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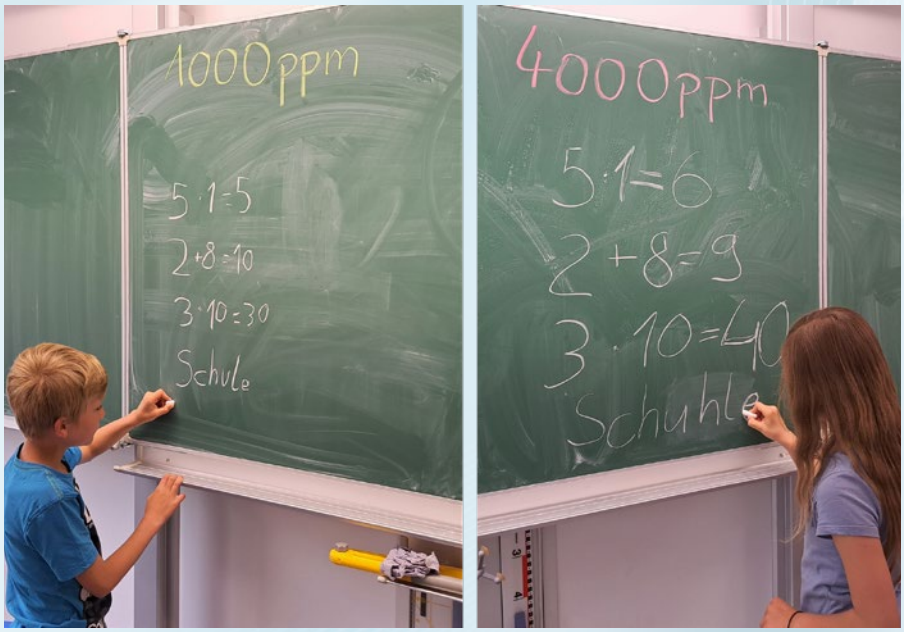
Literature review of scientific studies showing the relationship between productivity, concentration, health and indoor air quality parameters in school and work spaces

E. Hammer
C. Rose
Dipl.-Ing. F. Valentin
Dipl.-Ing. L. Schinke
Prof. Dr.-Ing. habil. J. Seifert



TECHNISCHE UNIVERSITÄT DRESDEN

Fachverband Gebäude-Klima e.V.

Zusammenfassung

Die Indoor Environmental Quality (IEQ, Innenraumqualität) beschäftigt sich mit den raumhygienischen, thermischen, akustischen und lichttechnischen Parametern im Raum. In der Vergangenheit wurden diese Parameter zwar als wichtige Kategorien für die Auslegung klimatechnischer Systeme angesehen, in der Praxis wurden sie jedoch bei der Planung von Heizungs-, Raumluft- und Klimasystemen nur unzureichend berücksichtigt. Die Neufassung der Richtlinie für die Gesamtenergieeffizienz von Gebäuden (EPBD Richtlinie EU 2024/1275) räumt der Raumlufthygiene sowie der Innenraumqualität als übergeordnetes Kriterium einen höheren Stellenwert ein.

Die raumlufthygienischen und thermischen Kriterien beeinflussen nicht nur das Wohlempfinden des Menschen, sondern auch dessen Leistungsfähigkeit. Die an der TU Dresden erstellte Studie zum „Zusammenhang zwischen Leistungsfähigkeit und Innenraumluftqualität in Schulen und an Arbeitsplätzen“ soll den aktuellen Stand des Wissens dokumentieren.

Ergebnisse einer Metastudie der TU Kopenhagen zeigen, dass bei einer Verringerung der CO_2-Konzentration von 2.100 ppm auf 900 ppm eine Steigerung der Verarbeitungsgeschwindigkeit bei Schulaufgaben und Tests um 12 % zu verzeichnen ist. Die Qualität der Ergebnisse in diesen Tests nimmt um 2 % zu. Weitere Ausführungen zeigen eine 5-prozentige Verbesserung der Lerngeschwindigkeit, wenn die CO_2-Konzentration im Raum von 2.300 ppm auf 900 ppm abgesenkt wird. Hinsichtlich der Anwesenheitsakzeptanz wurde eine Verbesserung um 2,5 % benannt, wenn die CO_2-Konzentration von 4.000 ppm auf 1.000 ppm reduziert wird. Die Studie zeigt auch, dass der Leistungszuwachs bei niedrigen CO_2-Konzentrationen höher war. Dies deutet darauf hin, dass die Probanden bei niedrigeren Konzentrationen empfindlicher auf eine Konzentrationsänderung reagieren als bei hohen Konzentrationen. Der größte Leistungszuwachs (Verarbeitungsgeschwindigkeit) trat auf, als die Konzentration von 1.600 ppm auf 900 ppm gesenkt wurde. Als Kennwert kann hier eine Steigerung der Verarbeitungsgeschwindigkeit um ca. 10 % detektiert werden.

Ebenfalls an der TU Kopenhagen wurde in einer Studie der Einfluss der Luftqualität und der Raumtemperatur auf die Leistung von Schülern analysiert. Ausgehend von einem Bezugsniveau wurde eine Absenkung der Innenraumtemperatur, eine Erhöhung der Lüftungsrate sowie eine stärkere Filtrierung und deren Auswirkungen auf die Leistungsfähigkeit der Schüler detektiert.

Hinsichtlich der Innenraumtemperaturen wurde ein Bereich von 20 bis 25 °C analysiert. Der Volumenstrom in den Klassenräumen wurde in einer Bandbreite von 3 bis 10 l/s variiert. Die Filtrierung der Raumluft erfolgte mittels elektrostatischer Filter, um die Konzentration an Schwebstoffen zu minimieren.

Die Auswirkungen dieser drei Maßnahmen auf die Leistungen der Schüler wurden bewertet, indem in Leistungstests die Geschwindigkeit und der Prozentsatz aller möglichen Fehler gemessen wurden. Die Studie ergab, dass eine Verdopplung der Lüftungsrate (im Bereich zwischen 3 und 10 l/s) die Bearbeitungsgeschwindigkeit um 8 % steigert. Ein Einfluss auf die Fehlerquote konnte nicht gemessen werden. Eine Senkung der Raumtemperatur von 25 auf 20 °C führte zur Steigerung bei sprachlich und mathematisch orientierten Tests. Im Mittel konnte eine Leistungssteigerung (Geschwindigkeit) von zwei Prozent je Kelvin Raumtemperaturabsenkung bestimmt werden. An der Fehlerhäufigkeit änderte sich hierbei nichts. Auch ein Einfluss der Schwebstoffkonzentration auf Bearbeitungsgeschwindigkeit und Fehlerrate konnte nicht gemessen werden.

Bei Analysen an drei Schulen in Bremen wurde der Einfluss verschiedener CO_2-Konzentrationen auf physiologische Kenngrößen wie Herzfrequenz und Aktivität gemessen. Die CO_2-Konzentrationen wurden durch Erhöhen der Lüftungsvolumenströme variiert. Eine

systematische Absenkung erfolgte jedoch nicht. In allen drei Schulen lag das Ausgangsniveau zwischen 950 und 1.450 ppm, abgesenkt wurde auf ein Niveau von 800 bis 1.000 ppm.

Als Ergebnis der Studie kann festgestellt werden, dass die Herzfrequenz zwischen 2 und 3 min^{-1} verringert werden kann. Hinsichtlich der Aktivität (Indikator für mangelnde Aufmerksamkeit) konnte die Studie zeigen, dass durch eine Absenkung der CO_2-Konzentrationen zwischen 10 und 30 % weniger Störungen im Unterricht erfolgten, was auf eine höhere Aufmerksamkeit der Schüler schließen lässt.

Eine breit angelegte Studie in Bildungseinrichtungen (Kindertagestätte / Klassenräume / Hörsaal) kam zum Ergebnis, dass bei einer Reduktion der CO_2-Konzentration von 2.000 ppm auf 700 ppm eine Steigerung der Schülerleistung um 21 % erreicht werden kann. Hinsichtlich der Temperatur stellen sich ähnliche Verhältnisse ein. Ein Absenken der Raumtemperatur von 22 °C auf 17,6 °C führte ebenfalls zu einer Leistungssteigerung von 21 %. Allerdings weisen die Autoren darauf hin, dass eine so niedrige Raumtemperatur in der Praxis wenig Akzeptanz erfahren wird.

Neben Ergebnissen der ausgewählten wissenschaftlichen Arbeiten enthält die Studie einen Überblick über folgende Richtlinien und Normen, die Grenzwerte zu CO_2-Konzentrationen im Raum dokumentieren:

- DIN EN 16798-1
- ASR A3.6-Lüftung
- VDI 6040 – Blatt 1
- Leitfaden Raumlufthygiene in Schulgebäuden

Die Analysen dieser Veröffentlichung zeigen, dass es eine ganze Reihe wissenschaftlicher Veröffentlichungen zum Thema raumklimatische Parameter und deren Einfluss auf die Leistungsfähigkeit von Personen im Raum gibt. Viele davon beziehen sich auf Schulen. Grundsätzlich kann den Veröffentlichungen entnommen werden, dass ein Zusammenhang zwischen einem höheren Luftwechsel (bzw. dem damit verbundenen niedrigeren CO_2-Gehalt) und einer daraus folgenden höheren Leistungsfähigkeit der Personen besteht. Hierbei ist das absolute Niveau der CO_2-Konzentrationen von signifikanter Bedeutung. Normative Verfahren spiegeln diesen Zusammenhang aktuell nur unzureichend wider. Besonders verwiesen sei in diesem Zusammenhang auf die europäische Richtlinie DIN EN 16798-1, die Grenzwerte als Differenz zur Außenkonzentration vorgibt. Weiterhin ungeklärt ist der Einfluss der CO_2-Konzentration hinsichtlich des Alters, der Diversität und des Geschlechts der Personen. Hierzu sollten weitere Untersuchungen durchgeführt werden.

Literature review of scientific studies showing the relationship between productivity, concentration, health and indoor air quality parameters in school and work spaces

- Final Report -

Client: FGK / Hoferstraße 5, 71636 Ludwigsburg
Dr.-Ing. C. Kandzia
Dipl.-Ing. C. Händel

Contractor: TUD / Institute of Energy Technology / Helmholtzstraße 14, 01062 Dresden
Editor: E. Hammer
C. Rose
Dipl.-Ing. F. Valentin / Dipl.-Ing. L. Schinke / Prof. Dr.-Ing. habil. J. Seifert

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1 Introduction

1.1 General

Nowadays, people spend about 80 to 90% of their lives indoors. Thus, air is the most important food for us. Crowded rooms, such as classrooms, increase the amount of CO_2 in the air. This is because air is breathed in and carbon dioxide is exhaled with every breath. Many studies show that this stuffy air with its high CO_2 and VOC content makes it harder for pupils to concentrate, makes them tired more quickly, gives them headaches and also reduces their performance.
Therefore, a constant supply of outdoor air is advisable, because it improves the mental and physical condition of the students, the teachers and the employees. Thus, higher performance can be achieved in a better learning atmosphere.

1.2 Challenge

Performance is influenced by the social environment, the position within the company, personal conditions and environmental conditions. However, according to current knowledge, there is no statement about how great the respective influence is and whether the various factors interact with each other. [1]
Likewise, there are only a few publications on indoor climate that examine the various factors such as air quality, temperature, etc. for their influence on performance and also look at this in sufficient detail. The assessment of pupils' performance is even worse, since the results of studies conducted in offices and with typical office tasks cannot be directly transferred to schools. Therefore, there is still sufficient need for research and studies in this area. [2]

1.3 Aim of the Work

The aim of this work is to conduct a literary study on the potential influence of fresh air supply on people's performance and health. For this purpose, all relevant literature sources are to be evaluated. The contents are to be structured and documented in a short report. In addition to national and international standards and secondary literature, this literature study should also include studies by international research groups and test facilities for laboratory and field tests.
The research is to be divided into two areas. Area one is workplaces and non-residential buildings and area two is residential ventilation. The first area is the main part of the research. However, it should also be examined which recommendations from the first area can be applied to the area of residential ventilation. The task was developed and awarded by the Fachverband Gebäude-Klima e.V. (Building Climate Association).

1.4 State of the Art

1.4.1 Air quality

Air quality is one of the most important factors influencing human satisfaction. To assess air quality, many studies usually use the CO_2-concentration as an indicator. This is acceptable because with good ventilation the other pollutants usually behave similarly. It is also difficult to identify and measure all pollutants in a room. Of course, this simplification also has its limits.
As a limit value for good air quality, the Pettenkofer scale, which was already established in the 19th century, is still mostly used today. This states that from 1000 ppm (parts per million), or the equivalent of 0.10% CO_2 concentration in the air, the air quality deteriorates, and the first negative effects occur, such as symptoms of fatigue.

1.4.2 Current state of schools

Since pupils in particular benefit from good indoor air quality, it is important to assess the current situation in schools. The air quality is assessed as a function of the CO_2-concentration. In Figure 1, the CO_2-concentration of 684 schools is measured, from which the mean value for the respective country was calculated. [3]

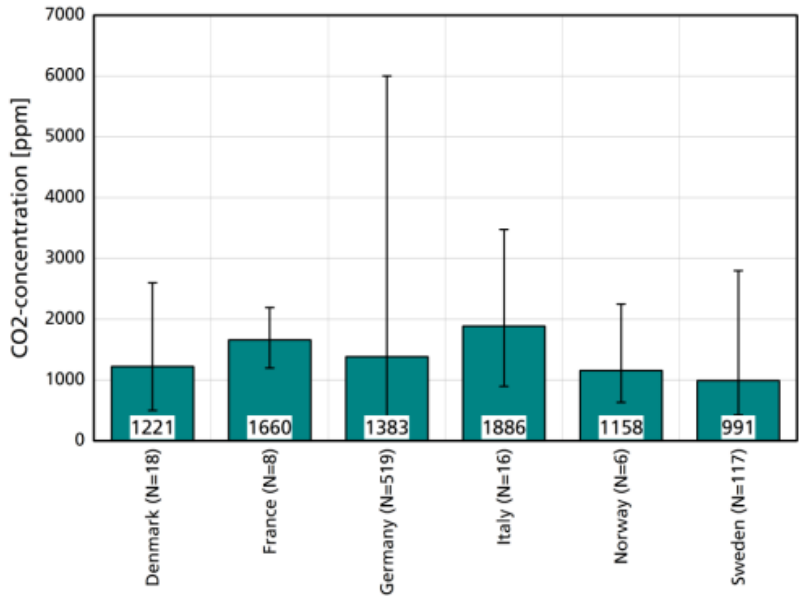

Figure 1: Measured CO_2 concentration in schools from six European countries. The bars represent the mean values and the lines the maxima and minima [3]

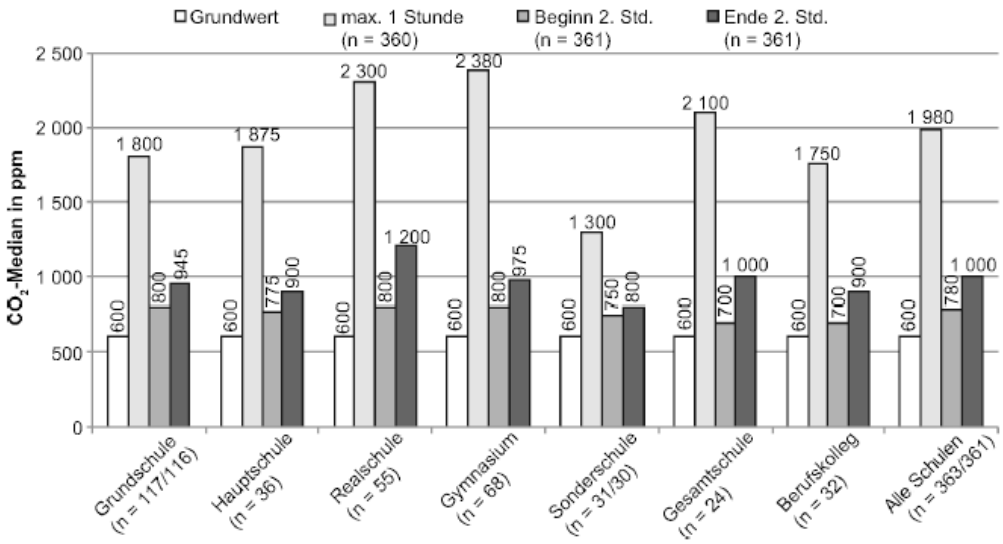

Figure 2: CO_2 medians for all situations depending on the school form. [4]

With reference to Figure 1, it is noticeable that only in Sweden the mean CO_2 concentration is below 1000 ppm. The highest mean value is found in the schools in Italy with 1886 ppm. However, it is also clear that in all countries the maximum CO_2-concentration is above 2000 ppm.D:\Arbeit\Forschung\Projekte\PJ-FGK\Arbeit\Bericht\Impact - CTVL001d4a2d0e6daf94a9784d4eb77cc2bc9d5 [3]

Also, in **Fehler! Verweisquelle konnte nicht gefunden werden.**, the CO_2-concentration is measured in 363 different rooms. The basic value of 600 ppm was determined first. During the first lesson, no ventilation was carried out. After this first lesson, the room was ventilated by means of shock ventilation and during the second lesson, the room was ventilated permanently via tilted windows. Here, too, it became apparent that the CO_2-concentration quickly reached very high levels, if the room was not ventilated for only one lesson. Likewise, the Pettenkofer standard can only be maintained with permanent tilt ventilation. [4]

2 Literature review

2.1 Methodology

During the literature research, articles from various trade journals and other scientific publications on the influence of indoor air quality on comfort, health and performance were selected. Standards and recommendations for achieving thermally comfortable indoor air quality were also considered. A distinction was made between residential ventilation and workplaces or non-residential buildings. The latter took up much more space in this research. Mainly online archives of libraries and thematically relevant journals were searched. However, publications from various German universities and scientific institutions were also taken into account. The estate of Dr. Wolfgang Bischof was also available for the research.
After a large amount of literature was collected, it was reviewed for quality, validity and reliability. First, studies without statistically significance or without a standardised performance test were eliminated. Tests measuring memory, reaction time and concentration were considered, but the simple comparison of those tests during high and low CO_2-concentration was not seen as a valid measure for the influence of air quality. Estimates and extrapolations without a solid basis were also not considered, and studies and articles with identical content were only included once in the evaluation. Results from intervention experiments counted as valid predictors [5]. Thus, the number of literatures was reduced from 41 to six high-quality studies, articles or standards. The relationship of indoor air CO_2-concentration to outdoor air CO_2-concentration is particularly important, because this is the only way to ensure the comparability of the studies.
The results of the remaining literature were discussed and could contribute to finding recommendations for action to improve indoor air quality and subjectively perceived thermal comfort. This not only has a positive impact on health, but also on performance and other aspects of our lives. However, since most studies did not report the ventilation rate, but only measured the CO_2-concentration, this is used as a measure of indoor air quality. [6]

2.2 Online research programmes

An online database-supported research tool was used to support the research. The programme used here is called "Research-Rabbit" and enables the search for studies, persons and subject groups. In a network or on a timeline, the relationships between different studies can be visualised in terms of their common content or authors. For the programme to know which studies to search for, the user must specify Research Rabbit studies. The programme then independently finds studies that are related to the specified studies [7]. In this case, Research Rabbit was given five studies. These were selected because they were written by recognised researchers in the field, were widely cited by other studies, and because they have a particular focus on the impact of student performance as a function of air quality. The studies used are presented in Table 1. One limitation of Research Rabbit is that it can only find published studies. Doctoral theses, articles in journals and other unpublished studies cannot be found. Manual research is still required for this. The advantage of only finding published studies is that in most cases they have gone through the peer review process and therefore the quality of the studies should be adequate. Figure 3 shows the results of the search in a network. It is easy to see that many studies have joint authors, which means that there is a great deal of exchange between the specialist groups in this area.

