A literature review on the relationship between outdoor ventilation rates in offices and occupant satisfaction

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Executive Summary

The main aim of office building ventilation is to dilute or remove pollutants and odours that can accumulate as a result of human activities, building materials, furnishings and equipment. The outdoor ventilation rate has the potential to influence occupant satisfaction, health and comfort, particularly in modern office buildings that are typically tightly sealed and ventilated solely through mechanical means.

We therefore conducted a literature review to examine the relationship between outdoor ventilation rates and the primary COPE project outcome, namely occupant satisfaction. Occupant satisfaction was operationalised both as direct ratings of indoor air quality made by office occupants (ie. satisfaction with and perceptions of aspects of indoor air quality) and indirectly through the use of sick building syndrome symptom reports. We were particularly interested to provide a context from which to select a reasonable and realistic outdoor ventilation rate to apply in experimental studies conducted within the COPE project.

Reviewed studies were selected on the basis of rigorous criteria, to ensure that only relevant and reliable studies were reviewed. Using these criteria, we selected ten key studies, including both field and laboratory methodologies.

The results from four of the reviewed studies concluded no evidence to support a significant relationship between outdoor ventilation rates and occupant satisfaction. However, findings from the remaining studies provided support that lower outdoor ventilation rates were associated with less favourable occupant satisfaction. In addition, three studies also suggested that occupant satisfaction may decline with particularly high outdoor ventilation rates. Finally, we found evidence from two studies that the relationship between outdoor ventilation rates and occupant satisfaction may be log-linear in nature, with satisfaction changing more rapidly at lower ventilation rates, as compared to higher rates.

We found that the conflicting results from the above studies could be resolved to some extent, by considering the outdoor ventilation rates over which studies were conducted. In accordance with previous literature reviews on this topic, we found that less favourable occupant satisfaction was most consistently associated with outdoor ventilation rates below 10 L/s.p. Thus, increasing outdoor ventilation rates to this level appears to be beneficial to occupant satisfaction. Above this level of outdoor ventilation, findings were more inconsistent and further systematic research is needed to clarify relationships. However, given the studies conducted to date, there is no strong evidence to suggest that increasing outdoor ventilation rates above 10 L/s.p is associated with further benefits to occupant satisfaction.

Comparisons between studies were noted to be complex, due to differences in ventilation measurement strategies, building characteristics, study designs and the measurement of occupant satisfaction. Furthermore, the effectiveness of a given outdoor ventilation rate in achieving occupant satisfaction is likely to be determined by factors typically not addressed in the reviewed studies, such as pollution loads in the indoor and outdoor environments, in the supply air and the ventilation system itself, and the adequate mixing of air in office spaces. Therefore, outdoor ventilation rates are unlikely to be the sole determinant of occupant satisfaction with indoor air quality. However, we were able to conclude that applying a minimum outdoor ventilation rate of 10 L/s.p is likely to avoid serious detriments to occupant satisfaction, provided that this level of outdoor ventilation is achieved locally and maintained over time.

Table of Contents

Tables and Figures

Outdoor Ventilation Rates in Offices and Occupant Satisfaction

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1.0 Introduction

The term *"ventilation"* derives from the Latin word *"ventilare"*, meaning *"to expose to the wind"* (Sundell, 1994). The American Society of Heating, Refrigerating and Air-Conditioning Engineers defines ventilation as *"the process of supplying and removing air by natural or mechanical means to and from any space"* (ASHRAE, 1999; p.4). The primary purpose of this process is to dilute or remove pollutants and odours which may accumulate as a result of human activities, building materials, furnishings and equipment (Menzies, Tamblyn, Farant, Hanley, Nunes & Tamblyn, 1993a; Jaakkola, 1994; Sundell, 1994; Jaakkola & Miettinen, 1995; Wargocki, Wyon, Sundell, Clausen & Fanger, 2000). It is generally believed that the ability of ventilation strategies to achieve this aim has the potential to influence occupant health, comfort and satisfaction, and as Jaakkola & Miettinen (1995; p.709) state, *"it is commonly accepted that ventilation is necessary for the wellbeing of the occupants."*

It is estimated that more than half of all employees in industrialised nations work in office buildings (Bloom, 1986). In North America, and increasingly elsewhere, these buildings typically have sealed windows and are ventilated solely through mechanical means. In addition, fresh air from outdoors is commonly combined with air recirculated from occupied spaces, primarily to assist in temperature control, air distribution and energy conservation (Jaakkola, Tuomaala & Seppanen, 1994a). Given the large proportion of time office workers spend in such environments, ventilation efficiency, and in particular levels of exposure to outdoor air, have the potential to greatly influence occupant health, comfort and satisfaction at work. Such considerations have led a number of authorities to develop standards for ventilation, to ensure that healthy and acceptable indoor air is achieved.

Historically, ventilation standards have tended to be based on the rate of outdoor ventilation required to maintain acceptable levels of body odour. Early standards, for example, were based largely on work by Yaglou, Riley & Coggins (1936) in which odour acceptability was assessed by panels of judges on initial entry to an occupied space. Following this work, ventilation standards remained largely unchanged for many years, at a typical recommendation of 7.5 litres of outdoor air per second per person (L/s.p) (ASHRAE, 1977). A number of researchers further developed research into odour assessments (eg. Berglund & Lindvall, 1979; Cain, 1979; Fanger & Berg-Munch, 1983; Fanger, 1988; Fanger, Lauridsen, Bluyssen & Claussen, 1988) and, as Sundell (1994) notes, odour remained the primary consideration for acceptable ventilation.

However, in response to the energy crisis of the 1970's, required ventilation rates were reduced considerably; in North America to a recommended rate of 2.5 L/s.p of outdoor air (ASHRAE, 1981). At around the same time, concerns arose over the possible adverse health effects of indoor air pollutants such as radon (Swedjemark, 1979) and formaldehyde (Anderson, 1979), and there was an increasing awareness of health complaints being made by employees in modern sealed and mechanically ventilated office buildings. Such health concerns gave rise to the term *"sick building syndrome"* (SBS), defined by the World Health Organisation (1983; p.6) as *"an increase in the frequency of building occupant reported complaints associated with acute non-specific symptoms (eyes, nose or throat irritation, headache, fatigue, nausea) in non-industrial environments that improve while away from the buildings."* In addition, SBS is also often characterised by skin irritation, difficulties concentrating and breathing problems (Seppanen, Fisk & Mendell, 1999).

The temporal coincidence of SBS and reduced outdoor ventilation rates led to widespread support for the argument that inadequate ventilation was a primary cause of SBS (Tamblyn, Menzies, Tamblyn, Farant & Hanley, 1992; Menzies et al, 1993a; Mendell, 1993; Sundell, 1994). Indeed, concerns over occupant health were incorporated into ventilation standards, leading to a recommended minimum outdoor ventilation rate of 10 L/s.p for North American office spaces (ASHRAE, 1989). This rate of outdoor ventilation continues to be the current standard (ASHRAE, 1999).

However, despite increased awareness of occupant health implications, the formation of standards is still primarily based on odour acceptability (Sundell, Lindvall & Stenberg, 1994a; Seppanen et al, 1999). Furthermore, the studies forming this basis have tended to be performed in laboratory settings, been focussed mostly on body odour rather than other pollutants, assessed the odour emissions of relatively inactive occupants, and used visitor panels rather than the occupants themselves as assessors (Palonen & Seppanen, 1990; Seppanen et al, 1999). Indeed, some European researches (eg. Fanger, 1988) have suggested that more acceptable outdoor ventilation rates should be as high as 50 L/s.p. Such changes, however, are likely to increase energy useage and lead to problems in temperature control, and the overall benefits to occupants remain somewhat unclear (Menzies et al, 1993a).

Thus, it is important to review recent scientific literature in order to determine evidence on outdoor ventilation rates and their impact on occupant reactions. Over the last decade, three literature reviews have been conducted that discuss outdoor ventilation rate studies to varying degrees. Mendell (1993) produced a review of 37 factors potentially related to office worker SBS symptoms, one of which was ventilation rates. Three years later, a review of the relationships between ventilation and indoor air quality in a variety of occupational settings was published by Godish and Spengler (1996). Most recently, Seppanen et al (1999) conducted a review on the associations of both outdoor ventilation rates and CO_2 concentrations to human responses in a number of occupational contexts. These three reviews provided a framework for the current review. However, our review differs from these previous works in terms of context, inclusion criteria and interpretation of some results. Such differences are highlighted within this report as appropriate, and our conclusions are compared to those drawn in previous reviews at the end of this paper.

The focus of the COPE project is on the impact of indoor office environment parameters on occupant satisfaction. As such, in this review we discuss the impact of outdoor ventilation rates on this outcome[1]. Occupant satisfaction is most directly measured using self-report ratings of indoor air quality, in which occupants are asked about their satisfaction with, or perceptions of, aspects of the indoor environment.

It is also reasonable to assume that occupants who experience environment-related health symptoms will also tend to be less satisfied with that environment. SBS symptom reports have been shown to be significantly related to environmental satisfaction in a number of studies (eg. Broder, Pilger & Corey, 1990; Hedge, 1988; Hedge, Burge, Robertson, Wilson & Harris-Bass, 1989). For example, in a study of 179 office workers, Broder et al (1990) found significant relationships between: satisfaction with odour and nasal symptom reports; satisfaction with workstation comfort and tiring easily; and satisfaction with fresh air and eye irritation, throat discomfort and overall number of symptoms reported. Therefore, since one of the major concerns of outdoor ventilation rates is the potential association with SBS, we also included papers that

[1] During the course of conducting this literature review, we also noted one study that used task performance as an outcome. As this outcome is not the main focus of the COPE project, the findings from this study are not included in our review. They are, however, briefly discussed in Appendix A.

measured SBS symptoms, and considered this outcome as an indirect assessment of occupant satisfaction. For the purposes of this review, we therefore use the term *"occupant satisfaction"* to include both ratings of indoor air quality and reports of SBS symptoms.

