACR	Ozone conc.*	Limonene	*Note*
1	1.0	Low	-	1.0	Low	-	1.0	Low	-	
2	1.0	High	-	1.0	High	-	1.0	Low	-	
3	3.0	High	-	3.0	High	-	3.0	Low	-	
4	0.3	High	-	0.3	High	-	0.3	Low	-	
5	0.3	High	-	0.3	High	+	0.3	Low	+	
6	3.0	High	-	3.0	High	+	3.0	Low	+	
7	1.0	Low	-	1.0	Low	-	1.0	Low	-	
8	0.3	High	-	0.3	High	+	0.3	Low	+	Rug and paper added to offices

*High: The O_3 concentration was about 50 ppb in the offices for 6 days and from 16 hours before and during sensory assessments it was reduced to about 10 ppb.
Low: The O_3 concentration was kept below 2 ppb by charcoal filtering of outdoor air.

A sensory panel comprising 34 - 38 subjects performed the sensory assessments. The subjects entered the offices in groups of 3 - 5 persons at a time and immediately assessed the acceptability of the air using the scale in Figure 1. There was at least a 4-min break between each assessment when the panel was seated in the "refreshing" room. The assessments were made according to a randomised plan and panellists were unaware of the environmental conditions.

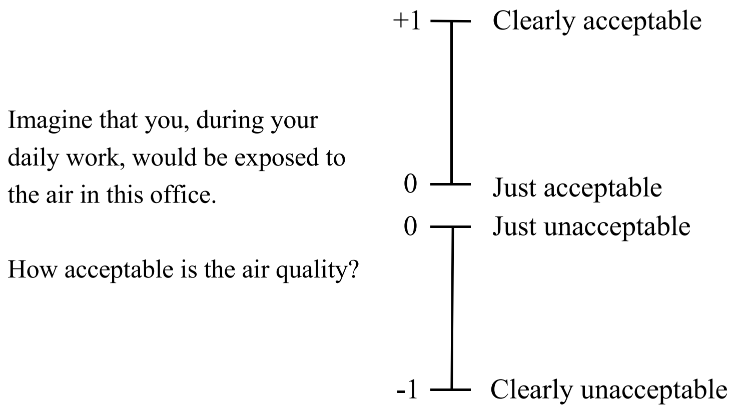

Figure 1. Acceptability scale and the accompanying question. The scale was not numbered during experiments, but the numbers were used for the data analysis.

RESULTS

A total of 41 subjects participated in the study 17 of which participated in all experiments. The difference of the mean acceptability votes between the group of 17 and the total number of subjects was negligible. The following results are therefore based on the results from all subjects.

The panel assessments of experiments 2, 3 and 4 are shown in Figure 2. In this figure and in the following figures the mean acceptability votes are converted to percentage of dissatisfied (Gunnarsen and Fanger, 1992). Increasing the air change rate from 1 to 3 h^{-1} had only a modest effect on perceived air quality which improved from 9 - 19 % dissatisfied to 2 - 11% dissatisfied. However, lowering the air change rate to 0.3 h^{-1} resulted in a more pronounced change in perceived air quality as percentage of dissatisfied increased to nearly 60 % in offices A and B with a high level of O_3, and 30 % in office C with a low level of O_3.

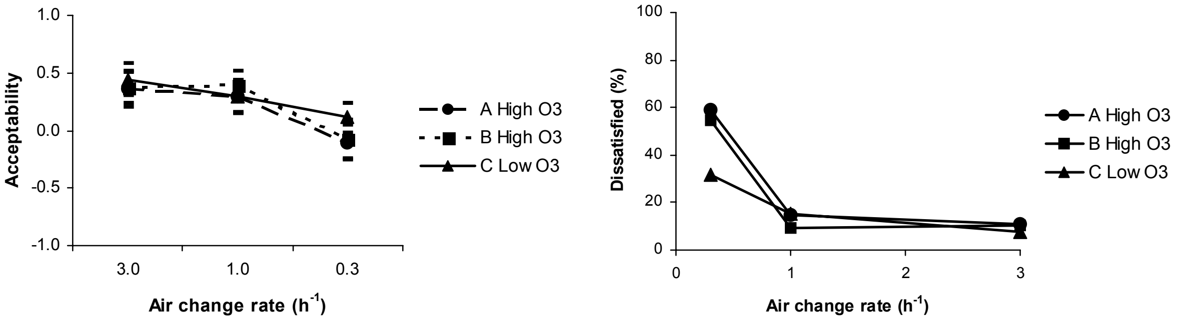

Figure 2. Perceived air quality expressed as the mean acceptability vote and percentage dissatisfied as a function of air change rate at different levels of O_3.

Figure 3 shows the percentage dissatisfied during the experiments at air change rates of 0.3 and 1.0 h^{-1}. Experiment 1 showed that initially the assessments in the three offices A, B and C were similar. This justified comparing effects between the three offices. The assessments of experiments 1 and 7 were similar indicating that the environmental treatments during experiments 2 - 6 were not carried over to experiment 7. At the air change rate of 0.3 h^{-1} the perceived air quality was best at the low level of O_3, i.e. 31 – 43 % dissatisfied, and worst at the high levels of O_3, i.e. 42 – 77 % dissatisfied. There is a clear effect of adding rug and paper to the offices, experiment 8. The deterioration seemed to be most pronounced when O_3 was present.