Table 1: Selected studies for Research Rabbit

study	autor	source
Associations between classroom CO_2-concentrations and student attendance in Washington and Idaho	D G Shendall et al.	[8]
The relationships between classroom air quality and children’s performance in school	P Wargocki et al.	[6]
Providing better thermal and air quality conditions in school classrooms would be cost-effective	P Wargocki et al.	[9]
A preliminary study on the association between ventilation rates in classrooms and student performance	R J Shaughnessy	[10]
The Effects of Outdoor Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children (RP-1257)	P Wargocki et al.	[11]

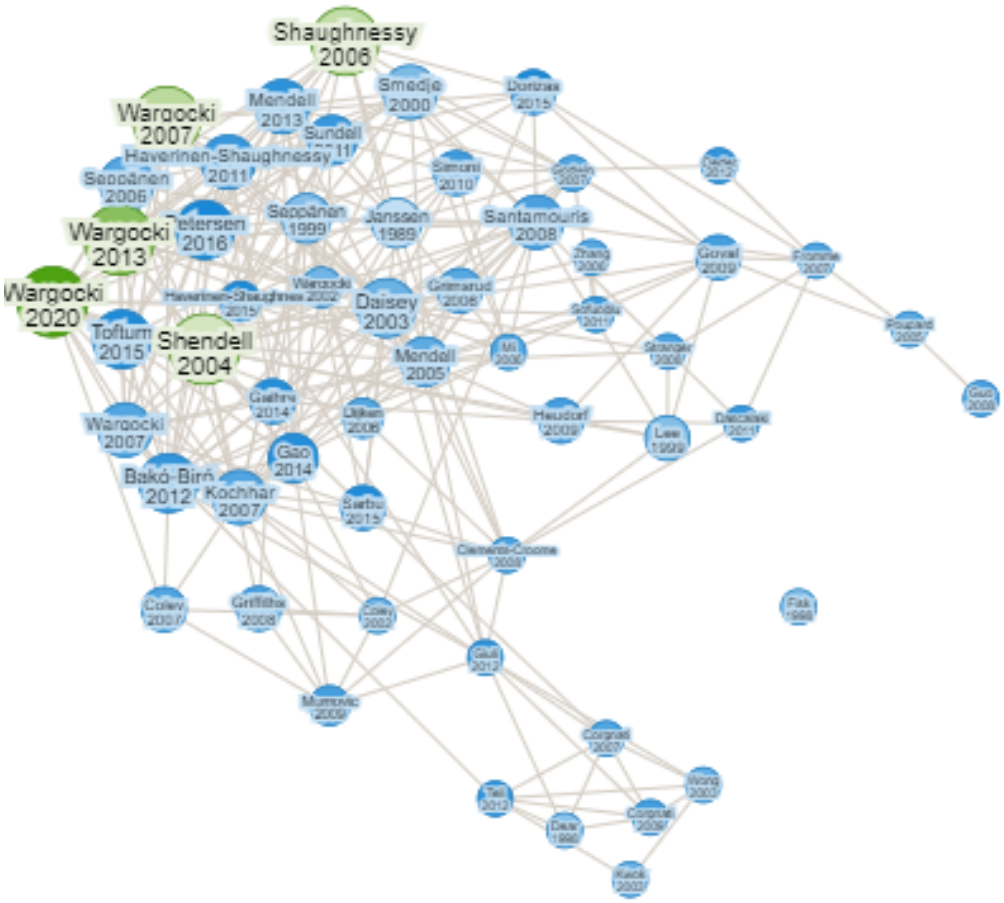

Figure 3: Results from Research Rabbit [7]

2.3 National studies

The Herman-Rietschel-Institute (HRI) of the TU Berlin dealt with the evaluation of air quality and ventilation effectiveness in a school room. For this purpose, a CFD simulation was carried out to check several scenarios of aerosol transmission and a reduction of pathogen concentrations through ventilation. [12]]
The Institute for Interdisciplinary School Research in Bremen (ISF) is using an intervention study to examine the effect of a ventilation requirement. The study was conducted at two primary schools and one secondary school [5].
The diploma thesis of Patrick Drexler from TU Wien examines the costs of improving the air quality in classrooms. For this purpose, an Excel-tool from the TU Vienna for thermal building simulation is extended. Based on this, the air quality is then evaluated, the influence on learning performance is estimated and countermeasures are proposed. The author's thorough literature research is noteworthy. Various studies on performance as a function of air quality are presented and classified. In addition, a survey was conducted at a school. [2]
Another scientific dissertation from the Technical University of Braunschweig by Jennifer König compares different ventilation options at schools, universities and primary schools. What is special about this work is that it is a long-term study. The results come from measurements and investigations over a period of 246 months [13]. The Commission for Indoor Air Hygiene of the Federal Environment Agency is currently working on recommendations and statements on various aspects of indoor air. The current appointment period is from 2022 to 2050 and deals with future room and building ventilation, especially influenced by new experiences due to pandemics, new building trends and recurring contaminants such as asbestos, formaldehyde and PCBs. A large part of this work is devoted to ventilation recommendations that take the energy balance into account. Especially for educational institutions and residential buildings.

2.4 International studies

In the field of indoor air quality, there are several research teams working on this topic. One of these research groups is employed at the Technical University of Denmark and is part of the Department of Environmental and Resource Engineering and specializes in indoor environment. Among the studies published are those on the relationship between school children's performance and indoor air quality. What distinguishes these studies from many others is that they do not just measure air quality, but relate it directly to student performance. [14]
Another research group is employed at the University of Tulsa and is called the Indoor Air Program. This research group also deals with the issue of indoor air quality in schools and its influence on students' school performance. Most of the studies are conducted in primary and secondary schools in the United States. [15]
Another US research group works at the Lawrence Berkeley National Laboratory and is called "Indoor Environment". This group also focuses on health and work performance in relation to indoor air quality. [16]
In addition to these research groups, there are a large number of other research groups, institutes and professorships that have worked on the topic of indoor air quality and performance in school settings. These include work at the Polytechnic University of Turin, the University of Bath, the Helsinki University of Technology, the California Department of Health and many other institutions. It should be noted that this topic is being researched by many research groups worldwide. However, the approach, the methodology of the studies, the data collection and the data evaluation differ greatly.

3 Detailed considerations

In this chapter, individual studies are examined in more detail. These studies were selected because they provide well-founded results, both methodologically and technically, compared to all other studies. The assumptions made are well founded, the measurements are statistically significant, the measurement methods and evaluation of the measurements are well presented and there is a good visualisation of the results.

Table 2: Comparison of selected studies

Number / titel of the study		Author	Publisher	Source
1	Luftqualität in Schulgebäuden	Ugolini, C; Belleri, A	Eurac Research	[17]
2	The Relationship between classroom air quality and children's performance in school	Wargocki, P; Porras-Salazar, J; Contreras-Espinoza, S; Bahnfleth, W	Building and Environment (Vol. 137)	[6]
3	Providing better thermal and air quality conditions in school classrooms would be cost-effective	Wargocki, P; Wyon, D.P	Building and Environment (Vol. 59)	[9]
4	Gesundheitsfördernde Einflüsse auf das Leistungsvermögen im schulischen Unterricht	Tiesler, G; Schönwälder, H.-G; Ströver, F.	Wirtschaftsverlag NW	[5]
5	Lüftungskonzepte in Bildungsstätten – Einfluss der Luftqualität auf die Leistungsfähigkeit von Schülern	König, J		[13]
6	Impact of the indoor environment on learning in schools in Europe	Grün, G; Urlaub, S	Frauenhofer-Institut für Bauphysik IBP	[3]

3.1 Study 1

This meta-study was carried out by the private research centre eurac research and financed by the Interreg Fund of the European Union.

The literature review deals with indoor pollutants in school buildings and their influence on students' performance. In the first part, the different pollutants are presented and their harmfulness is explained. In the second part, the effects on school children are analysed. A total of 12 studies are presented, analysed and their results compared with each other. [17]

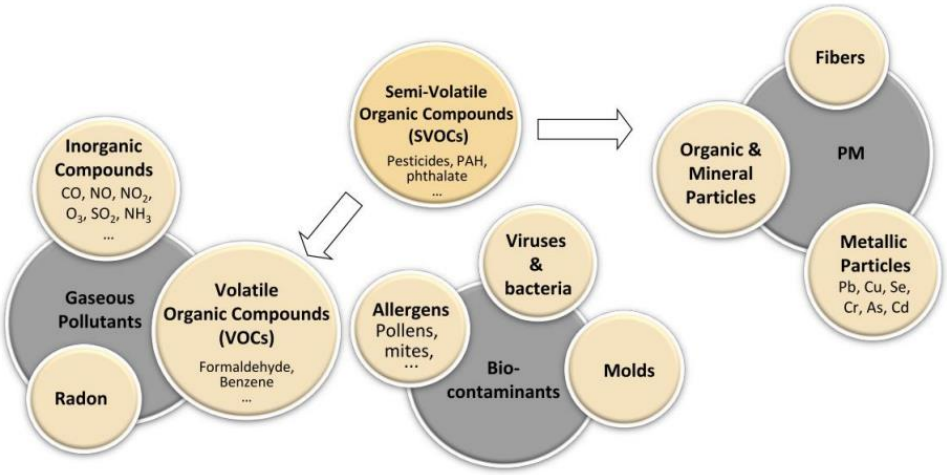

Figure 4: Classification of indoor pollutants [17]

The meta-study states that air quality has a direct but also an indirect influence on the performance of students. Insufficient air quality can lead to increased respiratory diseases and allergies, which result in reduced performance and higher absenteeism. Children are physiologically more vulnerable than adults in this regard because their immune systems are still developing and because the concentration of pollutants is relatively higher at a lower body weight. Effects can include dry cough at night, rhinitis and persistent cough. One study also found a link between high blood pressure and excessive levels of particulate matter. [17]

Result:

A quantitative analysis of all studies used is not possible because different methods of performance evaluations (test types, evaluation parameters, exposure conditions) were used. However, a qualitative analysis suggests that:

- Improved academic performance can be achieved through higher ventilation rates. Furthermore, performance increases when the CO_2-concentration decreases.
- Absenteeism decreases when CO_2-concentration decreases.
- There is no correlation between dust concentration and performance.

As a recommendation for action, this meta-study mentions more frequent checks of the building condition, measuring indoor parameters such as CO_2-concentration, humidity and temperature. Furthermore, it is also recommended to shorten the maintenance intervals of ventilation devices. [17]

3.2 Study 2

This meta-study was conducted under the leadership of Pawel Wargocki from the Technical University of Denmark. A total of 20 studies were compared. Learning outcomes are measured using psychological tests that compare cognitive performance. In addition, exam results and participation grades are used. The CO_2-concentration and, in some studies, the ventilation rate are used as indicators of air quality. [6]

Result:

The analysis of the studies used shows that when the CO_2-concentration is reduced from 2100 ppm to 900 ppm, there is an increase of 12 % in mental tests and school tasks in terms of processing speed. The quality of the results in these tests increases by 2 %. Figure 5 illustrates these influences. [6]

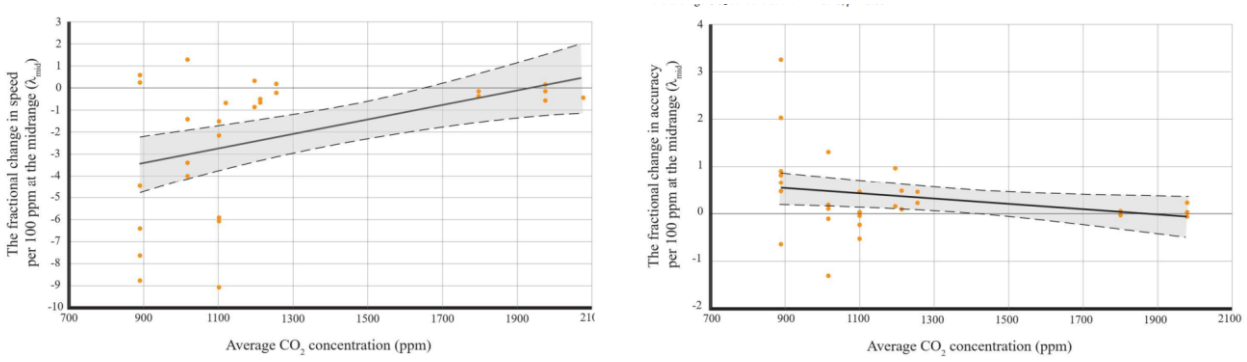

Figure 5: Influence on processing speed (left) and accuracy (right) [6]

Reducing the concentration from 2300 ppm to 900 ppm leads to a 5 % improvement in tests measuring learning speed. Furthermore, the study shows that lowering the CO_2-concentration from 4000 ppm to 1000 ppm resulted in a 2.5 % improvement in attendance. This is illustrated in Figure 6. [6]

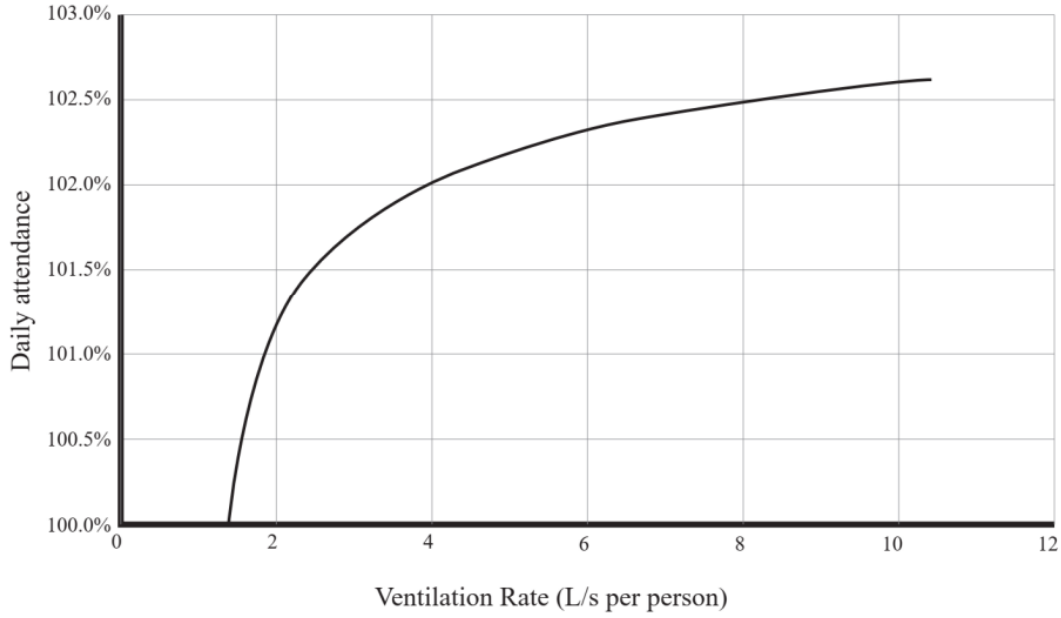

Figure 6: Presence rate as a function of the ventilation rate [6]

The study also shows that the increase in performance gains was higher at low CO_2-concentrations. This suggests that children are more sensitive to a change in concentration at lower concentrations than at high concentrations. The greatest increase in performance occurred when the concentration was lowered from 1600 ppm to 900 ppm. This is shown in Figure 7. The dotted lines are extrapolation of the data. [6]

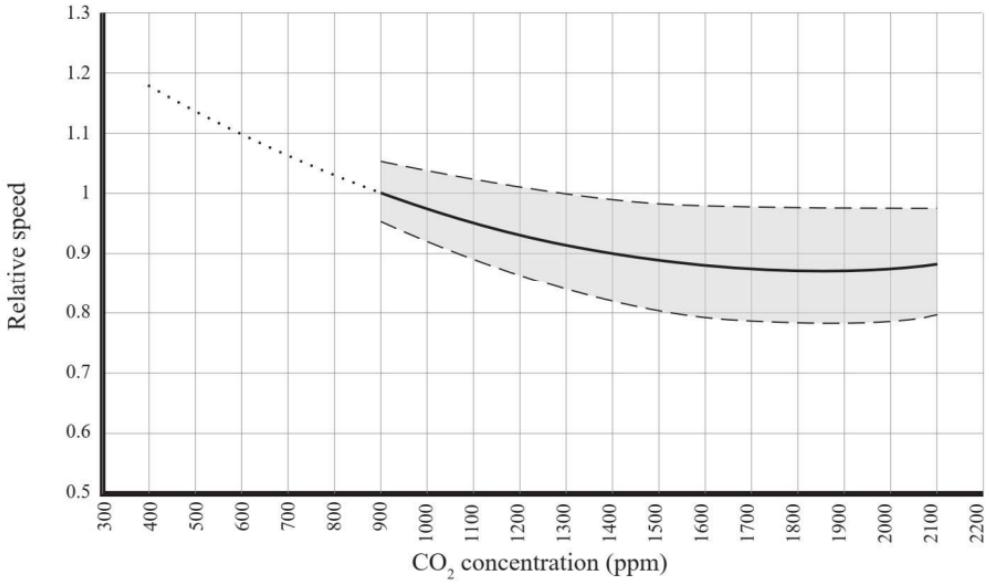

Figure 7: Influence of CO_2-concentration on processing speed [6]

It has been shown that an increased ventilation rate of 2 l/(s person) to 20 l/(s person) has a significant influence on the learning behaviour of pupils. In comparison with other studies carried out on adults, it should also be noted that the performance impact of inadequate air quality on schoolchildren is around five times higher than on adults. [6]

3.3 Study 3

The present study was conducted under the direction of P. Wargocki at the Technical University of Denmark and analyses both the influence of air quality and the influence of indoor temperature on student performance. Various interventions were carried out to find out whether:

1. decreasing of indoor temperature,
2. increasing the ventilation rate and
3. filtering suspended particles leads to an improvement in student performance.

The indoor temperature in the classrooms was lowered from 25 °C to 20 °C using split-cooling units. In order to improve the air quality in the classrooms, fans were installed to increase the ventilation flow into the room from 3 to 10 litres per second. In addition, electrostatic filters were installed to filter out suspended particles. This reduced the dust that settled on surfaces.
The impact of these three interventions on student performance was evaluated through performance tests. These consisted of language, maths and logical thinking tasks. Performance was measured in terms of speed and errors (percentage of all possible errors).