In the context of the COPE project, the aim of this literature review is to provide a context from which we can determine a reasonable and realistic outdoor ventilation rate to apply in experimental studies.

We conducted the review in four stages. Firstly, to ensure that only relevant and reliable studies were included, we developed and applied criteria for selection. Following this selection procedure, the main characteristics of the resulting studies were collated, and the findings from the selected studies were summarised. Finally, we considered methodological limitations that may influence reported findings and cause difficulties in making comparisons between studies.

2.0 Selection Criteria

The studies reviewed in this paper were selected from the COPEINFO database. This database, created as part of the COPE project, currently contains 693 records, the majority of which relate to the field of indoor air quality. The database is the result of detailed searches performed on a number of engineering, science, medical and psychological electronic literature databases, such as *EI Compendex, INSPEC, Current Contents, Ergonomic Abstracts, PsychInfo* and *Medline*. In order to maintain relevance, such searches were limited to the years 1985 to 2001, with greater focus being placed on more recent studies. The resulting database includes journal articles from sources including *Indoor Air, ASHRAE Transactions, Energy and Buildings, Journal of Environmental Psychology, Journal of Occupational Medicine* and *Environment International.* The database also includes records from conferences such as *Indoor Air, IAQ, CLIMA 2000,* and the *Human Factors and Ergonomics Society*, in addition to a number of books, book chapters and reports. Search terms used to collect records that are relevant to this review included the following: satisfaction; sick building syndrome; comfort; employee attitudes; health; human factors; indoor air quality; ventilation; indoor environment; offices; and employees. Thus, the COPEINFO database provides detailed information of recent research, from which to select articles relevant to the current literature review.

There were over 200 records in the COPEINFO database that focused on some aspect of ventilation. In order to ensure that the studies included in this review were relevant, reliable and methodologically sound, a two-stage selection process was developed.

The first stage of selection concerned the subject matter of papers. We selected studies conducted in office settings, the results of which had been published from 1990 onwards. We also included papers only if they featured both measurements of outdoor ventilation rates and one or more measures of occupant satisfaction, as discussed above. As the terms "ventilation" and "outdoor ventilation" are often used interchangeably, we were careful to ensure that selected papers were concerned with outdoor ventilation rates rather than total supply ventilation (ie. outdoor + recirculated air). In order to be able to compare papers, only those which measured outdoor ventilation rates in litres per second per person (L/s.p), or which gave sufficient information to enable calculation of these units, were included. In practice, no paper was excluded solely on the basis of this criterion. We also excluded papers that focused only on ventilation system characteristics, for example natural versus mechanical ventilation. As the focus of our review was the reaction of occupants rather than visitors to office spaces, we did not include studies that used panels of visitor subjects to assess satisfaction. After applying these selection criteria, 55 relevant studies remained.

Following these initial selection criteria, we assessed each paper in terms of the strength of research design, use of statistical analyses, measurement techniques and methodological strategies, and sufficient reported information to enable judgements of the reliability of findings.

This process proved to be extremely labour-intensive, since we found that study designs, approaches and the quality of reported information varied widely between studies. As such, we were not able to apply simple, blanket exclusions as in the first stage of selection, but rather had to judge each paper on its own relative merits, given the information available. We aimed to exclude studies where the design, methodology and/or amount of reported information gave rise to serious concerns over the reliability of results. Unfortunately, we were forced to exclude more than half of the papers assessed on the basis of this second stage of selection. Common reasons for excluding papers included: lack of information on sample size or characteristics; insufficiently large sample size; lack of blinding, control groups or cross-over trials in experimental studies; and the lack of statistical testing of the relationship between outdoor ventilation rates and human responses. The extent of these exclusions raises some concerns over the quality of design, analysis and reporting of studies in this field in general; an issue that will be returned to later in this review.

We also considered the issue of controlling for possible confounders, either in the study design or in statistical analyses. Controlling for extraneous factors which may influence results is an important design consideration, particularly as previous research has shown a number of personal, work-related, and physical characteristics to be associated with occupant responses. For example, Mendell's (1993) review indicated that a diverse range of factors, including air-conditioning, humidification, mechanical ventilation, temperature, humidity, wall-to-wall carpets, occupant density, job stress, female gender, atopy and the use of visual display terminals, have been shown to be associated with SBS symptom reports. In general, studies varied greatly in the extent to which potential confounders were considered. However, in accordance with Seppanen et al's (1999) review, we felt that included studies should control at least for personal occupant characteristics, either in the design of the study or in statistical analyses. Through this exclusion process, we selected ten studies to form the basis of this review.

Our selection criteria resulted in some differences in inclusion, as compared to the three literature reviews mentioned previously. These differences are largely attributable to the exclusion of studies not conducted in office settings (eg. Norback, Ingegerd & Widstrom, 1990; Wyon, 1992; Drinka, Schilling, Miller, Schult & Gravenstein, 1996), studies which focussed solely on comparisons between ventilation systems (eg. Skov, Valbjorn, Pedersen & The Danish Indoor Climate Study Group, 1990b; Zweers, Preller, Brunekreef & Boleij, 1992), studies which used only indoor CO_2 concentrations as an approximation of ventilation effectiveness (eg. Hodgson, Frohliger, Permar, Tidwell, Traven, Olenchock & Karpf, 1991; Hodgson, Muldoon, Collopy & Olesen, 1992; Hill, Craft & Burkart, 1992), studies using visitor panel assessments of indoor air quality (eg. Bluyssen, Fernandes, Groes, Claussen, Fanger, Valbjorn, Bernhard & Roulet, 1996), and studies which were excluded due to lack of reported information or concerns over research design or methodology (eg. Nagda, Koontz & Albrecht, 1991; Wu & Wang, 1996; Menzies, Tamblyn, Tamblyn, Farant, Hanley & Spritzer, 1990).

3.0 Description of Studies

The main characteristics of the studies included in this review are shown in Table 1. In practice, many of these studies were reported in more than one conference or journal publication, often in differing formats or focussing on different aspects of the collected data. For the purposes of this review, we selected the most recent or the most detailed publication as the primary source, with information from additional publications being included as appropriate. In addition, some of the papers reviewed included more than one statistical test of the data, either in testing several outcome measures, testing several subgroups of the data, or comparing several levels of outdoor ventilation rate. One paper, by Jaakkola, Heinonen & Seppanen (1991a) included two separate studies, each of which was considered separately. Therefore, although this review is based on ten studies, more than ten statistical tests and findings result from these papers.

As is shown in Table 1, the reviewed studies included six cross-sectional studies, three field experiments and one laboratory experiment. All of the experimental studies included acceptable strategies to ensure that occupants were blinded to outdoor ventilation rate conditions. The studies were conducted using between one and 160 office buildings, and included statistical analyses based on responses from between 30 and 1546 office occupants. Although only two of the ten studies were conducted in North America, the remaining European studies focused primarily on comparable mechanically ventilated buildings. Most studies were conducted in the winter, although two included spring measurements and one was conducted over an entire year.

Reported outdoor ventilation rates ranged from 0 to 70 L/s.p, although studies more commonly investigated ventilation rates in the range of 5 to 30 L/s.p. In addition, studies varied in the form of outdoor ventilation rates used in statistical analyses. For example, some studies used the full range of measured ventilation rates, whilst others used categories formed either on the basis of observed ventilation rates or with respect to nominal ventilation rates the study aimed to achieve. Where both categories and a range of outdoor ventilation rates were used in statistical analyses, details of both are shown in Table 1.

Studies involving assessments of occupant satisfaction by indoor air quality ratings were found to be relatively few, and only four of the reviewed studies contained such investigations. In all cases, ratings of indoor air quality were assessed using self-report questionnaires. More common were studies in which self-reported SBS symptom reports were used, and eight of the reviewed studies included such assessments. The study by Milton, Glencross & Walters (2000) focused on absence rates due to short-term sick leave. Sick leave rates provide a measure of occupant health, and, as this paper notes, a large fraction of all short-term sick leave can be accounted for by respiratory illness (Nichol, Lind, Margolis, Murdoch, McFadden, Hauge, Magnan & Drake, 1995; Bendrick, 1998). Thus, this study can be broadly considered as an assessment of SBS symptoms.

Many of the studies, particularly those involving SBS symptoms, reported their findings in the form of odds ratios. Odds ratios are defined by Seppanen et al (1999; p.233) as:

$$[a/(1-a)] / [b/(1-b)]$$

where a and b are the prevalences of the outcomes of the two groups under comparison, and a is the prevalence of the group with the higher prevalence. An odds ratio equal to 1.0 indicates no increased risk of adverse reactions for group a as compared to group b.

Table 1 shows the occupant satisfaction measures investigated in each study, along with the overall conclusions drawn regarding their associations with outdoor ventilation rates. Three of the studies found differing relationships between outdoor ventilation rates and occupant satisfaction, depending on the ranges of ventilation rates compared in statistical analyses. The findings from these studies, including more detail on the outdoor ventilation rates used, are summarised below.