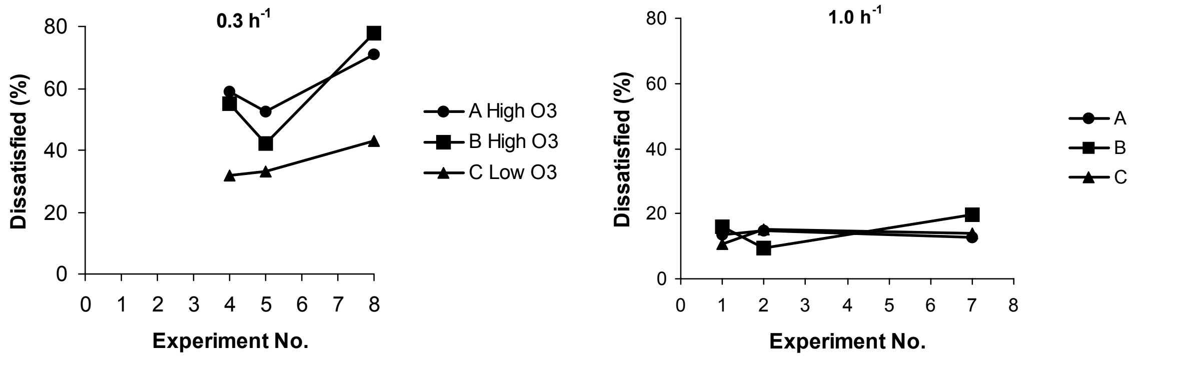

Figure 3. Percentage dissatisfied at different experiments at air change rates of 0.3 and 1.0 h^{-1}

Figure 4 shows percentage dissatisfied as a function of air change rate at different levels of O_3 and with and without limonene, experiments 5 and 6. At the high air change rate, the perceived air quality was good for all treatments, i.e. below 5 % dissatisfied. At the low air change rate, the perceived air quality was worst for the office exposed to O_3, better for the office exposed to O_3/limonene and best for the office exposed only to limonene. Figure 3 and 4 show no clear effect of adding limonene.

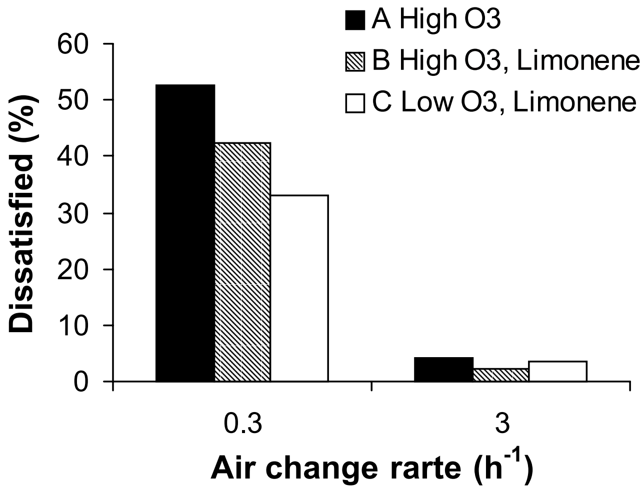

Figure 4. Percentage dissatisfied as a function of air change rate at different levels of O_3 and with and without limonene.

DISCUSSION

The investigated offices were selected to represent low-polluting offices, which was verified by the low percentage dissatisfied observed, e.g. 9-19 % dissatisfied at an air change rate of 1 h^{-1}. There was good agreement between the perceived air quality observed during experiments 1 and 7 both conducted under the same experimental conditions. This indicates that the exposure of the offices to O_3 and limonene did not influence the perceived air quality one week after the end of the last exposure.

Variations of air change rates between the two lowest levels of this investigation, 0.3 and 1.0 h^{-1}, had a pronounced effect on the perceived air quality, while practically no effect was observed for variations between 1.0 and 3.0 h^{-1}. This was the case regardless of whether limonene and/or O_3 were present in the offices. An increase of the air change rate by a factor of 3, from 1.0 to 3.0 h^{-1} would roughly decrease the concentration of pollutants emitted from internal sources to one third at most. Since the offices were low-polluting, such a decrease in the concentration, from an already relatively low level, only had a limited effect on the perceived air quality.

Adding O_3 to the offices had a negative effect on the perceived air quality in cases with low air change rates of 0.3 h^{-1} but no clear effect at higher ventilation rates. This is probably because the emission from internal pollution sources was low. The results indicate that O_3-reactions may influence the perceived air quality as long as the indoor concentration of pollutants is sufficiently high and ventilation rate sufficiently low. In the offices studied this seems to occur at 0.3 h^{-1} but not at the higher air change rates. This is in agreement with the results of Weschler and Shields (2000) who demonstrated that decreasing the air change rate causes the reactant concentration to increase more than the lower ventilation would justify when the time available for reactions increases. Therefore, effects of O_3 can only be expected at low air change rates. The results also show that this is true regardless of whether the floors have been treated with limonene or not.

When the pollution load is increased by adding rugs and paper to the offices the perceived air quality deteriorated further, apparently due to the resulting higher concentration of air pollutants. The effect was more pronounced in the presence of O_3. Furthermore, there is a weak indication that the addition of both O_3 and limonene enhanced the effect further. This first step of a large study focused intentionally on relatively low-polluted offices. Next step will be to study offices with a higher pollution load, resulting from e.g. new building materials and more paper and books at low ventilation rates.

CONCLUSIONS

For the relatively low-polluted offices of this study it is concluded that:

- Decreasing the air change rate from 1.0 to 0.3 h^{-1} deteriorated the perceived air quality considerably. This was most pronounced in the presence of O_3.
- O_3 or the combination O_3/limonene did not affect the perceived air quality at the high air change rates of 3.0 and 1.0 h^{-1}.
- The deterioration of the perceived air quality by adding more polluting materials to offices with low air change rates was most pronounced in the presence of O_3 and O_3/limonene.

The results confirm the importance of maintaining sufficient ventilation even for low-polluting offices in order to ensure good perceived air quality.

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