Results

Increasing the ventilation rate: The intervention showed that doubling the ventilation rate leads to an 8 % increase in performance (speed). If only the tests in which there is an improvement in performance are considered, the increase in performance is 14 %. No influence on the error rate could be measured. The results are shown in Figure 8. [9]

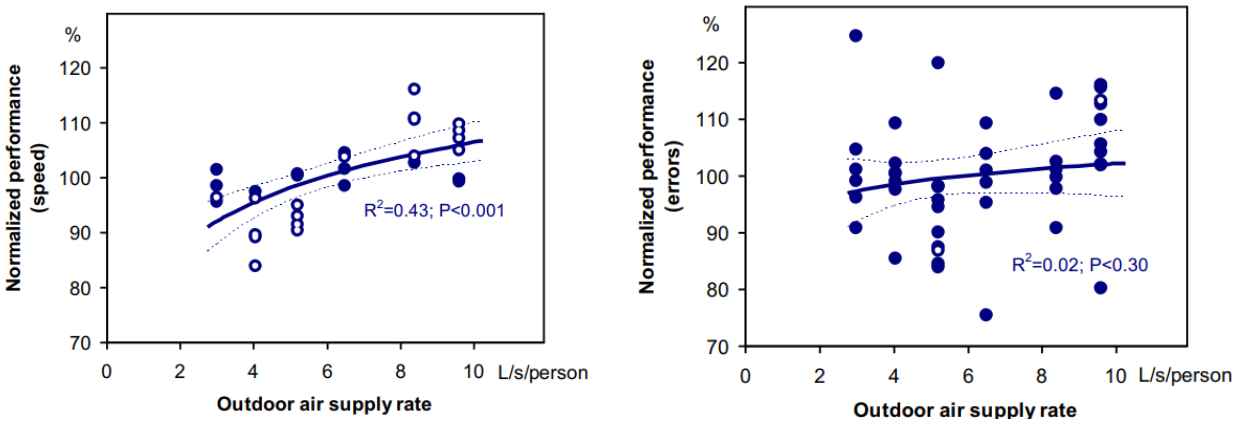

Figure 8: School performance as a function of the ventilation rate. Left: Processing speed, Right: Error rate [9]

Filtering of suspended particles: The study was unable to establish a correlation between a reduced concentration of suspended particles and the performance of pupils. It is concluded that performance is significantly influenced by gaseous pollutants, as these cannot be filtered out by the air filters. [9]
Lowering the temperature: Lowering the temperature from 25 °C to 20 °C led to a significant increase in two language and two maths tests. Lowering the temperature by 1 °C resulted in a 2 % increase in performance. If only the tests in which there is an improvement in performance are considered, the increase in performance is 4 %. The authors conclude that the indoor room temperature has an influence on the thermal comfort of the students. This can be seen in Figure 9. [9]

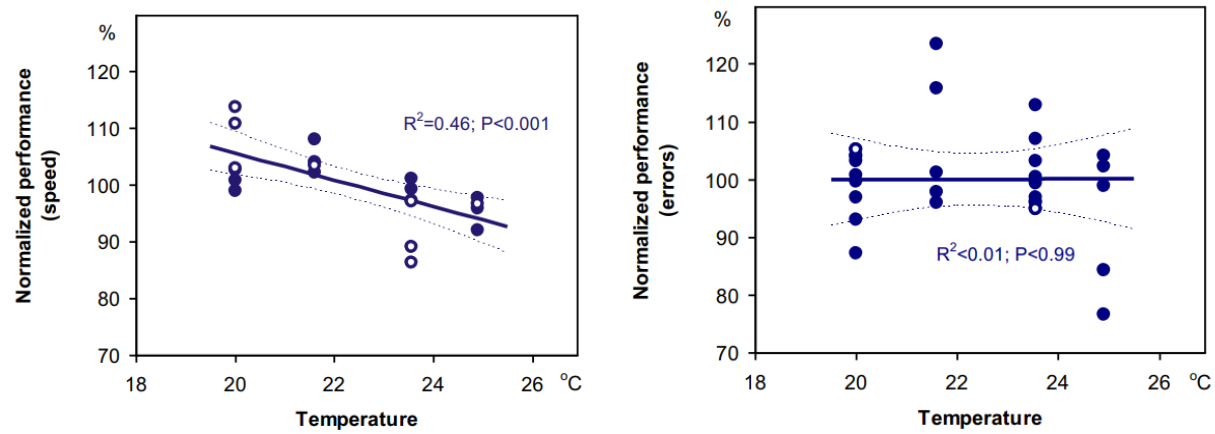

Figure 9: School performance as a function of indoor temperature. Left: Processing speed, right: error rate [9]

The study indicates that the performance improvements observed are greater than those observed in tests with adults. Pupils experience an increase in performance of up to 30 % due to improved ventilation. [9]

3.4 Study 4

The study was conducted by G. Tiesler, H.-G. Schönwälder and F. Ströver at two primary schools (schools 1 and 2) and one comprehensive school (school 3). All three schools are located in Bremen and the respective classes were selected on a voluntary basis. The study investigated the influence of altered CO_2-concentration, with the same workload, for example the same work task, on different stress reactions such as fatigue, heart rate and sweating. [5] Three questions arose in the process:

1. can a significant improvement in the quality of the room air - CO_2-concentration below 1500 ppm - be achieved by ventilating the room for a single interruption of approx. 3 minutes after a 20-minute lesson?
2. can an improved attentional performance or shorter reaction time be measured after approx. 3 minutes of ventilation of the room after the lesson?
3. does this change lead to lower levels of fatigue in pupils and teachers as measured by heart rate responses and other indicators?

As the influence of other disturbance variables was to be minimised, an attempt was made to measure on the same teaching days. The external conditions were also to be kept as constant as possible. CO_2 concentration, humidity, temperature and noise levels were measured continuously and simultaneously. [5]

Results

Influence on the average CO_2-concentration: Figure 10 clearly shows that the intervention had an effect. On the one hand, the CO_2-concentration was reduced in all schools. However, all schools also reached the Pettenkofer limit value of 1000 ppm or even fell below it [5]. Figure 11 shows the CO_2-concentration over the course of the day. Averaged from all lessons at the respective school. Due to very similar results, only school 2 is shown in Figure 10 and Figure 11 to show the effects [5].

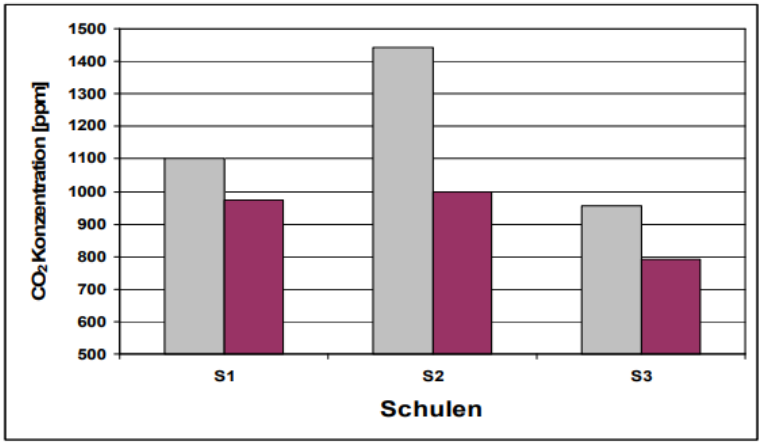

Figure 10: Average CO_2 concentration in the classroom, sorted by school; before ( ) and after ( ) the intervention [5]

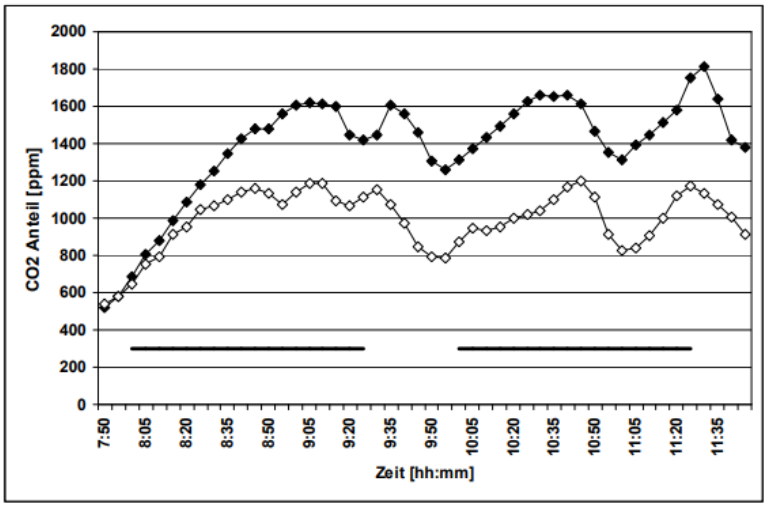

Figure 11: CO_2-concentrations over the course of the day for school 2, before ( ) and after ( ) the Intervention, lesson time (▬) [5]

Table 3 shows the frequency distribution of the CO_2-concentration before and after the intervention. All lessons are divided into five-minute sections and the exposure is determined. No distinction is made between the start of the lesson or the respective class. The Pettenkofer value of 1000 ppm and the much more conservative limit value of 1500 ppm were used as limits. As already illustrated in the two diagrams above, the frequency distribution also shows an improvement in the CO_2-concentration. The already acceptable value of school 3 before the intervention is due to the increased outside temperature. As these were up to 20 °C and higher, while the outside temperatures at school 1 were still partly in the freezing range. [5]

Table 3: Proportion of time in lessons in which the respective CO_2 limit value is still undercut [5]

	School 1		School 2		School 3	
	Before I.	After I.	Before I.	After I.	Before I.	After I.
< 1000 ppm	33,82 %	55,73 %	15,38 %	41,37 %	57,98 %	74,88 %
< 1500 ppm	66,67 %	97,23 %	55,82 %	84,74 %	84,31 %	95,27 %

Heart rate: The heart rate is used as an indicator of the intensity of the exertion. The disadvantage of this is that it depends on the individual person. Despite all this, the introduction of the intervention, and the resulting reduction in CO_2-concentration, shows its effect by reducing the average heart rate (HR) in all three schools. This is illustrated in Figure 12. [5]

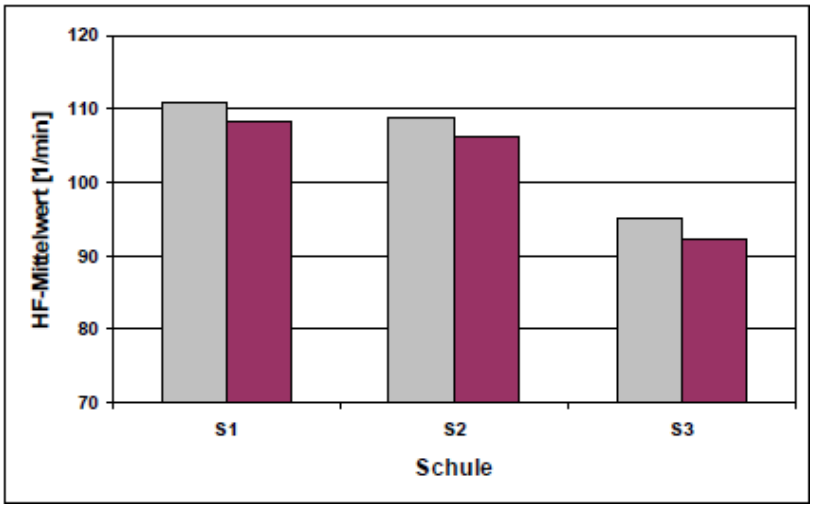

Figure 12: Average stress during lessons, shown as the mean value of the heart rate (HR) across all lessons in the schools, before ( ) and after ( ) the intervention [5]

Dys-functional activities: These include all activities that are observed during lesson time but do not contribute to the lesson. However, these are also characterised by the age and general habits of the respective schools [5].

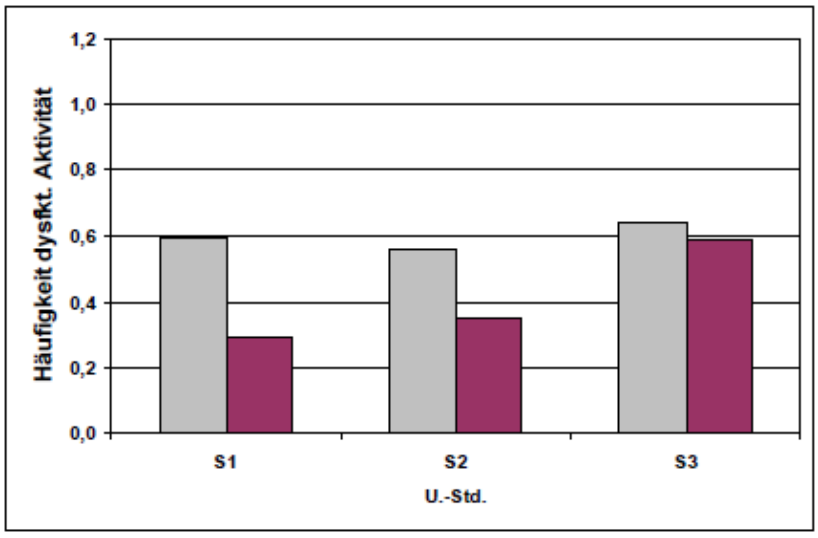

Figure 13: Frequency of "dysfunctional activity" during the teaching day at the schools, before ( ) and after ( ) the intervention [5].

The frequency of dysfunctional activities also improves in all three schools, as shown in Figure 13. While there is a clear improvement in the primary schools, there is only a slight improvement in the comprehensive school from 0.64 to 0.58 activities/min.
Directly related to the reduction in dysfunctional activity is the amount of discipline during lessons. Discipline is the teacher's reaction to the dysfunctional activities of the students. Here, too, there is a strong correlation with the tolerance of the teacher. Figure 14 shows the frequency of discipline at the various schools. There is therefore a direct influence of the ventilation break on a reduction in dysfunctional disturbances and thus a reduction in disciplinary behaviour.

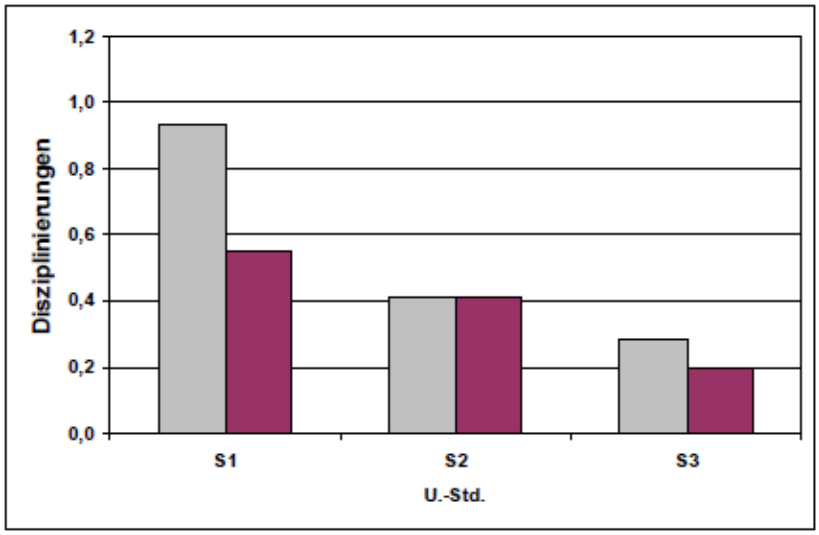

Figure 14: Frequency of "disciplining" during the school day at schools, before ( ) and after ( ) the intervention [5].

Attention: A distinction is made here between the different age groups, as attention performance is strongly dependent on age. Contrary to the hypothesis, there was an improvement in attention performance over the course of the lessons. What was also noticeable, however, was that after the introduction of the ventilation break, this did not increase as much. However, results from many other well-known labour science studies contradict this observation. It is therefore necessary to consider what other effects besides the normal fatigue effect influence the test result. The subjective perceived attention of the students is also reduced. This was recorded by the following question: "Were you able to concentrate well today?". The relative frequency of the different answers is shown in Figure 15.

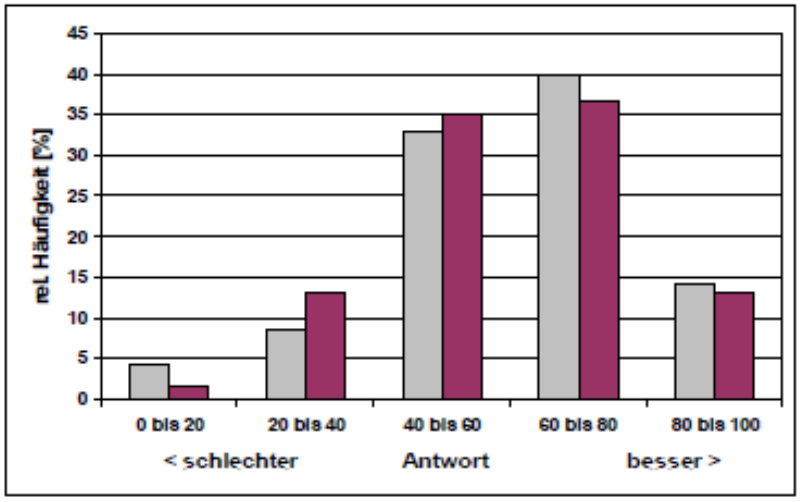

Figure 15: Answers, School 3, before ( ) and after ( ) the intervention [5].

3.5 Study 5

The PhD thesis was written by J. König and deals with various natural and mechanical ventilation concepts in a long-term study [13]. The study looked at the common room of a day care centre, ten school classrooms

and a university lecture hall. The study period covered a total of 246 months. Various hypotheses were put forward, which were analysed in the course of the study:

1. free ventilation is not sufficiently implemented
2. an improvement can only be achieved in the short term by raising awareness of this issue
3. mechanical ventilation systems inevitably lead to an improvement in indoor air quality and well-being
4. user-dependent control is more suitable than time control
5. the results for classrooms are transferable to lecture theatres
6. mechanical ventilation is not necessary for day-care centres

The following parameters were recorded to assess the indoor air quality: Indoor air temperature, relative indoor humidity, CO_2-concentration and window contacts/window openings. Performance was measured using concentration tests, which were also used in a study on health-promoting influences on performance [5], [13]Klicken oder tippen Sie hier, um Text einzugeben..

Results

In order to be able to compare the results with each other, the indoor air quality was divided into different categories in Table 4.

Table 4: Categories for assessing indoor air quality and thermal comfort [13]

Categories	A	B	C	D
CO_2 concentration in ppm	< 1000	1000 – 1400	1400 – 2000	> 2000
room-air temperature in °C	21 – 23	20 – 21; 23 – 24	19 – 20; 24 – 25	< 19; > 25
relative humidity in %	30 – 50	25 – 30; 50 – 60	20 – 25; 60 – 70	< 20; > 70

Performance:

This study also analysed the relationship between CO_2-concentration and room air temperature and performance. In Figure 16, the CO_2-concentration of 2000 ppm is set to 100 %. [13]

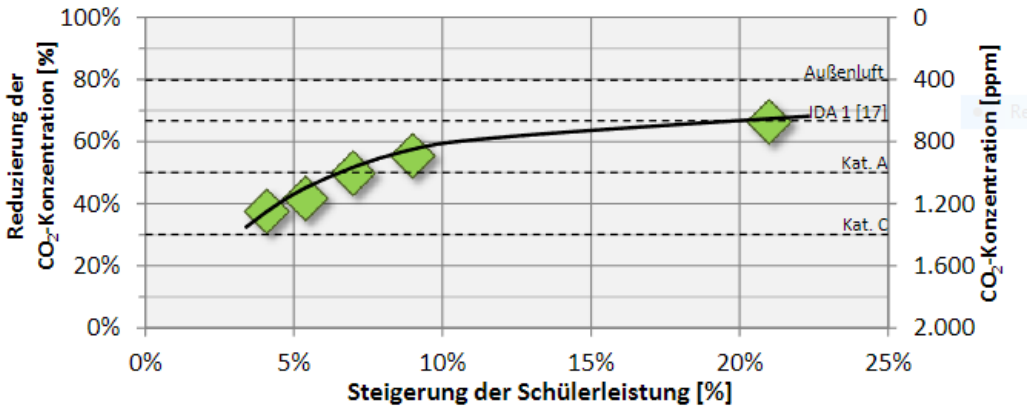

Figure 16: Influence of CO2 concentration Performance [13]

It can be seen from the increase in performance that the optimum CO_2-concentration is 700 ppm, i.e. a reduction of 65 %. [13] Figure 17 shows that performance is increased when the interior temperature is reduced. The lower limit of the performance increase is at around 18 °C with an increase of just under 21 %. As

the temperature decreases further, the performance decreases, which is due to the fact that thermal comfort is very limited at such low temperatures. Nevertheless, it should be noted that even 18 °C is in category D and therefore does not provide optimum thermal comfort.