4.0 Results of Reviewed Studies

In four of the reviewed studies no significant relationship between outdoor ventilation rates and occupant satisfaction (ie. ratings of indoor air quality or SBS symptoms) was found. Menzies et al (1993a), for example, conducted a six-period double-blind cross-over experiment, using 1546 Canadian office workers from 4 buildings. In this study, occupants randomly experienced two outdoor ventilation rates, each for three one-week periods. Using crude odds ratios, this study found no significant differences in SBS symptom reports between average outdoor ventilation rate conditions of 14 and 30 L/s.p. Analyses using subgroups argued to be

Table 1: Main Characteristics of Studies included in Review

Author, date	Type of study	Number of buildings	Number of subjects	Season	Location	Outdoor ventilation rates (L/s.p)	Symptoms	Ratings of indoor air quality
Palonen & Seppanen 1990	cross-sectional	5	580	winter	Europe	<5 – >15	-	↑ / ↓
Jaakkola et al 1991a	cross-sectional	1	938	winter	Europe	7 – 70 <15 – >35	↔	-
Jaakkola et al 1991a	experimental	1	902	winter / spring	Europe	6 – 26	↑	-
Menzies et al 1993a	experimental	4	1546	winter / spring	North America	14 – 30	↔	-
Jaakkola et al 1994a	experimental	2	72	winter	Europe	6 – 23	↔ / ↓	↔ / ↓
Sundell et al 1994a	cross-sectional	160	226 – 725	winter	Europe	2 – 50 <13.6->13.6	↑	-
Cochet et al 1995	cross-sectional	6	618	winter	Europe	6.4 – 13.4 4.2 – 19.8	↑	↑
Jaakkola & Miettinen 1995	cross-sectional	14	399	winter	Europe	<5 – >25 0 – 25	↑ / ↓	-
Milton et al 2000	cross-sectional	40	705	year	North America	12 – 24	↑	-
Wargocki et al 2000	lab experimental	lab	30	winter	Europe	3 – 30	↑	↔

Outcome effects: ↑ = more favourable outcome at higher outdoor ventilation rate ↓ = less favourable outcome at higher outdoor ventilation rate
↔ = no relationship between outcome and outdoor ventilation rate

more susceptible to SBS (eg. female gender, atopic illness), also failed to find a significant relationship between outdoor ventilation rates and SBS symptoms.

In the cross-sectional study reported by Jaakkola et al (1991a), based on 938 Finnish office workers from one mechanically ventilated building, outdoor ventilation rates in the range of 7 to 70 L/s.p (mean 26 L/s.p) were not found to significantly predict SBS symptom scores, either in bivariate analyses, nor using multivariate analyses which controlled for the effects of temperature, smoking habits, gender, atopy and psychosocial atmosphere. Furthermore, no significant differences were found between symptom reports when the measured ventilation rates were separated into four categories, representing outdoor ventilation rates of less than 15, 15 to 25, 25 to 35, and greater than 35 L/s.p, after controlling for gender, atopy, smoking habits and psychosocial atmosphere, although temperature differences were not controlled for in this latter analysis.

Jaakkola et al (1994a) conducted a four-period blinded cross-over trial, using two Finnish buildings. In this study, 72 occupants experienced two outdoor ventilation conditions, produced by manipulating the percentage of recirculated air whilst keeping the total air supply rate constant, each for two one-week periods. These two ventilation conditions resulted in average measured outdoor ventilation rates of 6 L/s.p and 23 L/s.p. Overall, this study found no significant differences between mean SBS symptom scores for the two conditions, either for individual symptoms or for composite mucosal, skin reaction, allergic reaction and general symptom scores. In addition, no significant differences in occupant perceptions of dustiness or stuffiness between the two ventilation rate conditions were found. This paper also reported an overall lack of significant differences between the number of occupants who experienced worse satisfaction (more symptoms, less favourable perceptions) during the lower outdoor ventilation rate as compared to the number of occupants who experienced better satisfaction during this condition. This latter finding was the case both for the total sample, and for a subsample containing only those employees who had reported specific symptoms or perceptions during the last twelve months.

Finally, Wargocki et al (2000) used a laboratory-based office environment to test the occupant responses of 30 female subjects, each experiencing outdoor ventilation rate conditions of 3, 10 and 30 L/s.p for a duration of 275 minutes each condition. As part of this study, occupants were asked to rate perceived air freshness, odour intensity and acceptability of air quality, both on entering the space (ie. acting as visitors) and during exposure. Although monotonic improvements were found with increasing outdoor ventilation conditions in relation to these perceptions on entering and re-entering the space, no significant differences were found during exposure in the office itself.

In contrast to the above findings, support for a significant relationship between increasing outdoor ventilation rates and improvements in occupant satisfaction were reported in the remaining reviewed studies.

Cochet, Riberon & Kirchner (1995) reported significantly higher symptom odds ratios for three French buildings which tended to have lower outdoor ventilation rates (average 6.4 L/s.p) as compared to three buildings with higher outdoor ventilation rates (average 13.4 L/s.p). Similarly, after removing the naturally ventilated building from their sample, Cochet et al (1995) found a significant correlation between outdoor ventilation rates and the percentage of occupants satisfied with indoor air quality as a whole.

Palonen & Seppanen’s (1990) study focused on dissatisfaction with odour, dustiness and stuffiness, as rated by 580 occupants from five Finnish office buildings. This study found a significant overall correlation between increased outdoor ventilation rates and more favourable occupant satisfaction, using the four ventilation rate categories of less than 5, 5 to 10, 10 to 15 and more than 15 L/s.p.

In the experimental part of Jaakkola et al's (1991a) study, the building under investigation was split into four zones, with each zone experiencing a different outdoor ventilation rate condition. Ventilation rates were reduced from normal operating conditions by 0%, 60%, 75% and 100%, with the resulting measured outdoor ventilation rates being on average 26, 10, 6, and 0 L/s.p respectively. Although no significant differences in symptom reporting were found after three days at the new outdoor ventilation rates, significant effects were observed three weeks after the intervention. At this time, symptom reports from a total of 902 occupants indicated a 14.8% decrease over time for the control group (26 L/s.p), as compared to an average 8.2% decrease for the three trial groups (average approx 6 L/s.p). These findings were adjusted for gender and pre-intervention symptom reports. However, although this significant difference between the control and combined trial groups was found, a significant trend across the four ventilation conditions was not supported.

Similar conclusions were also reported by Jaakkola, Reinikainen, Heinonen, Majanen & Seppanen (1991b), on the basis of a cross-sectional analysis of the data collected three weeks after the above intervention. Using a random sample of 564 occupants from the 0%, 60% and 75% reduction conditions, this study states that symptom reports improved significantly across increasing outdoor ventilation rate categories of less than 5, 5 to 10, 10 to 15 and above 15 L/s.p.

In Wargocki et al's (2000) laboratory experiment, SBS symptoms were reported in addition to the occupant perceptions discussed above. The results of this study found that subjects' reports of throat dryness, mouth dryness, difficulties thinking clearly and feeling bad were all significantly affected by the ventilation conditions. More specifically, it was found that these symptoms decreased monotonically with increasing outdoor ventilation rates of 3, 10 and 30 L/s.p. In addition, there was also evidence that fatigue and depression were significantly worse during conditions of reduced outdoor ventilation, although the absolute change in these symptoms was noted to be small. Finally, Wargocki et al (2000) observed that reports of decreased nose irritation at higher ventilation rates approached significance, and that throat irritation tended to be higher during exposure to the 3 and 10 L/s.p outdoor ventilation conditions.

Significant relationships between outdoor ventilation rates and occupant satisfaction were also reported by Sundell et al (1994a), using subsamples taken from cross-sectional data on 4943 Swedish office workers from 160 buildings. In a case-control study of 414 occupants from this sample, non-significant crude odds ratios were observed for outdoor ventilation rates below 13.6 L/s.p (the median outdoor ventilation rate for the whole study population), as compared to rates above 13.6 L/s.p. However, after restricting the sample to occupants from one- or two- person offices, a significant odds ratio of 1.7 was found. Larger offices were excluded from this analysis because *"…they differed from smaller rooms in a number of ways that might hide the influence of the ventilation parameters under study…"* (Sundell et al, 1994a; p.242).

Furthermore, in tests based on 266 occupants for whom psychosocial data had been collected, increasingly elevated odds ratios were reported after controlling for the presence of photocopiers and ventilation factors such as operating hours and recirculation (OR=2.1), and after controlling for these factors plus personal and work-related factors such as asthma, sensitivity to sunlight, amount of paperwork and work satisfaction (OR=2.3). These cumulative restrictions demonstrate the importance of controlling for confounding factors which may influence results, since the odds ratios in this study became larger after physical, work-related and personal factors were controlled for. Similar findings were also reported by Sundell, Lindvall, Stenberg & Wall (1994b), although the order in which factors were controlled for differed in these analyses of the data.

In a similar case-control study of 464 occupants selected from the same total sample, Stenberg, Eriksson, Hoog, Sundell & Wall (1994) also found significantly elevated odds ratios for low outdoor ventilation rates (less than 8.5 L/s.p) and for medium outdoor ventilation rates (8.5 to 13.6 L/s.p), both as compared to outdoor ventilation rates higher than 13.6 L/s.p.

Finally, in a cross-sectional study of 399 Finnish office workers from 14 mechanically ventilated buildings, Jaakkola & Miettinen (1995) found the prevalence of symptoms to be lowest in the outdoor ventilation rate range of 15-25 L/s.p, as compared to outdoor ventilation rates of less than 5 and 5 to 15 L/s.p, after standardising for age and gender. Furthermore, this study reported significant increases in odds ratios for the two outdoor ventilation categories below 15 L/s.p. More specifically, odds ratios ranging from 1.4 for lethargy to 8.9 for skin symptoms were found in relation to the outdoor ventilation rate range of 5 to 15 L/s.p, as compared to the 15 to 25 L/s.p category. In addition, odds ratios for the less than 5 L/s.p group were found to be generally higher, ranging from 2.1 to 41, with the highest odds ratios being in relation to skin symptoms (OR=41), nasal symptoms (OR=7.7) and eye symptoms (OR=5.6) composites. These reported odds ratios were adjusted for a wide range of personal, work-related, and building factors, including age, gender, atopy, smoking, ventilation system, sealed windows, carpets, photocopying, job stress and job tenure. Overall, these authors concluded that *"it seems that an outdoor air ventilation rate below 5 l/s per person is a strong determinant of ocular, nasal, pharyngeal, and skin symptoms, as well as general symptoms…"* (p.713).

As was previously noted, the study conducted by Milton et al (2000) used sick leave rates over one year as the occupant outcome. As part of a larger cross-sectional study, these researchers investigated organisational sick leave data from office workers at a large Massachusetts employer occupying 40 buildings. Total sick leave rates for 705 office employees working in "moderate" (average 12 L/s.p) and "high" (average 24 L/s.p) outdoor ventilation conditions were found to be largely similar. However, after restricting analyses to short-term sick leave and controlling for humidification, age, gender, occupant crowding and hours of non-illness absence, a significant relative risk of 1.53 was found for moderate outdoor ventilation rates, as compared to high outdoor ventilation rates. These findings were consistently reproduced in further analyses which progressively restricted the quantity of short-term sick leave. Milton et al (2000; p.216) concluded that;

> *" The relative risk of 1.53 for sick leave implied that 35% of short-term sick leave was attributable to lower ventilation among exposed workers, or 1.2 to 1.9 days of increased sick leave per person per year, depending on age and gender."*

As the researchers conducting this study were careful to include only sick leave which was likely to be influenced by the office environment, these findings imply a relationship between outdoor ventilation rates and SBS-related health.

In addition to the findings discussed above, two of the reviewed studies also provided some support for a log-linear relationship between outdoor ventilation rates and SBS symptoms. Sundell and colleagues (Sundell, 1994; Sundell et al, 1994a; Stenberg et al, 1994) plotted outdoor ventilation rates in the range of 2 to 50 L/s.p against SBS symptom odds ratios. The resulting graphs suggested a log-linear relationship such that symptom odds ratios increased more rapidly at lower outdoor ventilation rates than at higher outdoor ventilation rates.

In addition, in analyses reported by Sundell et al (1994a) and Sundell, Lindvall & Stenberg (1991), a subsample of data (restricted to those occupants from one- or two- person offices, from buildings where more than two rooms had been measured, and from buildings where at least fifteen occupants had responded) was used to investigate the association between SBS symptom prevalence and log-transformed outdoor ventilation rates. These analyses, conducted separately for 725 women from 27 buildings and for 625 men from 24 buildings, found significant negative linear relationships between log-outdoor ventilation rates and general symptoms for both men and women. Significant negative linear relationships were also found between log-outdoor ventilation rates and mucous membrane symptoms for women only, and between log-outdoor ventilation rates and skin symptoms for men only.

Jaakkola & Miettinen (1995) also investigated the existence of a log-linear relationship in their study, finding a linear increase in log-SBS symptom odds ratios for decreases in outdoor ventilation rates in the range of 0 to 25 L/s.p. This finding was significant in relation to eye, nasal, and skin symptoms, in addition to lethargy.

However, some indication that occupant satisfaction might become worse at higher outdoor ventilation rates was provided by three of the studies reviewed. Firstly, in addition to the three categories of outdoor ventilation rate (<5, 5-15 and 15-25 L/s.p) discussed previously, Jaakkola & Miettinen's (1995) study also included an outdoor ventilation rate category of 25 L/s.p and above. It was found that the prevalence of SBS symptoms was higher in this category, as compared to the 15 to 25 L/s.p group, and elevated odds ratio ranging from 1.1 for lethargy to 14.8 for skin symptoms were also observed.

Secondly, in the study by Jaakkola et al (1994a), there was some suggestion that occupants experienced less sneezing and coughing symptoms and better perceptions of odour under the lower outdoor ventilation rate condition (average 6 L/s.p) as compared to the higher outdoor ventilation rate condition (average 23 L/s.p).

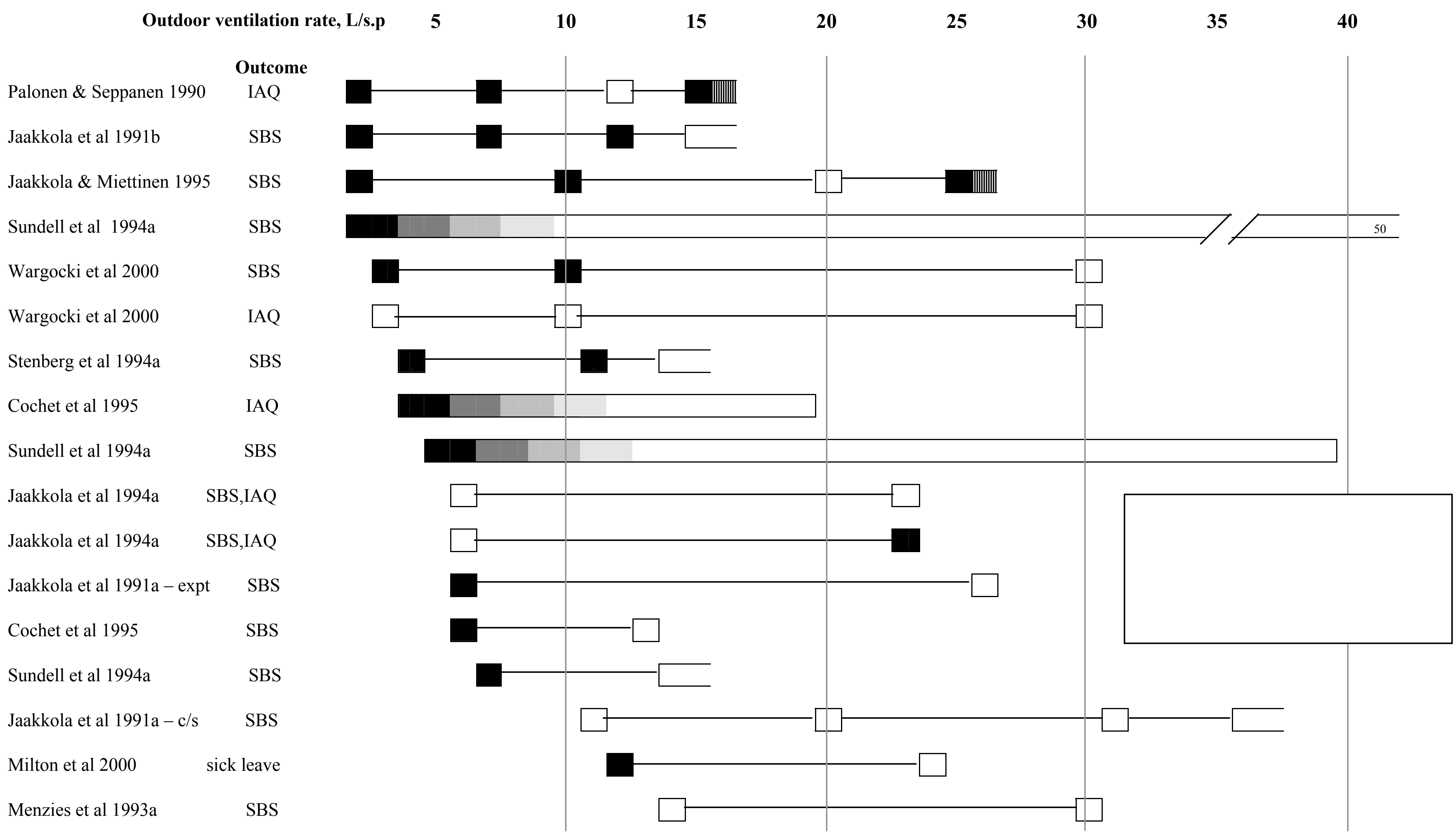
Finally, although Palonen & Seppanen's (1990) study reported an overall significant positive relationship between outdoor ventilation rate and occupant satisfaction, the reported percentages of dissatisfied occupants across the four ventilation categories used (<5, 5-10, 10-15, >15) suggested that there may be some increase in dissatisfaction with dustiness and stuffiness at the highest ventilation category.

Overall, the reviewed studies present conflicting evidence regarding the nature and existence of a relationship between outdoor ventilation rates and occupant satisfaction. These differences in findings may be due, at least in part, to methodological limitations associated with some of the studies, or to difficulties in comparing between studies. Such considerations are discussed in more detail in the next section.

The conflicting results discussed in this review can, however, be resolved to some extent by considering the outdoor ventilation rates over which studies were conducted. Figure 1, modified from similar diagrams by Seppanen et al (1999) and Mendell (1993), shows the main results of statistical tests conducted in the studies discussed above. More than ten results are shown as some studies reported different findings depending on the measure of occupant satisfaction used, and some studies reported several, qualitatively different, statistical tests of the data. Statistical analyses conducted over a continuous range of outdoor ventilation rates are depicted as a bar, with the shaded end indicating significantly less favourable occupant satisfaction. For those studies in which categories of ventilation were compared, the outdoor ventilation rate for each category is shown, with darker squares indicating significantly less favourable occupant satisfaction. In those studies where the compared categories were ranges of ventilation (eg. 5-15 L/s.p), the average outdoor ventilation rate is shown. In many cases, the upper and lower measured ventilation rates for range categories were not reported in the reviewed papers. The average of lower end ventilation ranges (eg. <5 L/s.p) can be reasonably estimated, since the minimum ventilation rate cannot fall below 0 L/s.p. However, for higher end ventilation ranges (eg. >35 L/s.p) an average cannot reasonably be computed, as the maximum ventilation rates were usually not reported. In these cases, the higher ventilation range is shown as an open-ended box.

As figure 1 indicates, the most consistent findings were reported for outdoor ventilation rates below 10 L/s.p, with less favourable occupant satisfaction being associated with outdoor ventilation rates below this level. Above 10 L/s.p, findings are more inconsistent, with some studies suggesting that increased risks of unfavourable satisfaction may also occur in the region of 10 to 15 L/s.p. At higher ventilation rates, most studies concluded little evidence for increased risks of unfavourable occupant satisfaction.

Figure 1: Outdoor Ventilation Rates and Occupant Satisfaction



In the three studies which suggested increased occupant dissatisfaction at higher outdoor ventilation rates, it is argued that sources of pollution in the ventilation system itself may have been spread more widely at higher ventilation rates (Jaakkola & Miettinen, 1995). Similarly, unless rates of recirculated air were reduced to compensate for higher outdoor ventilation rates, overall air velocity may have increased, leading to the distribution of pollution from sources present in the buildings and causing thermal comfort problems. Berglund & Lindvall (1986) also argue that occupants use a process of pattern recognition in sensing indoor air, and that, as high ventilation rates can lead to extreme air homogenisation, this may lead to sensory confusion for occupants. Finally, Seppanen et al (1999) also notes that two of the studies finding evidence of lower dissatisfaction at higher ventilation rates (Jaakkola et al, 1994A; Jaakkola & Miettinen, 1995) were both conducted during the Finnish winter, where very low humidities may have influenced results.