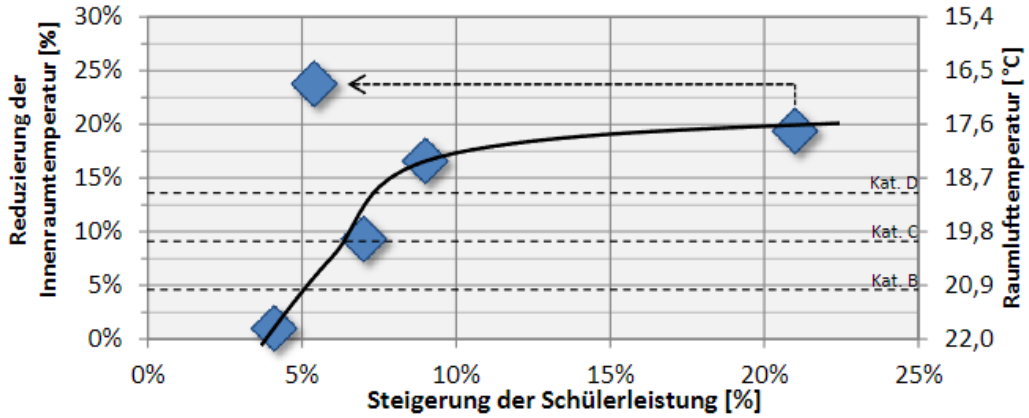

Figure 17: Influence of room air temperature on performance [13]

In conclusion, it can be stated that a reduction in the CO_2-concentration from 2000 ppm to 1000 ppm results in an increase in performance of around 7 %. A 3.5-fold air change is also required to maintain good indoor air quality in the long term. Satisfaction with thermal comfort is higher in naturally ventilated rooms.

3.6 Study 6

Over 200 original studies were analysed in this literature study. The authors came to the conclusion that there are only seven original studies that analyse different ventilation rates. There are also only five substantial publications on the influence of CO_2-concentration on learning behaviour. [3]

Result

All seven studies came to the conclusion that an increase in the amount of fresh air can increase the working speed by 15 %. The extent of the influence of the increased ventilation volume can be seen in Figure 18. [3]

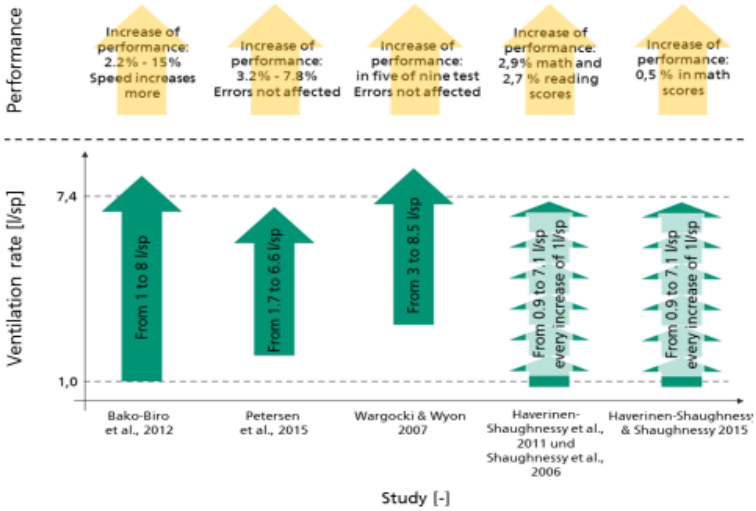

Figure 18: Overview of the influence of ventilation rate on learning outcomes from the most important studies. [3]

The five studies on the influence of CO_2-concentration on learning behaviour also came to the uniform conclusion that the ability to pay attention and concentrate decreases with increasing CO_2-concentration. The extent of the influence of increased CO_2-concentration can be seen in Figure 19. [3]

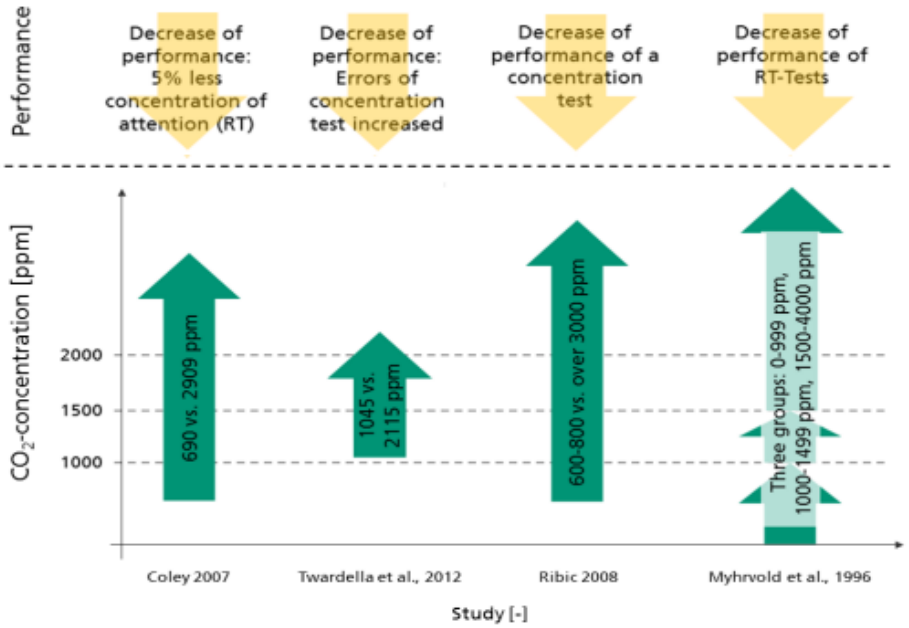

Figure 19: Overview of the influence of CO_2 concentration on learning outcomes from the most important studies. [3]

Further studies also concluded that the absence rate of pupils and teachers correlates with the CO_2-concentration. By increasing absenteeism in poor air quality.
The influence of daylight on learning and working behaviour should also be discussed again here. It was found that pupils who sat in rooms with the greatest amount of daylight performed 7 - 18 % better. In other words, more daylight means better performance.

4 Standards and guidelines

4.1 German standards and guidelines

Air pollution control is regulated in several directives, standards and recommendations. A distinction must be made between European directives and national legislation. European directives only specify the objective, i.e., limit values in the case of air pollution control. However, the states of the European Union can decide for themselves how these directives are implemented.
EN standards also exist at European level. These standards are drawn up by the European standards organizations. DIN represents German interests in these bodies. Once new EN standards have been adopted, they must be incorporated unchanged into the national body of standards and conflicting national standards must be withdrawn. This leads to a standardization of the body of standards within the European Union.
Furthermore, national regulations or laws are specified in technical rules, which in some cases are merely recommendations for action [18]. Figure 20 illustrates this process:

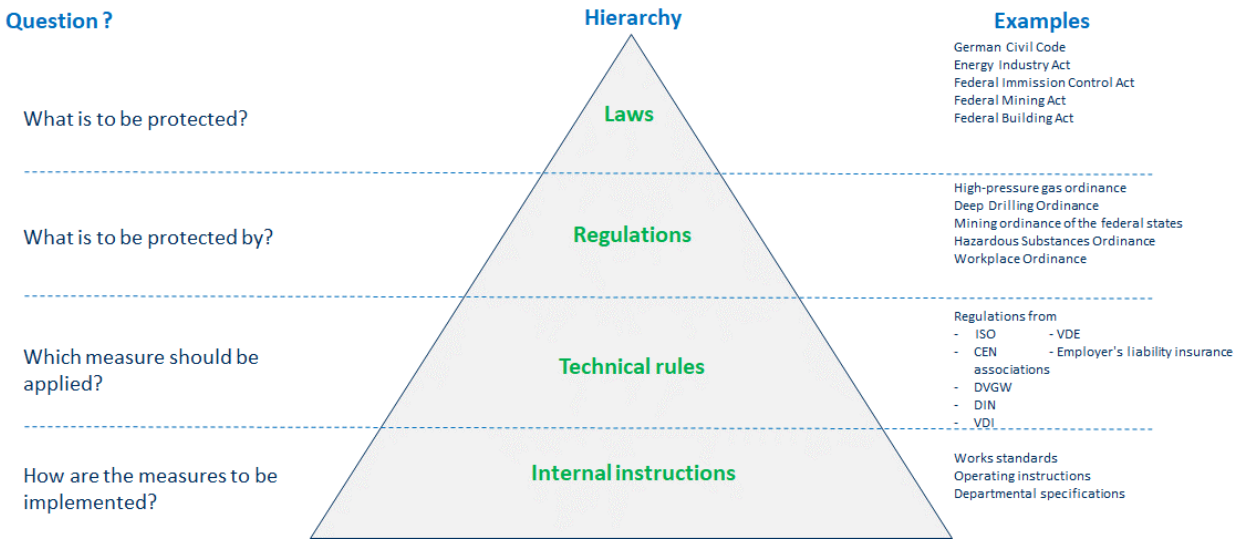

Figure 20: Extract from German occupational health and safety law according to IFA

Guideline 2008/50/EG

Directive 2008/50/EC on ambient air quality and cleaner air for Europe [19] regulates air pollution control in the European Union. The directive sets limit values for nitrogen oxides, nitrogen oxides, particulate matter, sulphur dioxide, benzene, carbon monoxide and lead. In Germany, it was implemented with the 39th Ordinance on the Implementation of the Federal Emission Control Act. The directive deals with limit values in outdoor air and does not address indoor limit values. Nevertheless, it is of great importance as outdoor air has a significant influence on indoor air quality.

DIN EN 16798

The European standard DIN EN 16798 is a series of standards with a total of 18 parts and deals with the most important technical rules in the field of building energy efficiency and ventilation, air conditioning and refrigeration systems DIN EN 16798 Part 3 Ventilation for non-residential buildings - Performance requirements for ventilation and air conditioning systems and room cooling systems replaces [20] which was valid until 2017, and DIN 1946 Part 2 [21], which was valid before that. This standard provides various tables with reference values for specific rooms, different groups of people in these rooms and activities that are carried out

in the rooms. According to DIN EN 16798-1, four comfort categories are defined as follows [22]Klicken oder tippen Sie hier, um Text einzugeben.:

- Category I (IEQI): High air quality must be ensured here. Recommended for rooms where there are very sensitive people (children, elderly people, disadvantaged people).
- Category II (IEQII): Normal air quality must be ensured here. This category is the design and operating category.
- Category III (IEQIII): Acceptable air quality is maintained. There is a risk of reduced performance of the people in the room.
- Category IV (IEQIV): Should only be used for rooms that are only occupied for a short time.

These categories are used in the standard to categorize various ventilation technology parameters. Different guideline values for CO_2-concentrations apply for rooms depending on the category. These are shown for living rooms and bedrooms in Table 5. It should be noted in this table that the CO_2-concentrations are described as differences between the indoor and outdoor air. This means that the permissible CO_2-concentration is described by the entry of CO_2 into the rooms by the people present.

Table 5: CO_2-concentration in occupied living spaces and bedrooms

Category	ΔCO₂-concentration for living spaces (ppm above outside air)	ΔCO₂-concentration for bedrooms (ppm above outside air)
I	550	380
II	800	550
III	1350	950
IV	1350	950

This first classification is specified in DIN EN 16798-2 for various building types. This also includes school buildings [23]. In this part, examples are given of the increase in CO_2-concentrations if there are people in these rooms and the room itself also contributes to pollution. For the room type "classroom", this is shown as an excerpt in Table 6:

Table 6: Example of the increase in CO_2-concentration due to people in the room (extract)Klicken oder tippen Sie hier, um Text einzugeben. [23]

Room type	Category	Occupancy Person/m2	ΔCO₂-concentration (ppm)		
			Very little soiling	Little soiling	Not a little soiling
Classroom	I	0,5	505	463	397
	II	0,5	722	661	567
	III	0,5	1263	1157	992
	IV	0,5	1543	1389	1502

Furthermore, the standard provides information on the minimum air volume flow in various mechanically ventilated rooms, both in terms of the number of people and the area. Table 7 shows this as an excerpt for reading rooms and classrooms for person-related and area-related volume flows:

Table 7: Minimum volume flow according to EN 16798-1 [22]

Room type	Example	Air volume flow	
		Person-related	Area-related
Classroom	Reading hall (IEQ_I)	10 [l/(s•pers.)]	13,3 [l/(s•m^2)]
	classroom, lecture hall (IEQ_I)	10 [l/(s•pers.)]	5 [l/(s•m^2)]

ASR A3.6-Ventilation

The technical guidelines for workplaces (in German: Arbeitsstättenrichtlinie ASR) implement and specify the regulations for workplaces applicable in Germany. This regulation is the German implementation of the EU Workplace Directive 89/654/EEC. The 21 ASRs deal with the safe operation of workplaces from an occupational health perspective. The employer is not obliged to comply with the ASRs, but must choose a different solution as part of the risk assessment that ensures at least the same level of safety and health protection [18]. ASR A3.6 Ventilation is of particular importance when considering indoor air quality. The regulations provide information on limit values for material loads, moisture loads and heat loads and specify requirements for free and mechanical ventilation systems. The ASR uses the CO_2-concentration as a measure for assessing air quality if employees and other people present are the main cause of material loads in the room. Recommendations for action are given for different CO_2-concentrations. These are summarized in Table 8:

Table 8: CO_2-concentration in the indoor air [18]

CO_2-concentration ppm	Actions
< 1000	• No further actions (unless an increase to over 1000 ppm is expected)
1000 - 2000	• Check and improve ventilation behavior • Draw up a ventilation plan • Ventilation actions (increase external volume flow or air exchange)
> 2000	• Further actions (increased ventilation, reducing the number of people in the room)

LASI-Guide LV16

The guideline of the State Committee for Occupational Health and Safety: "Parameters for assessing basic indoor climate parameters" compiles the guideline values for basic climate parameters from ASR 3.6 and other sources in order to make them easily available to specialist personnel. The guideline deals with the basic parameters of air temperature, humidity, air velocity and heat radiation. No particular reference is made to air quality [24].

VDI 6040 Sheet 1

School building guidelines are issued by the federal states themselves and therefore differ greatly from one another. Some refer to indoor air and its guideline values, while others do not mention the subject of

ventilation. VDI 6040 Sheet 1 "Room air technology - school requirements" deals in particular with requirements for CO_2-concentration in the room air for both mechanically ventilated and freely ventilated classrooms. These are shown in Table 9. The requirements therefore apply to classrooms and common rooms in which pupils from general and vocational schools are housed and learn [13].

Table 9: Requirements for thermal/air hygiene conditions [13]

Operative room temperature	Min. 20 °C, Max. 26 °C This assumes that users are not exposed to direct sunlight.
CO_2-concentration	During lesson time[1]: < 1.000 ppm: Harmless in terms of air hygiene 1.000-2.000 ppm: Hygienically questionable > 2.000 ppm: Not acceptable
[1] the average CO_2-concentration time-weighted over the duration of a lesson (45 min). Assumption of an outdoor air concentration of 400 ppm.	

Guidelines for indoor hygiene in school buildings

The "Guidelines for Indoor Air Hygiene in School Buildings" were drawn up by the Federal Environment Agency's Indoor Air Hygiene Commission in 2008 and are intended to help avoid mistakes when renovating existing school buildings and to provide assistance in terms of air hygiene for new buildings. The guidelines relate primarily to classrooms and common rooms in general and vocational schools. Guideline values for CO_2-concentration are given and summarized in Table 10. These guideline values correspond to other guideline values such as those in ASR 3.6.

Table 10: Guide values for CO_2-concentration in indoor air [25]

CO_2-concentration in ppm	Hygienic assessment	Recommendation
< 1.000	Hygienically safe	• No further action
1.000-2.000	Hygienically questionable	• Intensify ventilation measures (increase outside air volume flow or air exchange) • Check and improve ventilation behaviour
> 2.000	Hygienically unacceptable	• Check the ventilation of the room • Check far-reaching actions if necessary

4.2 International standards and directives

The ASHRAE Standard 62.1 is published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and describes the minimum air exchange rates for indoor spaces to maintain indoor air quality in order to minimize potential adverse health effects. The standard also provides instructions on how to establish indoor air quality. The ASH-RAE Standard 62.1 is therefore the US equivalent of DIN EN-16798, as it is used in the European Union. This standard also specifies air exchange rates for various rooms. The air change rates for classrooms are shown in Table 11.

Table 11: Minimum ventilation rate in the breathing zone [26] (translated)

Room type	Outdoor air volume flow	
	Person-related (l/s•Person)	Area-related (l/s•m²)
Classroom (age: 5-8 years)	5	0,6
Art classroom	5	0,9

4.3 European comparison of standards (selection)

A comparison of the country-specific ventilation rates can be seen in the Table 12.

Table 12: Comparison of air exchange rates in different European countries (taken from [27])

Country and Standard Reference	Whole building ventilation rate	Living room	Bedroom	Kitchen	Bathroom & WC	WC only	Requirement (RQ) or Recommendation (RC)
Brussels (NBN D 50-001)	3.6 m³/(h·m²) floor surface area	Minimum 75 m³/h (limited to 150 m³/h	Minimum 25m³/h (limited to 72m³/h)	Open kitchen Minimum 75 m³/h (exhaust)	Minimum 50 m³/hour (limited to 75 m³/h	Minimum 25 m³/h	RQ
Denmark (BR10)	Min. 0.3 l/s·m² (supply)	Min. 0.3 l/(s·m2) (supply)		20 l/s (exhaust)	15 l/s (exhaust)	10 l/s (exhaust)	RQ
France (Arrêté 24.03.82)	10-135 m³/h (depending on room number and ventilation system)			Continuous: 20 – 45 m³/h		Minimum 15 m³/h	RQ
Germany (DIN 1946-6)	15-285 m³/h			45m³/h (nominal exhaust flow)	45 m³/h (nominal exhaust flow)	25 m³/h (nominal exhaust flow)	RC
Italy (Legislative Decree 192/2005, UNI EN 15251)	Naturally ventilated: 0.3 – 0.6 vol/h	0.011 m3/s per person for an occupancy level of 0.04 persons/m2			4 vol/h		RC
Poland (Art 149 (1) – Journal of Laws 2002 No. 75, item. 690, as amended and PN-B-03430:1983/Az3:2000)	20 m³/h for each permanent occupant should be calculated	20 -30 m³/h for each permanent occupant (for public buildings) For flats, it is a summary of flow from all rooms		30 m³/h to 70 m³/h without windows	50 m³/h	30 m³/h	RC

	according to the Polish standard but not less than 20 m^3/h					
Sweden (BFS2014:13 – BBR21)	Supply: min 0.35 l/(s·m^2) floor area					RQ
UK (Approved Document F)	13-29 l/s (depending on bedrooms)		13-60 l/s (extract)	8-15 l/s (extract)	6 l/s (extract)	RC
EN 15251	0.35 – 0.49 l/(s·m^2)	0.6 – 1.4 l/(s·m^2)	14-28 l/s	10-20 l/s	7-14 l/s	

It is recognisable that many countries orientate themselves to the European standard, but also make their own specifications.

5 Residential Buildings

The data available for residential buildings is significantly less than for non-residential buildings. Significant studies are listed in the appendix. These mainly deal with the detection of pollution loads in buildings. The influence of ventilation systems is also addressed. However, there are no significant correlations with the performance of people.

Table 13: Requirements for naturally and mechanically ventilated buildings with regard to CO_2

Minimum and target values for indoor spaces permanently used by people as CO_2 concentration (absolute)	
Natural ventilated buildings	Mechanical ventilated buildings
Target range for indoor air < about 1000 ppm	Target range for indoor air < about 800 ppm
Minimum specification 1-MWg < approx. 1400 ppm	Minimum specification 1-MWg < approx. 1000 ppm
Minimum specification All individual values in the assessment period: < about 1900 ppm	Minimum specification All individual values in the assessment period: < about 1400 ppm
1-MWg = maximum moving average hourly value	

Another point that is addressed in the residential buildings is the VOC concentration and its change over time. In some studies, measurement-based analyses are carried out. A VOC reduction can be shown depending on the type of ventilation, but exact correlations are not available. The studies [28], [29] should be mentioned here. [30] and [31] investigated indoor environmental quality in more than 500 residences across France, focusing on various parameters and their correlation with building characteristics as well as socio-economic factors and occupant behaviors. The findings emphasize the need for a comprehensive risk assessment and the importance of factors like AER, specific humidity, smoking and outdoor air pollution levels. In [32] the relationship between indoor CO_2 levels, temperature, and sleep quality is investigated, highlighting the importance of proper ventilation for better sleep. The findings offer valuable insights for designing bedrooms to promote healthy sleep environments. In addition, [33] shows the importance of home maintenance for occupant health and healthcare demand, particularly among older age groups. It underscores the potential health consequences of living in poorly maintained homes and the role of homeowners and landlords in addressing housing quality issues.