The suggested possibility of log-linear relationships between outdoor ventilation rates and occupant satisfaction supports the pattern of findings outlined above. That is, if occupant satisfaction is more responsive to ventilation conditions at lower levels, then evidence to support a relationship will probably be easier to detect in outdoor ventilation ranges below 10 L/s.p. The effects of higher outdoor ventilation rates on occupant satisfaction may be more subtle and thus more difficult to detect, particularly in studies using a smaller number of occupants, fewer buildings and relatively short exposure periods.

Overall, research findings suggest that outdoor ventilation rates below 10 L/s.p are associated with an increased risk of occupant dissatisfaction. Thus, increasing outdoor ventilation rates to this level appears to be beneficial to occupant satisfaction. Above this level of ventilation findings are more inconsistent and more systematic research is needed to further clarify this relationship. However, given the studies conducted to date, there is no strong evidence to suggest that increasing outdoor ventilation rates above 10 L/s.p is associated with further benefits to occupant satisfaction.

5.0 Methodological Limitations

As was asserted earlier, during the course of conducting this review we noted a number of methodological limitations. Some of these criticisms apply to individual studies, whilst others are more general issues which make comparisons between studies difficult to make. These methodological concerns are discussed below, and focus on ventilation measurement issues, building characteristics, study design and methodology, and occupant satisfaction measurement. To aid our discussion, detailed characteristics of the reviewed studies are provided in Table 2.

5.1 Ventilation Measurement

The vast majority of studies were conducted in buildings equipped with mechanical supply and exhaust systems. Some alternative ventilation systems were also investigated, particularly in studies using a larger number of buildings, although in most cases differences between such ventilation systems were controlled for in statistical analyses. In the case of Wargocki et al's (2000) laboratory study, air was supplied by axial fans and left the space through a slot under the door; a system used to ensure that possible pollution from the ventilation system itself did not influence this study. Finally, Seppanen et al (1999) notes that the ventilation system used in the building studied by Jaakkola et al (1991a) was somewhat unusual, with air being supplied to hallways and being exhausted only from perimeter offices.

As indicated in Table 2, outdoor ventilation rate measurements were made using tracer gas, airflow measurements or CO_2 concentrations. The measurement strategies employed in the reviewed studies are likely to influence the accuracy of reported outdoor ventilation rates, with particular concerns being associated with calculations made from indoor CO_2 concentrations

Table 2: Detailed Characteristics of Studies

Author, date	Type of study	Number of buildings	Number of subjects	Season	Location	Outdoor ventilation rates (L/s.p)	Ventilation measurement	Ventilation measurement locations	Humidifi – cation	Recirculation	Smoking	Operable windows	Control confounders
Palonen & Seppanen 1990	c-s	5	580	win	E	<5 – >15	AF	many	N	some	some	Y	P
Jaakkola et al 1991a	c-s	1	938	win	E	7 – 70 <15 – >35	AF	410 (33%)	N	N	Y	Y	P, W
Jaakkola et al 1991a	expt	1	902	win / spr	E	6 – 26	AF	410 (33%)	N	N	Y	Y	P, W
Menzies et al 1993a	expt	4	1546	win / spr	NA	14 – 30	CO_2	>270	Y	Y	some	N	P, W, Ph
Jaakkola et al 1994a	expt	2	72	win	E	6 – 23	AF, TG	67 (100%)	N	Y	Y	Y	P, W, Ph
Sundell et al 1994a	c-s	160	226 – 725	win	E	2 – 50 <13.6->13.6	AF, TG	48-540	some	some	some	Y	P, W, Ph
Cochet et al 1995	c-s	6	618	win	E	6.4 – 13.4 4.2 – 19.8	AF, TG	30	some	some	no info	some	P
Jaakkola & Miettinen 1995	c-s	14	399	win	E	<5 – >25 0 – 25	AF, TG	many	N	N	some	some	P, W, Ph
Milton et al 2000	c-s	40	705	year	NA	12 – 24	CO_2	115 (76%)	Y	Y	N	N	P, W, Ph
Wargocki et al 2000	lab expt	lab	30	win	E	3 – 30	TG	1 (100%)	Y	N	N	N	P, W, Ph

Type of study: c-s = cross-sectional; expt = experimental

Season: win = winter; spr = spring

Ventilation measurement: AF = airflow; TG = tracer gas

Control for confounders: P = personal; W = work-related; Ph = physical

Location: NA = North America; E = Europe

(Persily, 1993; 1997). However, the variety of different strategies used, coupled with insufficient detail reported in some cases, make it difficult to quantify the quality and accuracy of outdoor ventilation rate measurements.

Studies also differed in terms of the number of measurement locations used to assess outdoor ventilation rates. Typically, outdoor ventilation measurements were made in some proportion of the studied office rooms, and were then estimated across the remaining zones. The proportion of rooms measured is given, where available, in Table 2. The frequency of ventilation measurements made at each location was generally not reported in detail, so it is unclear whether reported rates were based on single or repeated measurements. Overall, we noted a lack of reported information regarding the ventilation measurement strategies used in the reviewed studies. Whilst it is acknowledged that ventilation measurement is a complex process, often constrained by building characteristics, more detailed descriptions of the approach used in future studies would be beneficial in determining the likelihood that reported ventilation rates accurately reflect actual office conditions.

As was noted previously, reported outdoor ventilation rates ranged from 0 to 70 L/s.p, although studies more commonly investigated ventilation rates in the range of 5 to 30 L/s.p. Studies also varied in terms of the form of outdoor ventilation rates used in statistical analyses. We found information concerning the distribution of outdoor ventilation rates over ranges and categories to be inconsistently reported. Where such information was provided, study data suggested that the average ventilation rates on which statistical analyses were based often varied widely. For example, the highest category used in Palonen & Seppanen's (1990) study was >15 L/s.p, but the maximum ventilation rate measured was 70 L/s.p. Further information was not provided regarding the extent to which ventilation rates varied in this category between 15 and 70 L/s.p. In general, few of the studies in which ventilation categories were used reported the highest ventilation rate measured, resulting in an unknown range of ventilation rates across the highest category used. Similarly, Jaakkola et al (1991a) reported outdoor ventilation rates from 7 to 70 L/s.p, but the mean ventilation rate was 26 L/s.p. Such concerns raise the possibility that a relatively small number of extremely high outdoor ventilation rates may have influenced the results reported in the reviewed studies.

In addition, some studies (eg. Menzies et al, 1993a) indicated that difficulties were experienced in achieving nominal ventilation rates. Furthermore, although Jaakkola et al (1994a) were relatively successful in achieving designated proportions of recirculated air, the total air supply varied considerably (from 6 to 95.6 L/s.p), suggesting that the absolute values of outdoor air may also have varied notably around the reported means.

Overall, the measurement and statistical use of outdoor ventilation rates present some difficulties with respect to comparing studies. As has been previously stated, (eg. Seppanen et al, 1999; Menzies et al, 1990; Sundell, 1994; Mendell, 1993; Godish & Spengler, 1996), these concerns highlight the need for a more standardised approach to research in this field. In addition, more detailed reporting of relevant information would better enable the reader to judge the approaches applied in future studies.

5.2 Building Characteristics

The studies included in this literature review differed on a number of building characteristics. These differences are important considerations for two reasons. Firstly, in studies where building characteristics varied, these differences should be controlled for in statistical analyses. Secondly, differences between buildings make comparisons between studies more complex.

As Table 2 indicates, five of the reported studies included at least one building which used facilities to humidify the air. In addition, six studies were conducted in buildings which incorporated air recirculation to some degree. Further details of building ventilation systems, such as the use of air-conditioning, were not consistently reported. In relation to these two characteristics, Sundell et al (1994a) controlled for these differences in analyses, but Palonen & Seppanen (1990) and Cochet et al (1995) did not. Air recirculation and humidification both have the potential to influence pollution sources and pollution loads; factors which need to be considered when comparing between study results.

At least some smoking was allowed in seven of the reviewed studies. Tobacco smoke provides an additional source of indoor pollution and thus is likely to require a higher outdoor ventilation rate to remove this contamination. Of the studies where smoking policies differed between buildings or zones, exposure to tobacco smoke was controlled for by Jaakkola & Miettinen (1995) and Sundell et al (1994a), but not by Palonen & Seppanen (1990) nor Menzies et al (1993a).

Table 2 also shows whether studied buildings had operable windows or whether the windows in the building were sealed. Openable windows allow additional outdoor air into the building, which can influence both outdoor ventilation rates at the time of measurement and the rates of outdoor ventilation experienced by occupants on a daily basis. In the majority of European studies, windows were operable, although in three studies (Jaakkola et al, 1994a; Sundell et al, 1994a; Jaakkola & Miettinen, 1995) these windows were noted to be closed during ventilation measurements or were controlled for in analyses. Jaakkola et al (1994a), for example, collected information on how often and how long windows were open, and found little difference in window opening behaviour between the two outdoor ventilation conditions studied, suggesting that this factor was unlikely to have biased results. Seppanen et al (1999) noted that most studies were conducted in the winter, when windows were most likely to be closed, thereby minimising the potential for confounding by this factor. However, the operability of windows may still be an issue when comparing between studies, and the fact remains that the opening of windows may have influenced ventilation rates, either at the time of measurement or during the course of investigations. Jaakkola et al (1991a; p.118), for example, note in their study that *"the windows in the building were operable, which made it possible to compensate for the reduction in ventilation by opening windows."*

5.3 Study Design and Methodology

Although we developed and applied thorough selection criteria in conducting this literature review, a number of methodological limitations were noted in the selected studies.