6 Results and recommendations for action

The analyses of the various references shows that there are many studies on the subject. However, the quality varies greatly. The most significant results are documented in the following table.

Table 14: Summary of the literature study – non residential buildings

Titel	Autor	Result
scientific Literature		
The Relationship between classroom air quality and children's performance in school	Wargocki et al.	• 2100 ppm --- > 900 ppm increase of Processing speed of 12% / Quality of the results increase of 2 % • 2300 ppm --- > 900 ppm increase of learning speed of 5% • 4000 ppm --- > 1000 ppm Improvement in attendance from 2,5 % • The increase in performance was higher at low CO2 concentrations (children)
Providing better thermal and air quality conditions in school classrooms would be cost-effective	Wargocki et al.	• variation of the air change rate (3 l/s … 10 l/s) • Doubling the ventilation rate leads to an 8% increase in performance (speed) • no correlation between reduced suspended solids concentration and performance • Temperature (25°C … 20°C) --- > a reduction of 1 °C results in a 2 % increase in output
Lernleistungsbezogene Kosten von unterschiedlichen bauphysikalischen Konzepten für Schulgebäude. Einfluss der Luftqualität und des thermischen Komforts	Drexler	• $P = 0{,}1647524 \cdot T - 0{,}0058274 \cdot T^2 + 0{,}0000623 \cdot T^3 - 0{,}4685328$ T...operative room temperature [°C] P...human performance [%] taken from [34]
Standards and Guidelines		
EN 16798-1	CEN / TC 156	ΔCO_2-concentration for living spaces (ppm above outside air) • Kategorie I : 550 ppm • Kategorie II: 800 ppm • Kategorie III: 1350 ppm • Kategorie IV: 1350 ppm
ASR A3.6	-	CO_2-concentration ppm • < 1000 ppm (No further actions) • 1000 … 2000 ppm (Check ventilation) • > 2000 ppm (increase ventilation)
VDI 6040 Blatt 1	VDI	• Operative Room temperature 20 …. 26°C • CO_2-concentration according to ASR A 3.6

With regard to temperatures, it is clear from the literature that these should be between 20°C and a maximum of 26°C. About CO_2-concentrations, CO_2-values of < 1000 ppm should be aimed for in the room. Values > 2000 ppm are unacceptable and more intensive ventilation should be provided.

7 Summary

A comparison of the existing literature has shown that there is a negative influence on performance. The studies on this topic were conducted by various research groups from different countries and in different years. The topic of the influence of indoor CO_2-concentration on performance has been studied extensively in labour research since at least the 1950s. Studies on the influence of adults in this respect also had labour law implications. Studies focussing on schoolchildren only became the subject of scientific work later, but were taken up particularly in the 1990s. There was also an increase in publications on this topic in relation to the COVID-19 pandemic. It can generally be recognised that this research is being driven forward particularly in Scandinavia and North America.

Although the study design, the type of data collection and the analysis techniques differ, the qualitative results are consistent. The exception is only one of the compared studies. Some studies use the absolute CO_2-concentration, others the difference in concentration between indoor and outdoor air. This makes it difficult to compare the studies with each other. Both evaluation techniques have advantages and disadvantages that enable a more suitable presentation depending on the task of the studies.

The studies are also consistent with the results carried out on adults. It can be observed that the effects on the ability to concentrate are greater than in adults. Therefore, a closer look at this topic in adolescents is of increased interest. Most of the studies were carried out on school children of primary school age. Only little literature is available for the age between 14-18 years. However, based on the available data, it can be assumed that there is only a slight change in the influence of conduction compared to children of primary school age.

Only a few sources could be found with regard to ventilation in the home and its influence on the ability to concentrate and well-being. This can be explained by a lower relevance to labour science. There are fewer monetary resources available to finance studies on the topic of private well-being. Nevertheless, the results found are also applicable here. Generally speaking, productivity is not a top priority in everyday private life and recommendations for action such as airing the room in bursts have become established as a common practice.

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9 Annex A (Summary of reviewed articles)

9.1 General

Titel	Achieving Healthy Indoor Air
Autors	American Thoracic Society
Year	1995
Reference	[35]

Short summary and approach:

- Workshop of a broad range of professionals concerned with indoor air quality divided in 5 focus groups
    - design, construction and operation, Source control, Ventilation, Air Cleaning and treatment, potentially susceptible populations (e.g., Persons with Asthma and Allergies)
- Each group publishes a list of general recommendations for reducing problems caused by indoor air pollution, based on their expertise and known facts (no scientific investigation)
- Their aim is to supply a framework for developing and implementing control strategies to increase good indoor air quality (IAQ) and to identify buildings with occupants who are affected by building-associated illnesses

Important findings / results:

- Indoor air pollutants are linked to health responses through a sequence that moves from emission by the source through exposure, dose, and ultimately to the health response (see. fig. 1)

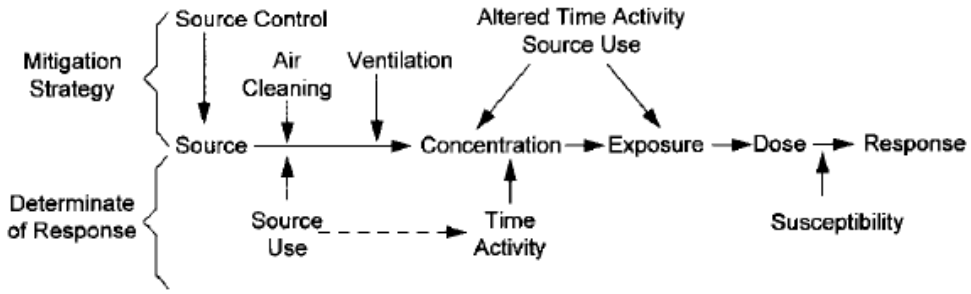


Figure 21: Sequence of health responses linked to indoor air pollution

- Source control should play a central role in any control strategy
- Reduction of exposure is recommended
- Issues in the design and retrofit of buildings to ensure good IAQ are:
    - site characteristics, climate and outdoor air quality, building age, constructions and maintenance, building envelope integrity
- Dilution by ventilation is an inescapably needed approach to managing indoor air pollution
- Airborne disease transmission should be given more consideration in HVAC design
- Critical need to improve general knowledge regarding the practical aspects of indoor air pollution
- Need for better approaches to identify sources of pollutants and find solutions for controlling them

Comments:

- Provides general background on the conceptual basis of healthy indoor air

Titel	Why we ventilate
Autors	J.M. Logue, M.H. Sherman, P.N. Price, B. B. Singer
Year	2011
Reference	[36]

Short summary and approach:

- paper presents results to identify air pollutants that drive the need for ventilation as part of a larger effort to develop a health-based ventilation standard
- it is divided in three sections
    - hazard analysis to identify pollutants that reach critical concentrations
    - impact assessment to identify pollutants that cause the most harm
    - implications for developing effective ventilation standards
- focus on non-biological indoor air pollutants
    - analysis compiled data from 86 articles to calculate representative mid-range and upper-bound concentrations for over 300 pollutants
- disease incidence and health damage models were synthesized to develop a methodology for quantifying IAQ
- to quantify and compare health damages the Disability Adjusted Life Year (DALY) metric is used

Important findings / results:

- compared to available standards and guidelines, fifteen diverse pollutants were identified as potential chronic or acute health hazards for many homes
    - fig 1 shows the most harmful pollutants in residential indoor air as a result of the analysis

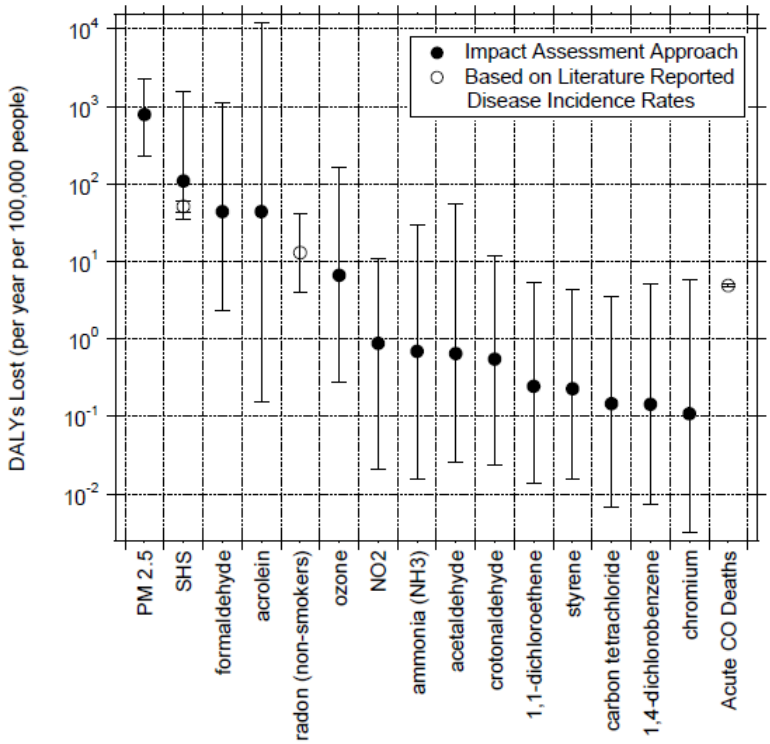


Figure 22: Estimated population averaged annual cost, in DALY's, of chronic air pollutant inhalation in U.S. residences, result for the 15 pollutants with highest mean damage estimates.

- For 90 % of sample sets, acrolein, formaldehyde and PM25 contributed more than 80 % of the total health damage
    - they account for the majority of chronic health problems
    - ventilation rates and incoming air filtration should be based on controlling those pollutants
- the current IAQ related health damage can be compared to health effects of road traffic accidents and all-cause heart disease
- the analysis shows, that the overall air exchange rate and the localized exhaust ventilation can improve good IAQ

Comments:

- Precise analysis of the most harmful pollutants and their effects on health damage measured in DALY
- the developed recommendations can be applied in residential homes and offices

Titel	Indoor Air Pollutants and the Impact on Human Health
Autors	Marios. P. Tsakas, Apostolos. P. Siskos, Panayotis. A. Siskos
Year	2011
Reference	[37]

Short summary and approach:

- Detailed introduction of indoor air pollutants and their sources
    - Radon (soil, building materials, outdoor air, tap water, domestic gas)
    - Oxides of nitrogen (NOx, HONO and HNO3, CO and SO_2, VOCs, Ozone, Particles, Microbial pollutants, Asbestos and manmade mineral fibres)
- The reviewed factors that influence air-pollution exposures have been specifically separated into two major components: time (activity) and concentration (location)

Important findings / results:

- Concentrations of chemically non-reactive pollutants in residences generally correlate with those outdoors
- IAQ is determined by complex dynamic relationships that depend heavily on occupant activity and highly variable structural characteristics
- Indoor air pollution (IAP) can be characterised as a „global environmental phenomenon “
- IAP is caused by a modern way of living and therefore expected to increase

Comments:

- All in all, an overview of the most important facts concerning IAQ

Titel	Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature
Autors	Yousef Al horr, Mohammed Arif, Martha Katafygiotou, Ahmed Mazroei, Amit Kaushik, Esam Elsarrag
Year	2016
Reference	[38]

Short summary and approach:

- The paper is a state-of-the-art literature review and considers a range of issues such as sick building syndrome, indoor air quality thermal comfort, visual comfort and acoustic comfort

Important findings / results:

- Design of buildings need to consider occupant well-being parameters right at the beginning
- Engineers need to take a range of factors into account:
  - sick building syndrome
  - thermal, visual and acoustic comfort
- green building designs do not guarantee comfort and occupant well-being
- More specific and in-depth considerations on occupant well-being is required along with the impact on building efficiency and sustainability
- it is suggested to monitor building and occupant performance during operations
- fig 23 show the year of publication used in this literature review

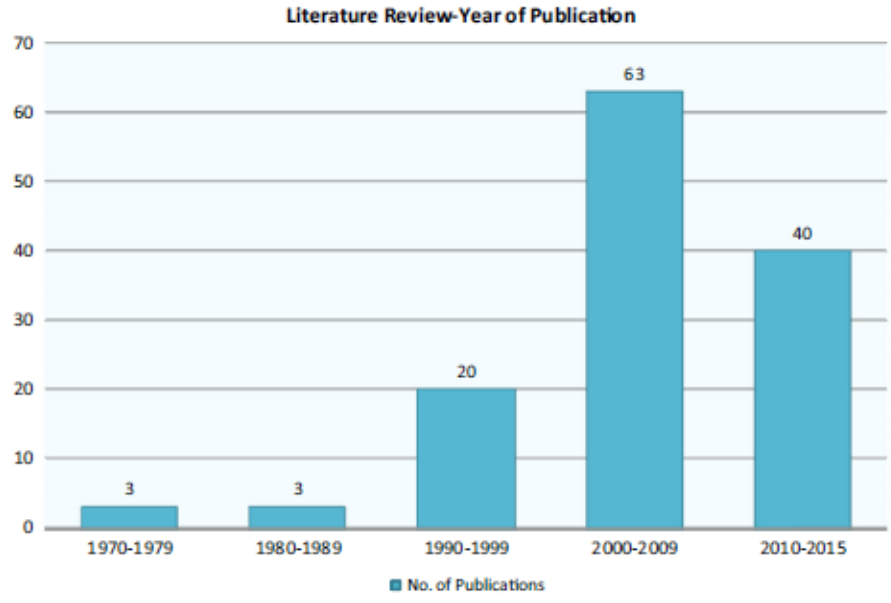


Figure 23: Frequency of year of publication used in the study.

Comments:

- Paper is helpful for researchers, designer, engineers and facility maintenance engineers
  - Good starting point for specific research

Titel	Healthy Homes Barometer
Autors	Velux Group
Year	2016
Reference	[39]

Short summary and approach:

- Analysis presenting key findings form a pan-European study investigating European citizens' experiences, attitudes and behaviour regarding health perception, home satisfaction and energy consumption
- Questionnaire answered by 14.000 Europeans across all Countries to ensure statistical representation
- Study is based on home wellbeing model by B. Wegener and M Fedkenheuer and includes:
    - Quality of sleep
    - Humidity Level of mould and damp
    - state of renovation
    - energy costs
    - relation to neighbours
    - size of home
    - indoor climate temperature and fresh air
    - daylight

Important findings / results:

- no healthy Europe without healthy homes
- home wellbeing and energy savings drive renovation
- the healthy home is a happy home
- Europeans overlook the importance of daylight
- more healthy homes require a common effort
- five characteristics of a healthy home
    - good sleeping conditions
    - comfortable indoor temperatures
    - fresh air
    - satisfactory daylight levels
    - appropriate humidity levels

Comments:

- This brochure is very general and biased by Velux – it should not be used for scientific conclusions

Titel	Indoor Air Quality and Health
Autors	Alessandra Cincinelli, Tania Martellini
Year	2017
Reference	[40]

Short summary and approach:

- Issue underlines the importance of IAQ studies and includes 22 contributions by some of the main experts in the field of indoor air pollution in public and private buildings and related health concerns
- the following topics have been conducted:
    - indoor air sampling to determine VOCs
    - indoor air in residential houses
    - influence of particle size on human indoor exposure to airborne HFRs
    - IAQ in enclosed environments
    - health risks of dampness and mould in houses (but only few in workplaces and schools)
    - microbiological contamination at a plant biomass processing thermal power station
    - human activity pattern
    - environmental tobacco smoke as well as second- and third-hand smoke
    - relation between outdoor pollutants and indoor concentration
    - ventilation rate (CO2 concentration)
    - potential conflicts between IAQ and passive houses or other highly energy-efficient buildings
    - determination of ultrafine particle concentrations in operating theatres
    - monitoring of VOC concentrations in anatomical pathology
    - household air pollution (HAP)
    - monitoring radon levels in households
    - diagnostic tool for proper IAQ management (monitoring in real time)

Important findings / results:

- None

Comments:

- good overview on current research topics related to IAQ

Titel	Indoor Air Quality in Inpatient Environments: A Systematic Review on Factors that influence chemical pollution in inpatient wards
Autors	Marco Gola, Gaetano Settimo, Stafano Capolongo
Year	2019
Reference	[41]

Short summary and approach:

- Systematic review on the current state of the art and knowledge related to chemical pollution in healing spaces and emerging strategies supported by scientific literature, for healthy inpatient rooms and their indoor air
- Analysis of papers from SCOPUS, DOA and PubMed databases between 1989 and 2017
- resulting work is divided into specific fields of interest
    - construction materials, installations, components
    - ventilation systems, processes
- the following factors of indoor air are classified:
    - outdoor air and microclimate (temperature, relative humidity, air velocity, air change, etc.)
    - management activities (management and maintenance activities, ventilation systems, HVAC, cleaning and disinfectant activities, etc.)
    - design factors (room dimensions, furniture, finishing materials, etc.)
    - human presence and medical activities (users' presence, their health status, and medical activities carried out in inpatient rooms)

Important findings / results:

- interdisciplinary knowledge needs to be taken into account:
    - needs of hospital users related to their activities and therapies
    - needs and problems related to users in relation to nosocomial infections
    - applications of the technologies and operating systems
    - risk analysis techniques
    - acceptable residual risk values
- there is a lack of specific protocols related to chemical pollution due to cleaning activities
- designers and healthcare professionals should attach to these recommendations:
    - design healthcare settings according to the different uses
    - support healthcare organization to identify the most optimal solutions for technical, functional, economics and management aspects
    - elaborate and monitor the management and maintenance procedures of environments and systems
    - train staff who will use or manage the spaces and systems
    - select materials strictly correlated to cleaning products and activities

Comments:

- good starting point for considering the importance of the topic and to stimulate the knowledge around this field of interest for improving studies, analysis, and simulations

9.2 Schools an Offices

Title	Association of Ventilation Rates and CO2-Concentrations with Health and other Responses in Commercial and Institutional Buildings
Authors	O. A. Seppänen; W. J. Fisk; M. J. Mendell
Year	1999
Reference	[42]

Focus of the study / methods

- This paper reviews existing literature on the relationship between ventilation rates and carbon dioxide concentrations in non-residential buildings, primarily offices, and their impact on health and other human outcomes.

Short summary and approach

- The review incorporates findings from 20 studies involving nearly 30,000 subjects that investigated the connection between ventilation rates and human responses.
- Additionally, 21 studies, with over 30,000 subjects, examined the relationship between carbon dioxide concentration and these responses.
- The authors analysed the associations between ventilation rates, carbon dioxide levels, and various health and perceived air quality outcomes.

Important findings / results

- Nearly all the studies found that ventilation rates below 10 L/s per person in all building types were linked to statistically significant deterioration in health or perceived air quality outcomes.
- Some studies indicated that increasing ventilation rates from 10 L/s per person to approximately 20 L/s per person led to further significant reductions in the prevalence of symptoms associated with Sick Building Syndrome (SBS) or improvements in perceived air quality.
- In the case of carbon dioxide levels, approximately half of the studies suggested that the risk of SBS symptoms continued to decrease significantly as carbon dioxide concentrations dropped below 800 ppm.
- The ventilation studies reported relative risks of 1.5 to 2 for respiratory illnesses and 1.1 to 6 for SBS symptoms when comparing low ventilation rates to high ventilation rates.

Comments

- This review underscores the critical importance of adequate ventilation rates and low carbon dioxide concentrations in non-residential buildings, as they are associated with improved human health outcomes and enhanced perceived air quality. It highlights the potential risks of inadequate ventilation in such environments.

Title	Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity in an Office with Two Different Pollution Loads
Authors	Pawel Wargocki; David P. Wyon; Yong K. Baik; Geo Clausen; P. Ole Fanger
Year	1999
Reference	[43]

Focus of the study / methods

- The study focused on assessing perceived air quality, Sick Building Syndrome (SBS) symptoms, and productivity in an existing office environment.
- The researchers aimed to investigate the impact of air pollution levels that could be modified by introducing or removing a pollution source in the office setting.