For example, several researchers have noted that Menzies et al's (1993a) study may have been confounded by seasonal differences in symptom reporting, caused by two buildings being studied in the winter and two in the spring (Godish & Spengler, 1996; Sundell, 1994; Mendell, 1993). Similarly, the experimental part of Jaakkola et al's (1991a) study was conducted over a period in which the season changed, which may have influenced both environmental conditions and occupant satisfaction (Godish & Spengler, 1996).

Some studies (eg. Jaakkola et al, 1994a; Wargocki et al, 2000) were conducted using relatively small numbers of occupants. These small sample sizes may restrict the power of statistical analyses and reduce the robustness of findings. In addition, although Menzies et al (1993a) used a large sample, the analyses in this study included occupants who completed at least two of the six weekly questionnaires, but only 40% of occupants actually completed every questionnaire. In some studies, the distribution of occupants across outdoor ventilation categories was found to be uneven. For example, in Jaakkola et al's (1991b) analysis of this study's data, the low outdoor ventilation categories were formed using relatively few occupants (Sundell et al, 1994a).

In the studies conducted by Sundell et al (1994a) and Jaakkola & Miettinen (1995), it was noted that ventilation measurements were made several months after building occupants completed response questionnaires. Although both of these studies excluded buildings or zones where obvious changes had taken place, there is still some possibility that the measured outdoor ventilation rates differed from conditions at the time when occupant satisfaction ratings were collected.

All the studies controlled for at least some personal characteristics. In addition, eight of the reviewed studies also considered the potential confounding effects of work-related and/or physical factors, either in the study design or in statistical analyses. However, we found that there was considerable variance in the extent to which individual confounders were incorporated into the reviewed studies; a limitation which has been noted by a number of other researchers (eg. Seppanen et al, 1999; Mendell, 1993; Sundell, 1994; Menzies et al, 1990; Milton et al, 2000; Wargocki et al, 2000; Jaakkola, 1994). The studies by Palonen & Seppanen (1990) and Cochet et al (1995), in particular, are weakened by the fact that they controlled only for personal characteristics.

The most serious concerns we encountered in relation to study design and methodology were the statistical techniques applied by both Palonen & Seppanen (1990) and Cochet et al (1995). Although these studies provide support for a relationship between outdoor ventilation rates and occupant satisfaction, both these studies used correlations in which occupant perceptions were aggregated in terms of percentage dissatisfied for each building or ventilation rate. This aggregation resulted in correlations based on only a few data points, and may have inflated associations more than alternative statistical approaches. In addition, in Cochet et al's (1995) study, SBS symptoms were compared between two groups of buildings. However, rather than forming these groups on the basis of the independent variable (ie. outdoor ventilation rates), building were categorised by the dependent variable (ie. SBS symptoms), a strategy likely to result in overinflated findings. Given these statistical concerns, and the limitations previously discussed in association with these studies, we considered these two studies to be weaker in design than the remaining papers included in this review, and as such, treated their findings with some caution.

5.4 Occupant Satisfaction Measurement

The most common measure of occupant satisfaction considered in the reviewed papers was SBS symptoms, assessed in all cases using self-report measures. However, as has been previously noted (eg. Seppanen et al, 1999; Sundell, 1994; Tamblyn et al, 1992; Menzies et al, 1990), the format of these measures differed considerably between studies. For example, due to the absence of a standardised questionnaire to assess SBS, there were differences between studies in terms of the individual symptoms assessed. Furthermore, whereas some studies focused their analyses on individual symptom reports, others used composite symptom scales based either on anatomical proximity (eg. nose, throat, eyes) or proposed causal mechanisms (eg. irritation, allergic reaction). In addition, the reviewed studies used a variety of recall periods, with occupants being asked to report symptoms experienced on the day of testing, or over the previous week, month or even year. Finally, there were differences in the criteria used to quantify SBS symptoms. Some studies used yes/no responses, whilst others referred to symptom frequency, symptom intensity or the presence of a combination of symptoms. These differences make comparisons between studies somewhat problematic and, as noted by Sundell et al (1994b; p.93),

> *" The different criteria of SBS, used in different studies, point towards a fundamental problem. We have no generally accepted definition of SBS and we do not know whether there is one syndrome, "SBS", or if different symptoms or groups of symptoms that persons perceive in non-industrial symptoms have different causes."*

Finally, it should be noted that none of the studies finding significant relationships did so for all measured SBS symptoms, suggesting that some symptoms may be more sensitive to outdoor ventilation rates than others (Sundell, 1994; Godish & Spengler, 1996).

Similar variations were also found in relation to the frequency and format of items intended to assess occupant satisfaction and perceptions. In addition, the wording of questions were not always reported in detail, leading to the possibility of occupant responses being influenced by how the question was framed. In particular, it was not always clear whether the used items focused on perceptual judgements (eg. “the room is dusty”) or on affective responses (eg. “I am satisfied with the amount of dust”, “the amount of dust is acceptable”) (Sensharma, Edwards & Seelen, 1993).

6.0 Conclusion

In this literature review we examined evidence of a relationship between outdoor ventilation rates and occupant satisfaction. We were consistent with previous reviews in highlighting the limitations of some studies and the difficulties involved in comparing studies in this field (Seppanen et al, 1999; Godish & Spengler, 1996; Mendell, 1993). In particular, variations in building characteristics, conceptualisations of SBS, adjustment for potential confounders, and strategies for ventilation measurement and use in analyses, represent significant challenges to study comparison. Whilst it is acknowledged that such variations are constrained in part by the buildings and organisations that researchers are able to gain access to, a move towards a more standardised approach would be beneficial in terms of consolidating research findings.

However, bearing these limitations in mind, the available information from the reviewed studies suggested that outdoor ventilation rates below 10 L/s.p are associated with detriments to occupant satisfaction. The nature of the relationship at higher outdoor ventilation rates was found to be less conclusive, although the overall culmination of evidence suggests that further benefits to occupant satisfaction are unlikely to occur when outdoor ventilation rates are raised above 10 L/s.p.

These conclusions are consistent with those found in previous literature reviews. For example, Godish & Spengler (1996; p.142) concluded that there was *“limited evidence to suggest that ventilation rate increases up to 10 L/s.p may be effective in reducing symptom prevalence and occupant dissatisfaction with indoor air quality and that higher ventilation rates are not effective.”*

Mendell’s (1993) also concluded that higher symptom prevalences were more consistently found at outdoor ventilation rates below 10 L/s.p, and that significant differences in symptom reporting tended not to be found in comparisons of ventilation rates above this level. Furthermore, of the assessments included in Seppanen et al’s (1999) review, the majority showed a higher prevalence for one or more occupant outcome at lower ventilation rates. These researchers also note that *“the findings of a significantly increased outcome were particularly consistent when the lower ventilation rate was below 10 Ls^{-1} per person.”* (p.239)

Several other issues suggest that the relationship between outdoor ventilation rates and occupant responses may be more complex than is sometimes considered. For example, as noted by Godish & Spengler (1996; p.140), *“The ability of general ventilation to reduce contaminant levels can be compromised by inadequate mixing of supply air in occupied spaces.”*

Contaminant removal efficiency may differ between spaces or within a space, due to ventilation strategies, air flow patterns and room characteristics (eg. Teijonsalo, Jaakkola & Seppanen, 1996; Haghighat, Zhang, & Shaw, 1996). Thus, reported outdoor ventilation rates may not adequately reflect the actual ventilation conditions in some parts of a building or room.

In addition, the ability of outdoor ventilation rates to remove contaminants is related to the nature and sources of pollutants present in the building under study (Godish & Spengler, 1996; Seppanen et al, 1999). Thus, a given outdoor ventilation rate may be sufficient to ensure favourable occupant responses in low polluting environments, but may be insufficient in high pollution load conditions. Current North American standards for outdoor ventilation rates in office spaces are set with the assumption that there are no unusual sources of pollution present in the building. Despite this fact, the reviewed studies varied considerably in the information provided about pollution loads. Whilst it is acknowledged that a comprehensive analyses of building contaminants may be time consuming and costly, some indication of the presence of any unusual pollution sources would be useful in interpreting results. This issue may be particularly important where pollution loads are likely to vary between buildings or zones (Mendell, 1993).

A further consideration is the fact that pollutant concentrations are also affected by the quality of the supply air. This is determined in part by recirculation rates, but will also be affected by the pollutants present in outdoor air, the location of the outdoor air intake relative to outdoor pollution sources and the ability of ventilation systems to filter out contaminants (Seppanen et al, 1999).

Finally, the ventilation system itself may constitute a source of pollution, and has been shown to be a source of VOCs (Molhave & Throsen, 1991) and a potential site for bacteria and fungi, particularly in ventilation systems which incorporate air-conditioning (Sverdrup & Nyman, 1990; Morey, 1988). As such, regular maintenance and cleaning of ventilation systems has been argued to be important to occupant responses (eg. Burge, Jones & Robertson, 1990; Bluyssen, 1993), and studies investigating the impact of outdoor ventilation rates should determine the potential for ventilation system pollution to affect results. Wargocki et al's (2000) study is particularly useful in this respect, since this study was conducted using a ventilation system argued to minimise the confounding potential of pollution from this source.

Overall, as Godish & Spengler (1996; p.142) noted,

> *"…the relationship between building ventilation conditions and air quality is relatively complex. As such, the use of general ventilation to mitigate building-related health complaints should be tempered by an understanding of the various factors than may limit its effectiveness and that it is not a generic solution to indoor air quality problems."*

This feeling is also echoed in an addendum to the latest ASHRAE ventilation standard, which states that;

> *"…compliance with the standard will not necessarily result in acceptable indoor air quality for a variety of reasons. The comfort and health effects of indoor environments are very complex and not fully understood. It is not possible at this time to create a standard that will provide acceptable indoor air for all occupants under all circumstances."* (ASHRAE 1999; p.1)

However, although outdoor ventilation rates should not be relied upon as the only mechanism to ensure adequate indoor air quality, the current review does confirm that outdoor ventilation rates do make an important contribution to occupant satisfaction. Our review suggests that applying a minimum outdoor ventilation rate at the current ASHRAE standard of 10 L/s.p, is likely to avoid serious detriments to occupant satisfaction, provided that this level of ventilation is achieved locally and maintained over time.

References

Andersen, I. (1979). Formaldehyde in the indoor environment – health implications and the setting of standards. In Fanger, P. O. & Valbjorn, O. (eds) *Indoor Climate* (65-87). Copenhagen: Danish Building Research Institute.

ASHRAE (1977). *ASHRAE Standard 62-77, Standards for natural and mechanical ventilation.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

ASHRAE (1981). *ASHRAE Standard 62-1981, Ventilation for acceptable indoor air quality.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

ASHRAE (1989). *ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

ASHRAE (1999). *ASHRAE Standard 62-1999, Ventilation for acceptable indoor air quality.* Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

Bendrick, G. A. (1998). Seasonal variation of grounding rates among B-52H aircrew. *Military Medicine, 163,* 692-694.

Berglund, B. & Lindvall, T. (1979). Olfactory evaluation of indoor air quality. In Fanger, P. O. & Valbjorn, O. (eds) *Indoor Climate* (141-157). Copenhagen: Danish Building Research Institute.

Berglund, B. & Lindvall, T. (1986). Sensory reactions to sick buildings. *Environment International, 12,* 147-159.

Bloom, D. E. (1986). Women and work. *American Demographics, 15,* 25-30.

Bluyssen, P. M. (1993). Do filters pollute or clean the air? *Air Filtration Review, 14*(2), 9-13.

Bluyssen, P. M., De Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P. O., Valbjorn, O., Bernhard, C. A., & Roulet, C. A. (1996). European indoor air quality audit project in 56 office buildings. *Indoor Air, 6*(4), 221-238.

Broder, I., Pilger, C., & Corey, P. (1990). Building related discomfort is associated with perceived rather than measured levels of indoor environmental variables. *Proceedings of Indoor Air'90. The 5th International Conference on Indoor Air Quality and Climate, Toronto, Canada.* (pp. 221-226). Ottawa, Canada: Canada Mortgage and Housing Corporation.

Burge, P. S., Jones, P., & Robertson, A. S. (1990). Sick Building Syndrome. *Indoor Air, 1,* 479-484.

Cain, W. S. (1979). Interactions among odours, environmental factors and ventilation. In Fanger, P. O. & Valbjorn, O. (eds) *Indoor Climate* (257-272). Copenhagen: Danish Building Research Institute.

Cochet, C., Riberon, J., & Kirchner, S. (1995). Reported symptoms, ventilation performance and building characteristics in six French office buildings. *Proceedings of Healthy Buildings '95: An International Conference on Healthy Buildings in Mild Climate, Milano, Italy. Vol. 3* (pp. 1359-1364). Milano, Italy: Healthy Buildings '95.

Drinka, P., Krause, P., Schilling, M., Miller, B., Schult, P. & Gravenstein, S. (1996). Report of an outbreak: Nursing home architecture and influenza-A attack rates. *Journal of American Geriatric Society, 44,* 910-913.

Fanger, P. O. (1988). Introduction of the olf and the decipol units to quantify air pollution perceived by humans indoors and outdoors. *Energy and Buildings, 12,* 1-6.

Fanger, P. O., & Berg-Munch, B. (1983). Ventilation requirements for the control of body odor. *Proceedings of the 2nd International Congress on Building Energy Management: Transitions in technologies and policies* (pp. 723-29).

Fanger, P. O., Lauridsen, J., Bluyssen, P., & Claussen, G. (1988). Air pollution sources in offices and assembly halls, quantified by the olf unit. *Energy and Buildings,* 12, 7-19.

Godish, T., & Spengler, J. D. (1996). Relationships between ventilation and indoor air quality: A review.

Indoor Air, 6, 135-145.

Haghighat, F., Huo, Y., Zhang, J. S., & Shaw, C. Y. (1996). The influence of office furniture, workstation layouts, diffuser types and location on indoor air quality and thermal comfort conditions at workstations. *Indoor Air, 6*(3), 188-203.

Hedge, A. (1988). Job stress, job satisfaction, and work-related illness in offices. *Proceedings of the Human Factors Society 32nd Annual Meeting. Vol 2* (pp. 777-779).

Hedge, A., Burge, P. S., Robertson, A. S., Wilson, S., & Harris-Bass, J. (1989). Work-related illness in offices: A proposed model of the sick building syndrome. *Environment International, 15,* 143-158.

Hill, B. A., Craft, B. F., & Burkart, J. A. (1992). Carbon dioxide, particulates, and subjective human responses in office buildings without histories of indoor air quality problems. *Applied Occupational and Environmental Hygiene, 7*(2), 101-111.

Hodgson, M. J., Frohliger, J., Permar, E., Tidwell, C., Traven, N., Olenchock, S. A., & Karpf, M. (1991). Symptoms and microenvironmental measures in nonproblem buildings. *Journal of Occupational Medicine, 33*(4), 527-533.

Hodgson, M. J., Muldoon, S., Collopy, P., & Olesen, B. (1992). Sick building syndrome symptoms, work stress, and environmental measures. *Proceedings of Indoor Air Quality '92: Environments for People* (pp. 47-56). Atlanta: ASHRAE.

Jaakkola, J. J. K. (1994). Sick building syndrome in relation to indoor air temperature, relative humidity and air change. *Proceedings of Thermal Comfort: Past, Present and Future, Watford, UK* (pp. 168-183). Garston, Watford, UK: Building Research Establishment.

Jaakkola, J. J. K., Heinonen, O. P., & Seppanen, O. (1991A). Mechanical ventilation in office buildings and the sick building syndrome. An experimental and epidemiological study. *Indoor Air, 2,* 111-121.

Jaakkola, J. J. K., Reinikainen, L. M., Heinonen, O. P., Majanen, A., & Seppanen, O. (1991B). Indoor air quality requirements for healthy office buildings: Recommendations based on an epidemiologic study. *Environment International, 17,* 371-378.

Jaakkola, J. J. K., Tuomaala, P., & Seppanen, O. (1994A). Air recirculation and sick building syndrome: A blinded crossover trial. *American Journal of Public Health, 84*(3), 422-428.

Jaakkola, J. J., & Miettinen, P. (1995). Type of ventilation system in office buildings and sick building syndrome. *American Journal of Epidemiology, 141*(8), 755-765.

Mendell, M. J. (1993). Non-specific symptoms in office workers: A review and summary of the epidemiologic literature. *Indoor Air, 3,* 227-236.

Menzies, R. I., Tamblyn, R. M., Tamblyn, R. T., Farant, J. P., Hanley, J., & Spitzer, W. O. (1990). Sick building syndrome: The effect of change in ventilation rates on symptom prevalence. The evaluation of a double blind experimental approach. *Proceedings of Indoor Air '90. The Fifth International Conference of Indoor Air Quality and Climate, Toronto, Canada* (pp. 519-524). Ottawa, Canada: Canada Mortgage and Housing Corporation.

Menzies, R., Tamblyn, R., Farant, J. P., Hanley, J., Nunes, F., & Tamblyn, R. (1993A). The effect of varying levels of outdoor air supply on the symptoms of sick building syndrome. *New England Journal of Medicine, 328*(12), 821-827.

Milton, D. K., Glencross, P. M., & Walters, M. D. (2000). Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints. *Indoor Air, 10*(4), 212-221.

Molhave, L. & Thorsen, M. (1991). A model for investigations of ventilation systems as sources for volatile organic compounds in indoor climate. *Atmospheric environment, 25A,* 241-249.

Morey, P. R. (1988). Microorganisms in buildings and HVAC systems: A summary of 21 environmental studies. *Proceedings of IAQ '88: Engineering solutions to indoor air problems* (p.10-24). Atlanta, GA: American Society of Heating, Refrigerating and Air-conditioning Engineers.

Nagda, N. L., Koontz, M. D., & Albrecht, R. J. (1991). Effect of ventilation rate in a healthy building. *Proceedings of IAQ '91: Healthy Buildings, Washington, DC.* (pp. 101-107). Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Nichol, K. L., Lind, A., Margolis, K. L., Murdoch, M., McFadden, R., Hauge, M., Magnan, S. & Drake, M. (1995). The effectiveness of vaccination against influenza in healthy, working adults. *New England Journal of Medicine, 333,* 889-893.

Norback, D., Ingegerd, M., & Widstrom, J. (1990). Indoor air quality and personal factors related to the sick building syndrome. *Scandinavian Journal of Work Environment Health, 16,* 121-128.

Palonen, J., & Seppanen, O. (1990). Design criteria for central ventilation and air-conditioning system of offices in cold climate. *Proceedings of Indoor Air'90. The 5th International Conference on Indoor Air Quality and Climate, Toronto, Canada* (pp. 299-304). Ottawa, Canada: Canada Mortgage and Housing Corporation.

Persily, A. K. (1993). Ventilation, carbon dioxide and ASHRAE Standard 62-1989. *ASHRAE Journal, 35,* 40-44.

Persily, A. K. (1997). Evaluating building IAQ and ventilation with indoor carbon dioxide. *ASHRAE Transactions, 103,* 1-12.

Sensharma, N. P., Edwards, P. K., & Seelen, J. (1993). A characterization of methodologies for assessing human responses to the indoor environment. *Proceedings of Indoor Air '93. The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland. Vol 1* (pp. 785-790). Helsinki, Finland: Laboratory of Heating, Ventilation and Air Conditioning, Helsinki University of Technology / Indoor Air '93.

Seppanen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and carbon dioxide concentrations with health and other responses in commercial and institutional buildings. *Indoor Air, 9*(4), 226-252.

Skov, P., Valbjorn, O., Pedersen, B. V., & The Danish Indoor Climate Study Group. (1990B). Influence of indoor climate on the sick building syndrome in an office environment. The Danish indoor climate study group. *Scandinavian Journal of Work Environment and Health, 16*(5), 363-371.