Short summary and approach

- The study employed a reversible intervention, allowing the office to be classified as either non-low-polluting or low-polluting, following European design criteria for indoor environments.
- A 20-year-old used carpet was used as the pollution source, placed behind a screen to make it invisible to office occupants.
- Five groups of six female subjects each were exposed to the office conditions twice, once with the pollution source present and once with it absent. Each exposure lasted for 265 minutes in the afternoon, one group at a time.
- During these exposures, subjects assessed perceived air quality and reported SBS symptoms while performing simulated office work.

Important findings / results

- When the pollution source was present in the office, 22% of subjects reported dissatisfaction with perceived air quality, compared to 15% when the pollution source was absent.
- In the presence of the pollution source, there was a significantly increased prevalence of headaches ($p < 0.04$) and significantly lower levels of reported effort ($p < 0.02$) during tasks requiring sustained concentration, such as text typing and calculation.
- During the text typing task, subjects worked significantly more slowly ($p < 0.003$) when the pollution source was present, typing 6.5% less text than when the pollution source was absent.
- The study concluded that reducing the pollution load in indoor air effectively improved the comfort, health, and productivity of building occupants.

Comments

- This study demonstrates the significant impact of air quality on occupant comfort, health, and productivity in an office environment. It highlights the positive effects of reducing indoor air pollution levels, indicating that improving indoor air quality can lead to better outcomes for building occupants.

Title	The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity
Authors	Pawel Wargocki; David P. Wyon; Yong K. Baik; Geo Clausen; P. Ole Fanger
Year	2000
Reference	[44]

Focus of the study / methods

- The study investigates perceived air quality, Sick Building Syndrome (SBS) symptoms, and productivity in a normally furnished office space.
- It specifically examines the impact of varying ventilation rates on these factors while keeping other environmental parameters constant.

Short summary and approach

- The office space, measuring 108 m³, was ventilated with outdoor airflow rates of 3, 10, or 30 L/s per person, corresponding to air change rates of 0.6, 2, or 6 h^(-1).
- Temperature was maintained at 22.75°C, relative humidity at 40%, and all other environmental parameters remained unchanged.
- Five groups of six female subjects were exposed to the different ventilation rates one group at a time, with each exposure lasting 4.6 hours in the afternoon.
- Subjects were unaware of the ventilation rate changes and adjusted their clothing to remain thermally neutral.
- They assessed perceived air quality and SBS symptoms at intervals and performed simulated normal office work.

Important findings / results

- Increasing ventilation rates led to a decrease in the percentage of subjects dissatisfied with air quality ($p < 0.002$), reduced the intensity of odours ($p < 0.02$), and improved the perceived freshness of air ($p < 0.05$).
- Ventilation rate increases also reduced the sensation of dryness of mouth and throat ($p < 0.0006$), eased difficulties in thinking clearly ($p < 0.001$), and made subjects feel generally better ($p < 0.0001$).
- The performance of four simulated office tasks improved with increasing ventilation rates, with text-typing performance showing formal significance ($p < 0.03$). On average, for each twofold increase in ventilation rate, performance improved by 1.7%.

Comments

- This study underscores the substantial benefits of higher ventilation rates on health, comfort, and productivity in office environments. It demonstrates that ventilation rates well above minimum standards and guidelines can lead to improved indoor air quality and overall well-being for occupants, consistent with a previous study that reduced pollution while maintaining ventilation rates.

Title	Do Indoor Environments in Schools influence Student Performance? A Review of Literature
Authors	G. A. Heath; M. J. Mendell
Year	2002
Reference	[45]

Focus of the study / methods

- The paper aims to critically review the available evidence on the relationships between indoor environmental quality (IEQ) in schools and student performance.
- The review initially focused on school environments but expanded to include studies on the performance of children and adults in various indoor settings, such as workplaces, residences, and controlled laboratory settings.

Short summary and approach

- The review examines the available evidence related to IEQ and its impact on the performance of occupants, including students.
- It considers factors such as ventilation rates, daylight or lighting conditions, and other potential influences, including pollen and certain types of carpets.
- The authors acknowledge limitations in the quantity and quality of available research findings, highlighting the need for further investigation.

Important findings / results

- The most persuasive evidence suggests that certain aspects of IEQ, such as low ventilation rates and inadequate daylight or lighting, may negatively affect the performance of occupants, including students in schools.
- Other potential influences, such as pollen and specific carpet types, are also identified but require further study.
- The paper emphasizes the need for focused, well-designed research to better understand the relationship between IEQ and performance in schools and other indoor settings.
- It suggests that there is sufficient evidence to warrant actions to safeguard IEQ in schools and to conduct further research to inform future policies and actions related to IEQ.

Comments

- This study highlights the importance of indoor environmental quality in various settings, particularly in schools, and its potential impact on the performance of occupants. It underscores the need for both immediate measures to improve IEQ in schools and continued research to inform future policies and actions in this regard.

Title	Associations between Classroom CO2-Concentrations and Student Attendance
Authors	Derek G. Shendell; Richard Prill; William J. Fisk; Michael G. Apte; David Blake; David Faulkner
Year	2004
Reference	[8]

Focus of the study / methods

- The study explores the association between student attendance in American public schools and indoor environmental quality (IEQ), specifically focusing on indoor carbon dioxide concentration (dCO2).
- Limited data exist on IEQ in schools and its impact on attendance, health, or performance, making this an important area of investigation.

Short summary and approach

- Data was collected from 409 traditional and 25 portable classrooms in 14 schools across six school districts in Washington and Idaho.
- Classroom attributes, student attendance, and school-level demographics (ethnicity, gender, socio-economic status) were included in multivariate modeling.
- The study measured short-term indoor CO2 concentrations and their association with student absence.
- It also explored the relationship between ventilation rates and student attendance.

Important findings / results

- Approximately 45% of the studied classrooms had short-term indoor CO2 concentrations exceeding 1000 parts-per-million (ppm).
- A 1000 ppm increase in dCO2 was associated with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), which corresponds to a relative 10% to 20% increase in student absence.
- Ventilation rates estimated from dCO2 and other data were not found to be associated with student absence.
- Traditional classrooms had 2% higher ADA compared to portable classrooms.

Comments

- This study highlights the significant impact of indoor carbon dioxide concentrations on student attendance in American public schools.
- Adequate classroom ventilation is suggested as a practical means of reducing student absence, and it may be achieved through teacher and staff training on ventilation system operation and maintenance or the use of improved automated control systems.
- The study calls for larger school studies to further investigate the relationships between student attendance, occupant health, student performance, and IEQ in schools, particularly focusing on longer-term CO2 concentrations and more accurate ventilation rate measurements.

Title	Ventilation and performance in office work
Authors	O. Seppänen; W. J. Fisk; Q. H. Lei
Year	2005
Reference	[46]

Focus of the study / methods

- The study aims to evaluate the potential work performance benefits associated with increased ventilation rates, specifically focusing on the relationship between ventilation rate and work performance.

Short summary and approach

- The authors analysed existing literature that examined the connection between work performance and ventilation rates.
- They conducted statistical analyses with weighting factors to combine the results of various studies, including laboratory experiments and real building assessments.

Important findings / results

- Almost all the reviewed studies reported performance improvements with higher ventilation rates.
- On average, there was a 1–3% improvement in performance for every 10 l/s-person increase in outdoor air ventilation rate.
- The performance increase was more significant when ventilation rates were below 20 l/s-person but became almost negligible at rates over 45 l/s-person.
- Statistically significant performance improvements were observed with increased ventilation rates up to 15 l/s-person with a 95% confidence interval (CI) and up to 17 l/s-person with a 90% CI.
- The study demonstrated a quantitative relationship between work performance and ventilation rates, showing a continuous performance increase per unit increase in ventilation rate within a wide range (from 6.5 l/s-person to 65 l/s-person).

Comments

- This study establishes a clear relationship between ventilation rates and work performance, with a demonstrated performance improvement as ventilation rates increase. The findings suggest that incorporating this relationship into ventilation design and feasibility studies may be beneficial in enhancing productivity, compared to the current practice, which often overlooks the link between ventilation and work performance.

Title	A preliminary study on the association between ventilation rates in classrooms and student performance
Authors	R. J. Shaughnessy; U. Haverinen-Shaughnessy; A. Nevalainen; D. Moschandreas
Year	2005
Reference	[10]

Focus of the study / methods

- The study explores the association between indoor air quality (IAQ) in classrooms, as indicated by classroom carbon dioxide (CO2) concentrations, and student performance on standardized aptitude tests.

Short summary and approach

- Data on classroom CO2 concentrations were collected in fifth-grade classrooms across 54 elementary schools within a US school district.
- The study examines the relationship between classroom-level ventilation rates (represented by CO2 concentrations) and test results in math.
- The research aims to understand whether poor IAQ, specifically ventilation, is linked to student academic performance.

Important findings / results

- The preliminary results suggest a significant association ($p < 0.10$) between classroom-level ventilation rates (CO2 concentrations) and math test results.
- Nonlinear effects may also need consideration to better represent this association.
- A larger sample size is needed to draw more definitive conclusions.
- Future studies could focus on gathering more evidence regarding the association between classroom ventilation rates and academic performance, the linear/non-linear nature of this association, and the possibility of establishing a "no observed adverse effect level" for adequate ventilation concerning academic performance in schools.
- Improving guidance and regulatory actions to ensure adequate ventilation in schools is seen as an opportunity for enhancing the design and management of school facilities.

Comments

- This study provides preliminary evidence suggesting an association between classroom ventilation rates (CO2 concentrations) and student math test results. Further research with a larger sample size is needed to confirm these findings and explore the nature of this relationship. Improved ventilation in schools is seen as a potential opportunity to enhance student performance and overall IAQ.

Title	The effects of classroom air temperature and outdoor air supply rate on performance of school work by children
Authors	Pawel Wargocki; David P. Wyon
Year	2006
Reference	[47]

Focus of the study / methods

- The study conducts two independent field intervention experiments in mechanically ventilated classrooms receiving 100% outdoor air.
- It aims to modify indoor air quality by manipulating the outdoor air supply rate and filter condition and assess the impact on the performance of schoolwork by 10- to 12-year-old children.

Short summary and approach

- Outdoor air supply rate and filter condition were modified for one week at a time in a blind crossover design.
- The study involved two classes of schoolchildren who performed various schoolwork exercises as part of their normal lessons.
- Children marked visual analogue scales to indicate their environmental perceptions and symptom intensity.
- Sensory panels of adults who were blind to conditions were used to assess air quality.

Important findings / results

- When the outdoor air supply rate increased from 3.0 to 8.5 L/s per person, the children perceived fresher air and significantly improved their speed in performing numerical and language-based tasks.
- A significant effect of ventilation rate on work rate was observed in 70% of statistical tests, although there were no significant effects on errors.
- The improvements in work rate were likely due to enhanced indoor air quality, as indicated by sensory panels, children's perceptions, and the reduction in average CO2 concentration from 1300 to 900 ppm (a marker of reduced bioeffluent concentration).
- The study did not test the effect of replacing a soiled filter with a new one due to design limitations.

Comments

- This study underscores the importance of improving indoor air quality and ventilation in classrooms, as it found that increasing outdoor air supply rates had a positive impact on children's work speed and perceived air quality. However, further research may be needed to explore other factors like filter condition and potential interactions with ventilation rate.

Title	The effects of moderately raised classroom temperatures and classroom ventilation rate on the performance of schoolwork by children
Authors	Pawel Wargocki; David P. Wyon
Year	2007
Reference	[48]

Focus of the study / methods

- The study conducts two independent field intervention experiments in school classrooms during late summer in 2004 and 2005.
- It focuses on manipulating air temperature using cooling units and, in one experiment, outdoor air supply rates to assess their impact on the performance and perceptions of 10- to 12-year-old children during schoolwork.

Short summary and approach

- The experiments manipulated air temperature by operating or idling split cooling units and, in one case, outdoor air supply rates.
- The conditions were established for one week at a time in a blind crossover design with repeated measures on two classes of schoolchildren.
- Pupils performed several schoolwork exercises, including numerical and language-based tasks, during their normal lessons.
- Children provided feedback on their environmental perceptions and the intensity of any symptoms using visual analogue scales.

Important findings / results

- Changing the air temperature from 25°C to 20°C (77°F to 68°F) improved thermal sensation from slightly too warm to neutral.
- The performance of two numerical and two language-based tests significantly improved with the lower temperature, mainly in terms of task speed, while error rates remained negligible.
- When the outdoor air supply rate was increased from 5.2 to 9.6 L/s (11.0 to 20.3 cfm) per person, the performance of four numerical exercises improved significantly.
- The results indicate that providing means to avoid elevated temperatures in classrooms, especially during increased thermal loads like warm weather, can lead to improved educational attainment.

Comments

- This study highlights the importance of maintaining comfortable air temperatures in classrooms, as reducing temperatures from 25°C to 20°C had a positive impact on the performance of schoolchildren, particularly in terms of task speed. The findings emphasize the potential benefits of temperature control for educational outcomes.

Title	Gesundheitliche Bewertung von Kohlendioxid in der Innenraumluft
Authors	Umweltbundesamt
Year	2008
Reference	[49]

Short summary and approach

- Unlike mechanically ventilated buildings that have specific guidelines outlined in DIN EN 13779, there hasn't been a more recent guideline for naturally ventilated indoor spaces since the recommended threshold of 1000 ppm of carbon dioxide proposed by Pettenkofer in 1858.
- An ad-hoc working group consisting of the Environmental Agency and the Supreme State Health Authorities derives health-based guideline values for carbon dioxide in indoor air by evaluating current intervention studies.

Important findings / results

- According to these guidelines, concentrations below 1000 ppm of carbon dioxide in indoor air are considered safe, concentrations between 1000 and 2000 ppm are considered noticeable, and concentrations above 2000 ppm are deemed unacceptable.
- Therefore, the ad-hoc working group, in addition to Total Volatile Organic Compounds (TVOC) values, provides another overarching tool for assessing indoor air quality.

Comments

- The ad-hoc working group has developed guidelines for carbon dioxide in indoor air to evaluate air quality in naturally ventilated indoor spaces. This can help ensure health and hygiene in such areas and offers a useful aid for assessing indoor air quality.

Title	Gesundheitsfördernde Einflüsse auf das Leistungsvermögen im schulischen Unterricht
Authors	Gerhart Tiesler; Hans-Georg Schönwälder; Frauke Ströver
Year	2009
Reference	[5]

Focus of the study / methods

- The text discusses the concept of school ergonomics, which focuses on creating favourable working conditions for both students and teachers in schools. This perspective distinguishes itself from school hygiene, which primarily aims to prevent health hazards in the school environment.

Short summary and approach

- The authors of this study delve into optimizing the workload and working conditions in schools, prompted in part by discussions about humanizing work and the fundamental principles of their task in accident insurance companies.
- The study examines fatigue in the teaching-learning process in schools and through the school. It considers factors such as the concentration of CO2 gas in classroom air during instruction and the teaching methods used.
- The research is conducted through a field experiment that introduces short ventilation breaks (2-3 minutes) during half of the class period to assess the impact on student fatigue, cognitive performance, attention, reaction time, and self-assessment of performance.

Important findings / results

- The results of the study were more nuanced and surprising than anticipated, challenging traditional assumptions about CO2 concentration in classroom air as a measure of school hygiene.
- The conclusions from this study revolve around several key themes: re-evaluating the accepted norm of CO2 concentration levels above 1000 ppm, analysing continuous CO2 concentration measurements and their variations based on ventilation rules, and considering the impact of CO2 concentration changes on student performance and well-being in schools.

Comments

- This study re-evaluates the traditional understanding of CO2 concentration in classroom air and its effects on student performance, providing valuable insights and challenging existing knowledge in the field of school ergonomics.

Title	Benefits and Costs of Improved IEQ in U.S. Offices
Authors	W. J. Fisk; D. R. Black; G. Brunner
Year	2011
Reference	[50]

Focus of the study / methods

- The study aims to estimate the benefits and costs associated with improving indoor environmental quality (IEQ) in U.S. office buildings.

Short summary and approach

- The authors analyse various scenarios, including increasing ventilation rates, adding outdoor-air economizers and controls, maintaining indoor temperatures below 23°C in winter, and addressing dampness and mold issues to improve IEQ.

Important findings / results

- The estimated benefits of implementing these IEQ improvement scenarios are substantial, encompassing enhanced work performance, reduced sick building syndrome symptoms, decreased absenteeism, and improved thermal comfort for office workers.
- The combined annual economic benefit of these scenarios is approximately $20 billion.

Comments

- The study highlights the significant potential for economic and health-related benefits by improving IEQ in office buildings. Prioritizing measures that simultaneously enhance health and productivity while saving energy is recommended.

Title	Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance
Authors	Usha Satish; Mark J. Mendell; Krishnamurthy Shekhar; Toshifumi Hotchi; Douglas Sullivan; Siegfried Streufert; William J. Fisk
Year	2012
Reference	[51]

Focus of the study / methods

- This study aims to assess the direct effects of increased indoor carbon dioxide (CO2) concentrations, within the range of typical indoor levels, on decision-making performance.

Short summary and approach

- The authors exposed 22 participants to different CO2 concentrations (600, 1,000, and 2,500 ppm) in an office-like chamber.
- Participants completed decision-making tests and provided feedback on health symptoms and perceived air quality.
- The study was conducted in a controlled environment with constant ventilation rates and temperature.

Important findings / results

- At 1,000 ppm CO2, moderate and statistically significant decrements were observed in six out of nine scales of decision-making performance compared to 600 ppm.
- At 2,500 ppm CO2, large and statistically significant reductions occurred in seven scales of decision-making performance, except for the focused activity scale, which increased.

Comments

- The study suggests that increased indoor CO2 concentrations can have adverse effects on human decision-making performance, potentially limiting energy-saving measures that reduce outdoor air ventilation in buildings. Further research is needed to confirm these findings.

Title	Indoor air pollution on nurseries and primary schools: impact on childhood asthma - study protocol
Authors	Sofia I. V. Sousa; Catarina Ferraz; Maria C. M. Alvim-Ferraz; Luisa G. Vaz; Agostinho J. Marques; Fernando G. Martins
Year	2012
Reference	[52]

Focus of the study / methods

- This epidemiological study aims to investigate the association between long-term exposure to pollution mixtures, including indoor air pollution (IAP), and the development and exacerbation of childhood asthma.

Short summary and approach

- The study will be conducted in 8 nurseries and 8 primary schools, including sites influenced by traffic and background sites in urban and rural areas.
- It will analyze exposure to urban and rural pollution, as well as traffic emissions, including children's homes in the study.
- Data will be collected through validated questionnaires filled out by parents and medical exams to assess the prevalence, incidence, and exacerbation of asthma.

Important findings / results

- The study aims to provide insights into the role of environmental factors, particularly indoor air pollution, in childhood asthma among different age groups.
- It seeks to contribute to the development of preventive measures, addressing priority issues identified by the European Commission, the European Environmental Agency, and the World Health Organization.

Comments

- This study addresses a critical public health concern by investigating the impact of pollution mixtures and indoor air pollution on childhood asthma. Its findings can inform preventive measures and policies to protect children's health.

Title	Impact of Independently Controlling Ventilation Rate per Person and Ventilation Rate per Floor Area on Perceived Air Quality, Sick Building Symptoms and Decision Making
Authors	Randy Maddalena; Mark J. Mendell; Katia Eliseeva; Wanyu R. Chan; Douglas P. Sullivan; Marion Russell; Michael G. Apte; Usha Satish; William J. Fisk
Year	2013
Reference	[53]

Focus of the study / methods

- This study explores the impact of ventilation rates on indoor environmental quality (IEQ) and human performance in a simulated office environment. It aims to determine the relative importance of controlling occupant-related or building-generated pollutants through ventilation.

Short summary and approach

- The authors conducted two studies with 32 subjects, allowing independent control of ventilation per occupant and ventilation per floor area in a simulated office.
- Various measurements, including particle concentrations, CO2 levels, ozone, and volatile organic compounds, were continuously logged.
- Participants' perceived air quality (PAQ), sick building syndrome (SBS) symptoms, and decision-making performance were assessed using online instruments.

Important findings / results

- Changes in outdoor air ventilation rates had a significant impact on human decision-making performance, even when PAQ and SBS symptoms remained unaffected.
- Reductions in either occupant-based ventilation rates or floor-area-based ventilation rates negatively affected decision-making measures.
- These results provide evidence that ventilation rates influence human performance, emphasizing the importance of adequate ventilation for cognitive function.

Comments

- This study underscores the significance of outdoor air ventilation rates in maintaining optimal cognitive function in indoor office environments. Adequate ventilation is crucial not only for health and comfort but also for productivity and decision-making. Further research can help identify the optimal ventilation rates for different occupancy and floor area scenarios.

Title	Providing better thermal and air quality conditions in school classrooms would be cost-effective
Authors	Pawel Wargocki; David P. Wyon
Year	2013
Reference	[9]

Focus of the study / methods

- This paper summarizes the authors' research on how classroom conditions impact the performance of schoolwork by children, particularly focusing on indoor environmental quality (IEQ) in school classrooms.

Short summary and approach

- The authors conducted research to understand the effects of classroom conditions on children's performance of schoolwork.
- They examined factors such as thermal comfort, air quality, and outdoor air supply rates in school classrooms.
- The research aimed to highlight the consequences of inadequate indoor environmental conditions in classrooms.

Important findings / results

- Classroom conditions, including temperature and air quality, often fall below recommended standards and building codes.
- Inadequate classroom conditions, driven by the need to conserve energy, can lead to a significant reduction in children's schoolwork performance, by as much as 30%.

Comments

- This study underscores the importance of maintaining good indoor environmental quality in school classrooms. Poor conditions, driven by energy conservation measures, can have a detrimental impact on children's performance and should be addressed to provide a conducive learning environment.

Title	Beurteilung der CO2 Konzentration in Klassenräumen
Authors	H.-D. Neumann; M. Buxtrup
Year	2013
Reference	[4]

Focus of the study / methods

- The study focuses on measuring carbon dioxide (CO2) levels and room climate conditions in various classrooms in North-Rhine/Westphalia, Germany, with an emphasis on understanding indoor air quality and ventilation.

Short summary and approach

- The authors conducted measurements in 363 classrooms across 111 different schools.
- They assessed CO2 concentrations during lessons with closed windows and evaluated how frequently CO2 levels exceeded recommended values.
- The study also looked at the impact of brief and thorough ventilation during breaks on room air quality.
- Temperature conditions in the classrooms were considered, especially during the winter months.

Important findings / results

- In nearly 50% of cases, CO2 concentrations exceeded 2000 ppm during lessons with closed windows, which is considered "hygienically unacceptable" by the German Federal Environment Agency.
- Primary schools were found to comply with acceptable CO2 levels more frequently.
- Brief and thorough ventilation during breaks significantly improved room air quality.
- Continuous ventilation with tilted windows after breaks helped maintain CO2 levels around 1000 ppm.
- The study suggests that, even with tilted windows, classroom temperatures rarely dropped below 20°C during winter, providing a reasonably comfortable room climate.

Comments

- The study highlights the importance of monitoring and improving indoor air quality in classrooms. Adequate ventilation, especially during breaks, plays a crucial role in maintaining acceptable CO2 levels and creating a comfortable learning environment for students.

Title	Lernleistungsbezogene Kosten von unterschiedlichen bauphysikalischen Konzepten für Schulgebäude. Einfluss der Luftqualität und des thermischen Komforts.
Authors	Partick Drexler
Year	2015
Reference	[2]

Focus of the study / methods

- The study focuses on factors that influence the learning efficiency of pupils, particularly building physics factors like thermal comfort and air quality (CO2), which can be controlled through planning and design.

Short summary and approach

- The authors aimed to calculate and assess air quality and temperature in classrooms, connecting these factors to the learning efficiency of students.
- They adapted and enhanced an Excel-Tool for thermal building simulation developed at TU-Wien to evaluate air quality in classrooms.
- The study included suitable models for evaluating the learning efficiency of pupils based on a systematic literature review.
- A survey at the primary school Lavantgasse was conducted to incorporate real ventilation practices of teachers into the calculations.

Important findings / results

- The study aimed to provide methods and recommendations to improve the learning efficiency of pupils based on prevailing conditions in classrooms.
- Structural measures and user practice recommendations were simulated, evaluated, and their cost-benefit ratios were presented.

Comments

- The study focuses on enhancing the learning environment by considering factors like thermal comfort and air quality in classrooms. It aims to provide practical recommendations and insights for improving the learning efficiency of students based on real-world conditions and practices.

Title	Impact of the indoor environment on learning in schools in Europe
Authors	Gunnar Grün; Susanne Urlaub
Year	2015
Reference	[3]

Focus of the study / methods

- The study focuses on the indoor environmental conditions in classrooms and their impact on the learning efficiency of students.

Short summary and approach

- The authors discuss various factors such as thermal comfort, air quality, and lighting in classrooms that can affect the learning environment.
- They highlight the importance of proper ventilation, temperature control, and lighting for creating conducive learning spaces.
- The study emphasizes the need for improvements in classroom conditions to enhance the learning experience of students.

Important findings / results

- The study points out that many schools do not provide adequate indoor environments, with issues such as poor ventilation, overheating, inadequate lighting, and unhealthy air quality.
- Recommendations include maintaining proper ventilation rates, achieving recommended CO2 concentrations, and ensuring sufficient daylight in classrooms.
- Improving indoor environmental conditions can lead to increased student performance and reduced absenteeism.

Comments

- The study underscores the significance of creating a comfortable and healthy indoor environment in classrooms to support effective learning. It highlights the need for schools to address factors like ventilation, temperature, and lighting to enhance the overall learning experience of students.

Title	Lüftungskonzepte in Bildungsstätten - Einfluss der Luftqualität auf die Leistungsfähigkeit von Schülern
Authors	Jennifer König
Year	2015
Reference	[13]

Focus of the study / methods

- The study examines the influence of air quality on student performance in educational institutions, particularly in classrooms.
- It assesses the effectiveness of different ventilation strategies in maintaining a comfortable learning environment.

Short summary and approach

- The authors conducted a long-term study involving ten classrooms in four schools, a group room in a nursery, and a university lecture hall over a period of 246 months.
- They examined the impact of various ventilation systems and strategies on indoor air quality and learning outcomes.
- The study explores both mechanical ventilation systems and user-motivated free ventilation concepts.

Important findings / results

- The study emphasizes the importance of maintaining good indoor air quality in classrooms to enhance student learning and performance.
- Mechanical ventilation systems and user-motivated ventilation strategies were tested and found to have an influence on the learning environment.
- Individualized ventilation concepts, proper planning, and user engagement are crucial for ensuring a high indoor air quality in classrooms.

Comments

- The study underscores the significance of ventilation strategies in educational institutions to create a conducive learning environment.
- It highlights the need for tailored ventilation concepts, user motivation, and proper planning to maintain good indoor air quality, ultimately benefiting student performance.

Title	The effect of increased classroom ventilation rate indicated by reduced CO2 concentration on the performance of schoolwork by children
Authors	S. Petersen; K. L. Jensen; A. L. S. Pedersen; H. S. Rasmussen
Year	2015
Reference	[54]

Focus of the study / methods

- The study investigates the impact of increased classroom ventilation rates on the performance of children aged 10–12 years.

Short summary and approach

- The authors conducted a double-blind crossover intervention at two different schools, involving two classrooms at each school.
- They used four different performance tests as surrogates for short-term concentration and logical thinking to assess the impact of increased outdoor air supply rates.
- Data from complete pairs of test responses were included in the analysis, and no corrections were made for learning or fatigue effects.

Important findings / results

- The study found that increasing the outdoor air supply rate from an average of 1.7 to 6.6 litre per second (l/s) per person had a significant positive effect on the number of correct answers in all four performance tests: addition (6.3% improvement), number comparison (4.8% improvement), grammatical reasoning (3.2% improvement), and reading and comprehension (7.4% improvement).
- There was no significant effect on the number of errors in any of the performance tests.
- Questionnaire responses from students regarding their perception of the indoor environment, Sick Building Syndrome symptoms, and motivation indicated that students perceived the classroom air as more comfortable and experienced less eye discomfort in the recirculation condition compared to the fresh air condition.

Comments

- The study provides evidence that increasing ventilation rates in classrooms can have a positive impact on the short-term concentration and logical thinking of children during schoolwork.
- The findings support the need for practical actions to improve ventilation rates in schools to create healthier and more productive learning environments.
- The authors suggest that further experiments and investigations are desirable to build a stronger statistical basis for these conclusions and to better understand the underlying mechanisms behind the observed effects.

Title	Lufthygiene in der Schule am Beispiel der CO2-Konzentration und ihre Auswirkungen auf die Gesundheit von Lehrpersonen sowie von Schülerinnen und Schülern; Erhebung des aktuellen Kenntnisstandes unter Nutzung systematischer Literaturrecherche und Experteninterviews
Authors	Carina Windau
Year	2015
Reference	[55]

Focus of the study / methods

- The study focuses on indoor air quality in schools, specifically examining carbon dioxide concentration (CO2) in classrooms and its impact on the health of teachers and students.

Short summary and approach

- The authors use systematic literature review and expert interviews to assess the current state of knowledge regarding air quality in schools.
- They describe the air quality in various schools in Germany and analyze ventilation management, with a particular emphasis on window ventilation.
- The study presents the situation at a vocational school in Münster, Westphalia, through expert interviews and compares it with relevant literature.
- The authors argue for the importance of raising awareness about air hygiene in schools among schools, teachers, and students.

Important findings / results

- The study underscores the relevance of air hygiene in schools, especially concerning CO2 concentration and its potential impact on the health of teachers and students.
- It highlights the significance of effective ventilation management, particularly through window ventilation, in schools.
- Expert interviews and literature analysis contribute to shedding light on the situation in schools and emphasize why air hygiene is a critical concern.

Comments

- The study emphasizes the importance of air hygiene in schools and advocates for raising awareness about this issue among schools, teachers, and students.
- It is based on thorough literature review and expert interviews to present the current state of knowledge.
- The work contributes to increasing awareness about indoor air quality in schools and protecting the health of teachers and students.

Title	Occupant productivity and office indoor environment quality: a review of the literature
Authors	Al horr, Y., Arif, M., Kaushik, AK., Mazroei, A., Katafygiotou, M. and Elsarrag, E.
Year	2016
Reference	[56]

Short summary and approach:

- literature review: Study reviews over 300 papers with focus on physical aspects of an office environment
- Outlines eight Indoor Environmental Quality (IEQ) factors
    - Indoor air quality and ventilation
    - Thermal comfort
    - Lighting and daylighting
    - Noise and acoustics
    - Office layout
    - Biophilia and views
    - Look and feel
    - Location and amenities
- Proposes a conceptual model of different factors affecting occupant productivity and presents a comprehensive discussion and analysis

Important findings / results:

- Application of local control systems in different task zones of an office could help to maintain an overall occupant comfort and productivity
- Introduction of Biophilia and availability of views should be part of basic design principles of a workplace design
- a convenient office location with transport accessibility and proximity to various amenities could help to improve office productivity and well-being of the employees
- method using remote sensors, BIM and a GIS system can be utilised for collecting and analysing both quantitative and qualitative data alongside the visual and spatial representations of data analysis on occupant comfort and satisfaction
- the three main physical parameters in IAQ study are: ventilation rate, indoor pollutant levels and outdoor air monitoring
- the paper recommends measurement of four physical parameters concerning thermal comfort: radiant temperature, relative humidity, air temperature and velocity
- factors that contribute to healthy indoor lighting levels: luminance level, daylight and artificial light ration and glare index
- suggestion to observe and monitor indoor and outdoor sound levels
- use surveys to analyse factors like „Look and Feel" or Office Design
- High correlation between the identified factors

Comments:

- Another comprehensive literature reviews
- just general findings and results

Titel	Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments
Autors	Joseph G. Allen, Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, John D. Spengler
Year	2016
Refernce	[57]

Short summary and approach:

- Simulation of indoor environmental quality (IEQ) conditions in green (low concentration of VOCs) and conventional (high concentration of VOCs) buildings
- Evaluation of the impacts on an objective measure of human performance: higher-order cognitive function
- tested on 24 participants on 6 full work days in environmentally controlled office spaces, blinded to test conditions
- additional conditions simulated: high outdoor air ventilation (green +) and elevated CO_2 levels

Important findings / results:

- cognitive scores were 61 % higher on green building days and 101 % higher on green + days than on conventional building day
- cognitive function is significantly better at low concentration of VOCs and high ventilation
- findings have wide-ranging implications

Comments:

- high quality study with very clear result

Titel	Physische Gesundheit in der Arbeitswelt
Autors	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin; Dr. Kersten Bux; Carolin Polte
Year	2016
Reference	[58]

Short summary and approach:

- Focus of the review is on the indoor environment in the workplace and its impact on physical health

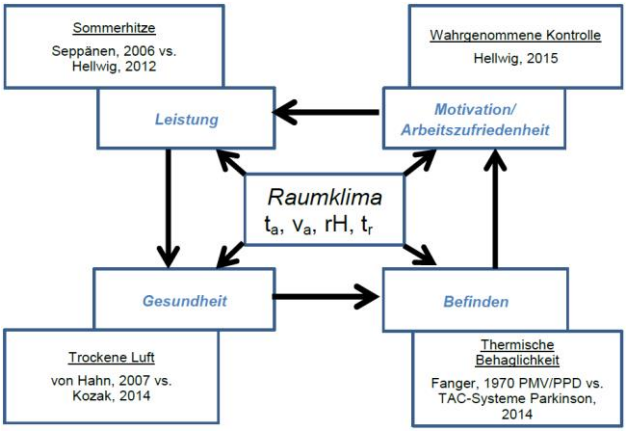


Figure 24: Publications to different indoor air quality issues.

- A distinction was made between two main characteristics:
  - Characteristic A: moderate comfortable climate (extended comfort range, e. g. office, logistics centre)
  - Characteristic B: Climate due to high technological loads (cold/heat work, e. g. cold store, steel foundry)
- The factors studied include temperature, humidity and velocity of the air, as well as the thermal radiation of the enclosing surfaces

Important findings / results:

- Permanently low humidity in winter can cause skin problems and irritation of the eyes
- The effect of heat on cognitive performance ranges from a significant reduction to an increase and is highly dependent on individual conditions
- TAC systems ("personally controlled task ambient systems") should be tested in the context of the temperate Central European climate
  - Investigation of the influence on the thermal comfort and the potential for energy savings.
- Studies in the future should place more emphasis on the effectiveness of a regulation in the context of building design and its interaction with air handling systems
- Description of the required level of responsiveness of the system from: Building shape - AHU system - Building automation - User
- Supplemental literature review on perceived control and mood disorders needed
- Further need for research on the direct relationship between dry air and mental health is not seen

Comments:

- Literature study mainly deals with indoor climatic factors
- with regard to indoor air quality, only humidity is considered

Titel	Airplane pilot flight performance on 21 maneuvers in a flight simulator under varying carbon dioxide concentrations
Autors	Joseph G. Allen; Piers MacNaughton; Jose Guillermo Cedeno-Laurent; Xiaodong Cao; Skye Flanigan; Jose Vallarino; Francisco Rueda; Deborah Donnelly-McLay; John D. Spengler
Year	2017
Reference	[59]

Short summary and approach:

- Typical CO_2 concentration on a flight deck is below 1000 ppm, the 95th percentile though, can be as high as 1400 ppm, which is a reason to investigate the impact on cognitive functions of pilots
- 30 active commercial airline pilots were recruited to fly three 3-h flight segments in an approved simulator (each segment at a different CO_2 concentration: 700, 1500, 2500 ppm)

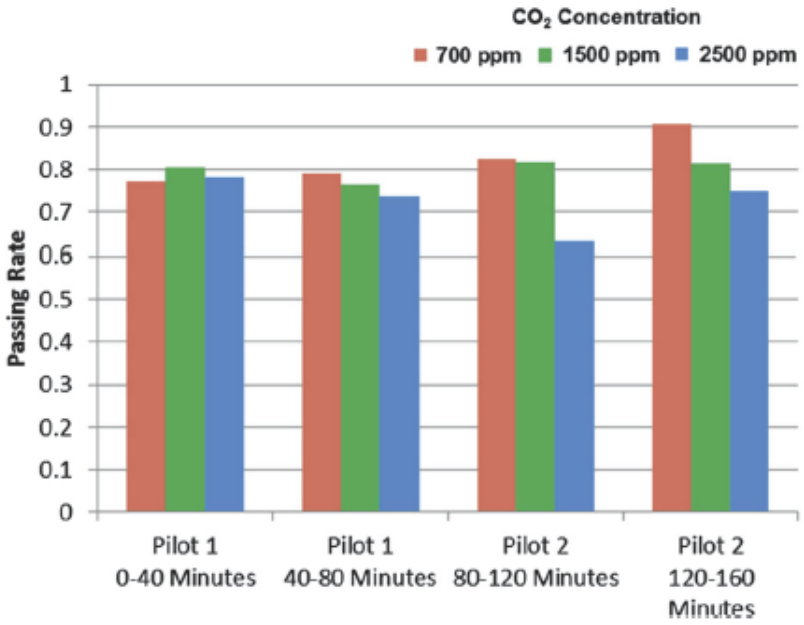


Figure 25: Airplane pilot flight performance on 21 maneuvers in a flight simulator under varying carbon dioxide concentrations.