Stenberg, B., Eriksson, N., Hoog, J., Sundell, J., & Wall, S. (1994). The sick building syndrome (SBS) in office workers. A case-referent study of personal, psychosocial and building-related risk indicators. *International Journal of Epidemiology, 23*(6), 1190-7.

Sundell, J. (1994). On the association between building ventilation characteristics, some indoor environmental exposures, some allergic manifestations and subjective symptom reports. *Indoor Air, supplement 2,* 1-148.

Sundell, J., Lindvall, T., & Stenberg, B. (1991). Influence of type of ventilation and outdoor airflow rate on the prevalence of SBS symptoms. *Proceedings of IAQ'91: Healthy Buildings, Washington, DC.* (pp. 85-89). Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Sundell, J., Lindvall, T., & Stenberg, B. (1994A). Associations between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants. *Environment International, 20*(2), 239-251.

Sundell, J., Lindvall, T., Stenberg, B., & Wall, S. (1994B). Sick building syndrome (SBS) in office workers and facial skin symptoms among VDT-workers in relation to building and room characteristics: Two case referent studies. *Indoor Air, 4*(2), 83-94.

Sverdrup, C. F., & Nyman, E. (1990). A study of microorganisms in the ventilation systems of 12 different buildings in Sweden. *Proceedings of Indoor Air'90. The International Conference on Indoor Air Quality and Climate, Toronto, Canada* (pp. 583-588). Ottawa, Canada: Canada Mortgage and Housing Corporation.

Swedjemark, G. A. (1979) Ventilation requirements in relation to the emanation of radon from building materials. In Fanger, P. O. & Valbjorn, O. (eds) *Indoor Climate* (405-421). Copenhagen: Danish Building Research Institute.

Tamblyn, R. M., Menzies, R. I., Tamblyn, R. T., Farant, J. P., & Hanley, J. (1992). The feasibility of using a double blind experimental cross-over design to study interventions for sick building syndrome. *Journal of Clinical Epidemiology, 45*(6), 603-12.

Teijonsalo, J., Jaakkola, J. J. K., & Seppanen, O. (1996). The Helsinki Office Environment Study: Air change in mechanically ventilated buildings. *Indoor Air, 6*(2), 111-117.

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air, 10,* 222-236.

World Health Organisation (1983). *Indoor pollutants: Exposure and health effects. EURO reports and studies #78,* Copenhagen: World Health Organisation Regional Office for Europe.

Wu, X., & Wang, G. (1996). Fresh air make up, air distribution principle, and sick building syndrome. *Proceedings of Indoor Air '96. The 7th International Conference on Indoor Air Quality and Climate, Nagoya, Japan. Vol. 2* (pp. 919-922). Tokyo, Japan: Indoor Air '96 and Institute of Public Health.

Wyon, D. P. (1992). Sick buildings and the experimental approach. *Environmental Technology, 13,* 313-322.

Yaglou, C. P., Riley, E. C., & Coggins, D. I. (1936). Ventilation requirements. *ASHRAE Transactions, 42*, 133-162.

Zweers, T., Preller, L., Brunekreef, B., & Boleij, J. S. M. (1992). Health and indoor climate complaints of 7043 office workers in 61 buildings in the Netherlands. *Indoor Air, 2,* 127-136.

Appendix A: Outdoor Ventilation Rates and Performance

There is, in general, a lack of research into the effects of indoor air quality on task performance at work. This is, at least in part, because of methodological issues such as difficulties in quantifying "performance", particularly for jobs which do not consist of routine tasks (Nunes, Menzies, Tamblyn, Boehn & Letz, 1993), problems in isolating the effects of indoor air quality from others which may influence performance, and the reluctance of organisations to participate in field experiments in which conditions detrimental to performance may be imposed (Wyon, 1996).

Although a review by Wyon (1996; p.13), on the effects of indoor environment parameters on productivity, states that *"…conventionally acceptable indoor working environments may be affecting human performance by various mechanisms by as much as 5% to 15%"*, this conclusion is drawn largely from evidence on the performance effects of the thermal environment in industrial occupations. In relation to outdoor ventilation rates in office environments, although it is generally believed that ventilation strategies have the potential to affect occupant performance, several researchers have noted the lack of research into this issue (eg. Wyon, 1996; Wargocki, Wyon, Sundell, Clausen & Fanger, 2000; Sensharma, Woods & Goodwin, 1998). Indeed, little work has been conducted since an early, influential investigation concluded that simulated office tasks were not significantly affected by reduced ventilation rates resulting in indoor CO_2 concentrations of 3000 to 4000 ppm (New York State Commission on Ventilation, 1923).

Some indirect evidence on the relationship between outdoor ventilation rates and performance is provided by a cross-sectional study in which indoor CO_2 concentrations, which may be considered a rough estimation of ventilation efficiency, affected school children's performance on a number of tasks (Myhrvold, Olsen & Lauridsen, 1996). In addition, some studies have suggested that SBS symptoms and perceived indoor air quality affect both self-reported productivity (Hall, Leaderer, Cain & Fidler, 1991; Raw, Roys & Leaman, 1990) and objective task performance (Nunes et al, 1993; Kroner & Stark-Martin, 1994). However, direct evidence on the effects of outdoor ventilation rates is scarce and this area of enquiry is largely under researched.

This assertion was supported during the course of conducting the present literature review, as we encountered only one study which used performance as an outcome. In this study, conducted by Wargocki et al (2000), the performance of four typical office tasks, namely text typing, addition, proof reading and creative thinking, were assessed at outdoor ventilation rates of 3, 10 and 30 L/s.p. 30 female subjects completed the tasks, whilst exposed to each outdoor ventilation rate for a duration of 275 minutes.

Wargocki et al (2000) noted that subjects tended to rate the effort required to complete tasks as higher under lower outdoor ventilation conditions, although this difference was not large enough to achieve significance. For the text typing, addition and proof reading tasks, researchers found a trend of improved performance with higher outdoor ventilation rates. In regression analyses, using log-transformed ventilation rates and combined measures of speed and accuracy, these researchers found improvements in performance with increasing outdoor ventilation rates, although these effects were only formally significant in relation to the typing task. These log-linear relationships suggest that changes in performance were greater at lower outdoor ventilation rates, and follow a similar pattern to log-linear relationships suggested for occupant satisfaction (eg. Sundell et al, 1994a; Jaakkola & Miettinen, 1995). Thus, although some of the above findings were short of formal significance, consistent patterns were observed across tasks. Wargocki et al (2000; p.231) concluded that:

> *"…considering that the relationship between performance and ventilation follows a logarithmic function, it was estimated that every two-fold increase in ventilation rate above 3 L/s per person would produce a 1.1% increase in overall performance in the text typing task and a 2.1% increase in overall performance in the addition and proof reading tasks."*

In relation to the creative thinking task, Wargocki et al (2000) found that performance improved when outdoor ventilation rates were increased from 3 to 10 L/s.p, and that this difference in performance was significant when weighted for originality on the given task. However, no further benefit was found from increasing the outdoor ventilation rate from 10 to 30 L/s.p.

Overall, Wargocki et al's (2000) study provides evidence that increased outdoor ventilation rates in the range of 3 to 30 L/s.p may be associated with improvements in task performance. However, it is clear that more studies of this kind are needed to further clarify the existence of this relationship. In particular, studies conducted in field settings, in which the performance of full-time office occupants is assessed over longer periods of time, would be beneficial in generalising the findings from Wargocki et al's (2000) study to "real world" settings.

References for Appendix A

Hall, H. I., Leaderer, B. P., Cain. S., & Fidler, A. T. (1991). Influence of building-related symptoms on self-reported productivity. *Proceedings of IAQ '91: Healthy Buildings, Washington, DC.* (pp. 33-35). Atlanta, GA.: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Jaakkola, J. J., & Miettinen, P. (1995). Type of ventilation system in office buildings and sick building syndrome. *American Journal of Epidemiology, 141*(8), 755-765.

Kroner, W. M., & Stark-Martin, J. A. (1994). Environmentally responsive workstations and office-worker productivity. *ASHRAE Transactions, 100*(2), 750-755.

Myhrvold, A. N., Olsen, E. & Lauridsen, O. (1996). Indoor environment in schools – Pupils' health and performance in regard to CO_2 concentration. *Proceedings of Indoor Air '96, The 7th International Conference on Indoor Air Quality and Climate, Vol 4*.,369-374.

New York State Commission on Ventilation (1923). *Report of the New York State Commission on Ventilation.* Dutton, New York: New York State Commission on Ventilation.

Nunes, F., Menzies, R., Tamblyn, R. M., Boehn, E., & Letz, R. (1993). The effect of varying levels of outdoor air supply on neurobehavioural performance function during a study of sick building syndrome (SBS). *Proceedings of Indoor Air'93. The 6th International Conference on Indoor Air Quality and Climate, Helsinki, Finland.* (pp. 134-140). Helsinki, Finland.

Raw, G. J., Roys, M. S., & Leaman, A. (1989). Further findings from the Office Environment Survey: Productivity. *Proceedings of Indoor Air '90: 5th International Conference on Indoor Air Quality and Climate, Ottawa, Canada* (pp. 231-236). Ottawa, Canada: Canada Mortgage and Housing Corporation.

Sensharma, N. P., Woods, J. E., & Goodwin, A. K. (1998). Relationships between the indoor environment and productivity: A literature review. *ASHRAE Transactions: Research, 104,* 686-701.

Sundell, J., Lindvall, T., & Stenberg, B. (1994A). Associations between type of ventilation and air flow rates in office buildings and the risk of SBS-symptoms among occupants. *Environment International, 20*(2), 239-251.

Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., & Fanger, P. O. (2000). The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air, 10,* 222-236.

Wyon, D. P. (1996). Indoor environmental effects on productivity. *Proceedings of IAQ '96: Paths to Better Building Environments* (pp. 5-15). Atlanta, GA: American Society of Heating, Refrigerating, and Air Conditioning Engineers.

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