- ventilation rates during the rest remained the same
- Pilots were blinded to test and exposures randomized

Important findings / results:

- compared to 2500 ppm, the odds of passing a maneuver at 1500 ppm were 1,52 times higher and 1,69 times higher at only 700 ppm
- the findings suggest, that there is a direct effect of CO_2 on performance, independent of ventilation

Comments:

- Study showing to impact of CO_2 concentration on cognitive functions

Titel	Richtlinie zur Bewertung der Innenraumluft: Kohlenstoffdioxid als Lüftungsparameter
Autors	Peter Tappler
Year	2017
Reference	[60]

Short summary and approach:

- Mostly compilation of findings from studies on the influence of CO_2 concentration on the well-being and performance of people
- Studies on CO_2 in indoor spaces and educational facilities are considered separately, as the concentration in educational facilities reaches significantly higher concentrations than, for example, a bedroom due to the specific use and at the same time the performance of the users in these rooms is more in demand
- Based on the findings from the literature, a strategy for measuring the variable CO_2 concentration is presented and a classification scheme is developed
- In a further section, literature sources are analysed in more detail with regard to the toxicology and general effects of CO_2 on humans
- The following figure shows, for example, the correlation between CO_2 concentration and the number of dissatisfied people in a room (according to ECA 1992)

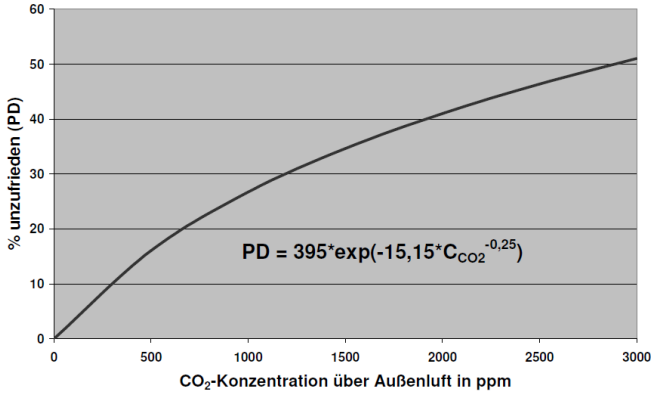


Figure 26: Percentage of dissatisfaction depending on CO_2 -Concentration

Important findings / results:

- Classification scheme for the CO_2 concentration in indoor spaces

Klasse	Beschreibung	Arithmetischer Mittelwert der Momentanwerte für CO_2 [ppm]
Klasse 1	Ziel für Innenräume für den dauerhaften Aufenthalt von Personen	≤ 800
Klasse 2	Richtwert für Innenräume für den dauerhaften Aufenthalt von Personen, in denen geistige Tätigkeiten verrichtet werden bzw. die zur Regeneration dienen	≤ 1000
Klasse 3	Allgemeiner Richtwert für Innenräume für den dauerhaften Aufenthalt von Personen	≤ 1400
Klasse 4	Richtwert für Innenräume mit geringer Nutzungsdauer durch Personen	≤ 5000
Außerhalb der Klassen	Für die Nutzung durch Personen nicht akzeptabel	> 5000

Comments:

- Provides reliable results for the effects of CO_2 concentration indoors

Titel	ASR A3.6: Technische Regeln für Arbeitsstätten – Lüftung
Autors	BAuA – Ausschuss für Arbeitsstätten
Year	2018
Reference	[61]

Short summary and approach:

- The guideline specifies the requirements for ventilation of the workplace ordinance
- Applies to workplaces in enclosed work spaces and takes into account work procedures, physical stress and number of employees as well as other persons present
- Determination of requirements for free ventilation and air handling units

Important findings / results:

- The following measures are recommended depending on the CO_2 concentration:

CO_2-Konzentration [ml/m^3] bzw. [ppm]	Maßnahmen
<1000	• Keine weiteren Maßnahmen (sofern durch die Raumnutzung kein Konzentrationsanstieg über 1000 ppm zu erwarten ist)
1000-2000	• Lüftungsverhalten überprüfen und verbessern • Lüftungsplan aufstellen (z. B. Verantwortlichkeiten festlegen) • Lüftungsmaßnahme (z. B. Außenluftvolumenstrom oder Luftwechsel erhöhen)
>2000	• weitergehende Maßnahmen erforderlich (z. B. verstärkte Lüftung, Reduzierung der Personenzahl im Raum)

- Standard values for the moisture load:

Lufttemperatur	relative Luftfeuchtigkeit
+20 °C	80 %
+22 °C	70 %
+24 °C	62 %
+26 °C	55 %

Comments:

- useful for the design and planning of ventilation concepts in workplaces

Titel	Do indoor CO_2-levels directly affect perceived air quality, health, or work performance?
Autors	William Fisk, Pawel Wargocki, Xiaojing Zhang
Year	2019
Reference	[62]

Short summary and approach:

- Article summarizes the findings of 10 recent studies investigating whether increased CO_2 concentrations (with other factors constant) influence perceived air quality, health or work performance of people

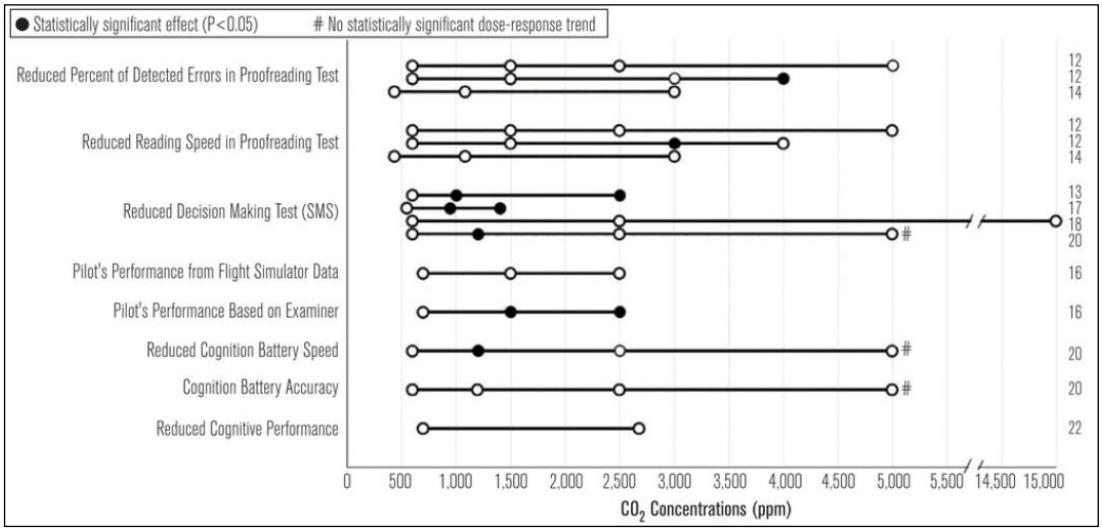


Figure 27: Associations of CO_2 concentrations with cognitive performance

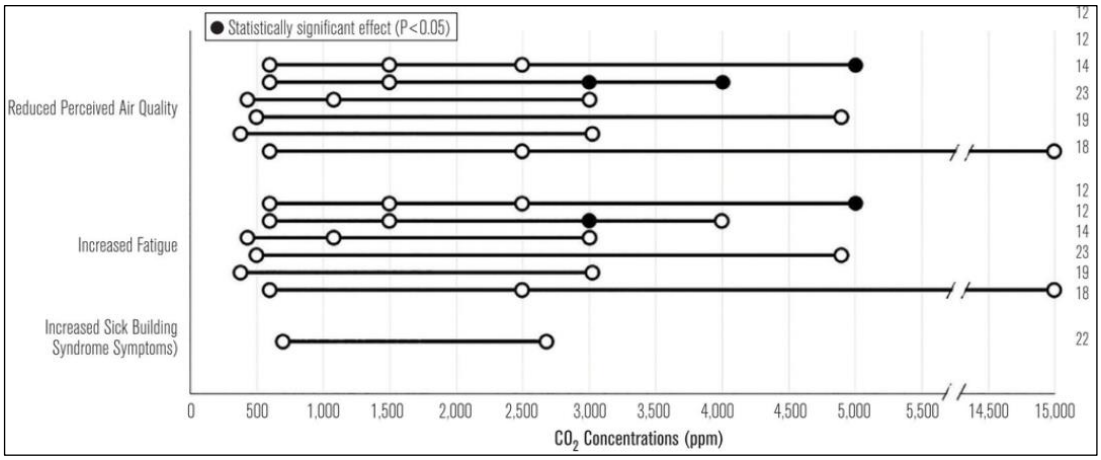


Figure 28: Associations of CO_2 concentrations with perceived outcomes

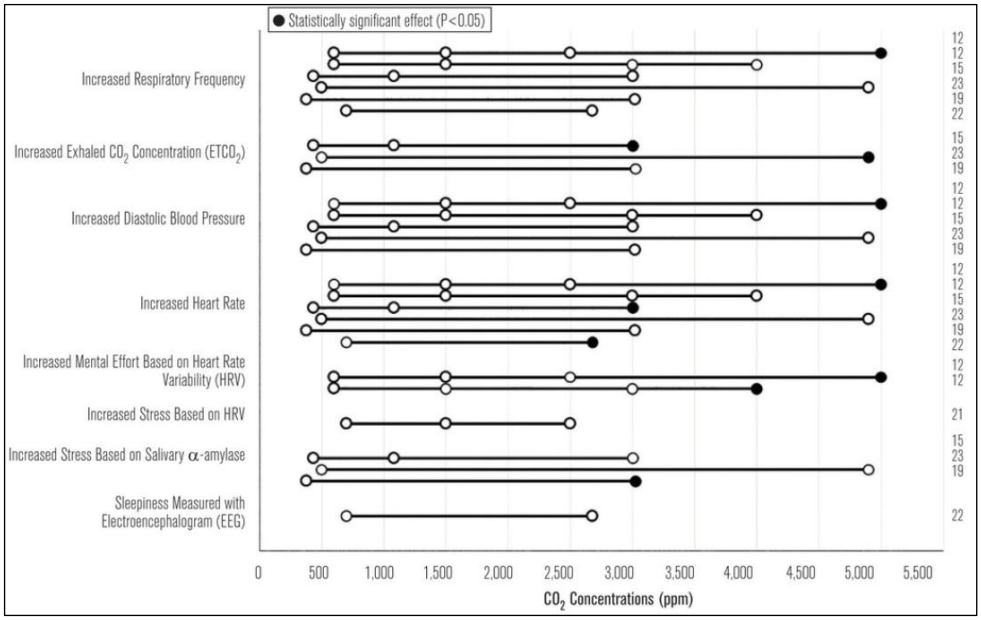


Figure 29: Associations of CO_2 concentrations with physiological outcomes

Important findings / results:

- limited evidence that CO_2 levels below 5000 ppm influence perceived air quality, acute health symptoms or physiological outcomes other than end-tidal CO2 and heart rate
- the results of research on the effects of moderate CO_2 concentrations on cognitive performance are not consistent
- there is substantial, but still inconsistent evidence that performance on challenging tests of decision-making worsened by CO_2 concentrations below 1000 ppm
- further research is needed to address discrepancies among the current findings
- additionally, effects on children, the elderly and people with health problems have not been investigated
- also, long term effects of periodic exposure need to been identified

Comments:

- On point summary of recent studies concerning CO_2 concentration

Titel	Indoor Air Quality and Cognitive Performance
Autors	Steffen Künn; Juan Palacios; Nico Pestel
Year	2019
Reference	[63]

Short summary and approach:

- paper uses data from official chess tournaments to study the impact of indoor air quality on cognitive performance of individuals
- the authors merged measures of air quality inside a tournament venue with information about the quality of the chess moves evaluated by a specific chess engine

Important findings / results:

- poor indoor air quality hampers cognitive performance significantly
- an increase in the indoor concentration of fine particulate matter (PM2.5: penetrates lungs and brains) by 10 µg/m3 increases erroneous moves by 26,3 %
- the effect of CO2-concentration is smaller and only matters during phases of high time stress
- exploiting temporal and spatial variation in outdoor pollution, they suggest a short-term and transitory effect of fine particulate matter on cognition
- a high-skill human cognition is already affected by **moderate** variation in particulate pollution

Comments:

- Robust study about the impact of fine particulate matter on cognitive performance with very clear and impressive results

Titel	Indoor air quality of newly built low-energy preschools – Are chemical emissions reduced in houses with eco-labelled building materials?
Autors	Josefin Persson; Thanh Wang; Jessika Hagberg
Year	2019
Reference	[64]

Short summary and approach:

- In this study, the indoor air quality (IAQ) was investigated in newly built low-energy and conventional preschools by monitoring the indoor air temperature, relative humidity, particle-size distribution and levels of carbon dioxide (CO_2), nitrogen dioxide (NO_2), formaldehyde and total volatile organic compounds (TVOC)

Important findings / results:

- preschools constructed with environmentally friendly building materials (such as Swan Eco-label) had lower initial TVOC levels compared to those preschools constructed with conventional building materials
- IAQ and indoor chemical emissions are strongly dependent on the functioning of the ventilation system
- exposure to acrolein and crotonaldehyde might lead to respiratory-tract irritation among occupants

Comments:

- Good investigation about the impact of chemical emissions on indoor air quality in preschools

Titel	Luftqualität in Schulgebäuden – WP3 Stand der Technik und Marktübersicht – Task 3.1 Überblick über den Stand der Technik: Kriterien und Parameter, die die Luftqualität in Schulgebäuden beeinflussen
Autors	Chiara Ugolini; Annamaria Belleri
Year	2019
Reference	[65]

Short summary and approach:

- Literature review to identify the main indoor air pollutants in school buildings (kindergarten to high school) and its sources
- Analysis of pollutants measured in schools, taking into account their characteristics, sources and limits
- Description of the most important European projects on air quality in schools incl. their methods
- Investigating the effects of school air quality on student and teacher performance and absenteeism
- References to guidelines and best practices for improving air quality in schools
- The aim of the study is to define parameters that determine air quality in school environments

Important findings / results:

- There is a correlation between poor ventilation and chronic cough (see figure)

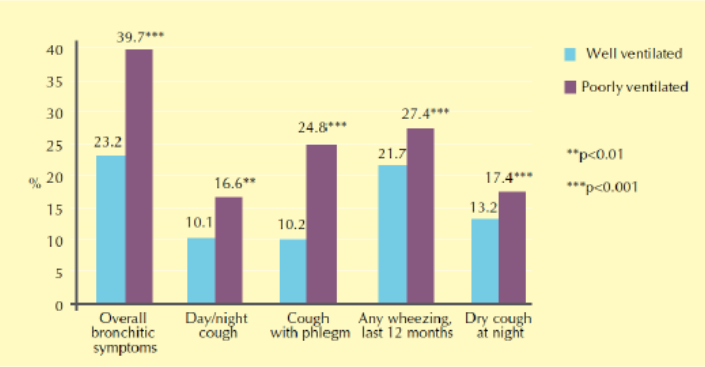


Figure 30: Comparison between well and poorly ventilated buildings

- When analysing ventilation alternatives, also consider the costs and benefits associated with air quality!
- Examples of specific measures for good air quality management:
    - Ensure adequate ventilation through proper natural ventilation
    - Ensure adequate ventilation by introducing decentralized mechanical ventilation systems in classrooms
    - Dehumidification work, water leak/infiltration/mould removal
    - Insulation and cleaning of the walls with "photocatalytic" paints
    - Use of "poison-eating" plants
    - Removal of materials containing harmful substances and use of furniture and upholstery materials that are low in harmful substances (e.g., with the EcoLabel environmental label)
    - Overhaul and refurbishment of HVAC systems

Comments:

- Detailed literature review on air quality studies in school buildings

Titel	Messtechnische Untersuchungen der Raumluftqualität in Schulen
Autors	Prof. Dr. Klaus Wolfrum
Year	2019
Reference	[66]

Short summary and approach:

- 4 classrooms at 3 schools in Karlsruhe were investigated
- Measured variables include the heat output, room air temperature, supply temperature, CO_2 concentration and electricity consumption
- The following influencing factors were investigated with regard to the room air temperature, the heat output and the CO_2 concentration: room occupancy, supply temperatures, thermostat setting and ventilation duration

Important findings / results:

- CO_2 itself is not the problem, but indicates problematic situation
- CO_2 limit value was exceeded on all teaching days investigated
    - Already in the first lesson
    - up to 40% of the teaching time
    - Maximum values above 3500 ppm

Notwendige Luftwechselrate und resultierende Heizleistung
für Beispielraum mit A = 60 m², V = 200 m³, belegt mit 30 Personen

$$30\ \text{Personen} \cdot \frac{7\ \text{Liter}}{\text{s} \cdot \text{Person}} = 756\ \frac{\text{m}^3}{\text{h}}$$

ca. 4 Luftwechsel / h nur für Personen

$$756\ \frac{\text{m}^3}{\text{h}} \cdot \underbrace{0{,}34\ \frac{\text{Wh}}{\text{m}^3\ \text{K}}}_{\text{Wärmekapazität von Luft}} \cdot \underbrace{20\ \text{K}}_{\text{Erwärmung von 0°C auf 20°C}} = 5{,}1\ \text{kW}$$

Benötigte Heizleistung (ohne Wärme-Rückgewinnung) wg. Personen

- Indoor air quality in classrooms or training rooms must be ensured by intensive air exchange (approx. 4-5 air changes per hour)
- Window ventilation is not suitable for ensuring an indoor climate conducive to performance, especially during the heating season
- Taking into account the normative requirements (especially DIN EN 15251) is necessary to provide a healthy indoor environment:
    - Heating according to demand
    - Mechanical ventilation
    - Mechanical cooling

Comments:

- Well conducted metrological investigation with clear result regarding CO_2 concentration in schools

Titel	The relationship between classroom air quality and children´s performance in school
Autors	Pawel Wargocki; Jose Ali Porras-Salazar; Sergio Contreras-Espinoza; William Bahnfleth
Year	2020
Reference	[6]

Short summary and approach:

- the authors used data from published studies to derive systematic relationships between learning outcomes and air quality in classrooms of elementary schools
- classroom IAQ was characterized by the CO_2-concentration
- for tests and school tasks, fractional changes in performance were regressed against the average concentrations of CO_2 at which they occurred

Important findings / results:

- reducing CO_2-concentration from 2100 ppm to 900 ppm would improve the performance in tests and tasks by 12 % (including speed at which tasks are performed) and by 2 % with respect to errors made

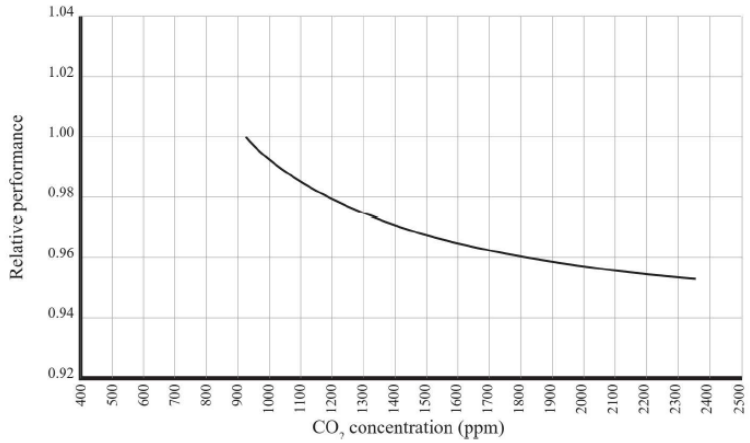


Figure 31: Relative performance depend on the CO_2-concentration.

- other similar results suggest that increasing the ventilation rate in classrooms from 2 L/s-person to 10 L/s-person can bring significant benefits in terms of learning performance and pupil attendance

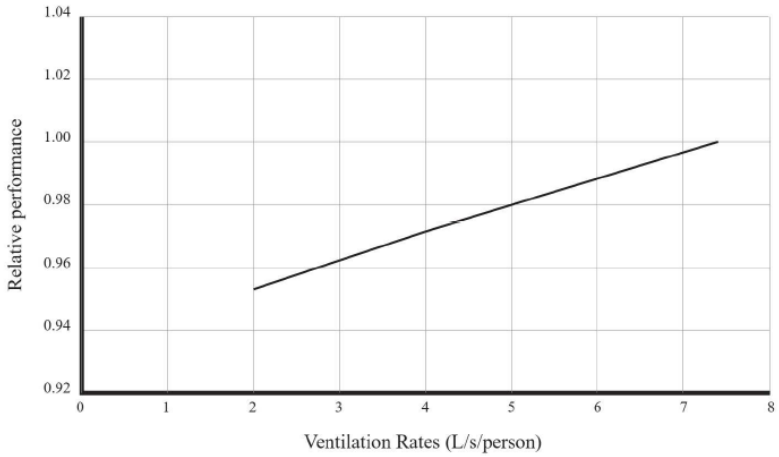


Figure 32: Relative performance depend on the ventilation rates.

- they also provide a strong incentive for improving classroom air quality and can be used in cost-benefit analyses

Comments:

- Good assessment of IAQ in terms of CO2-concentration and ventilation rate in schools

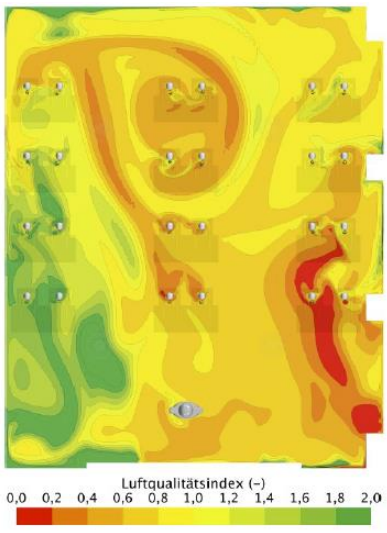
Titel	Luftgetragene Erreger und Luftqualität in Innenräumen am Beispiel eines Klassenzimmers – Verteilung der Erreger und Bewertung der Lüftungseffektivität
Autors	Eugen Lichtner; Martin Kriegel
Year	2021
Reference	[12]

Short summary and approach:

- Investigation of the effectiveness of different ventilation measures as well as the use of partition walls in a classroom with regard to the reduction of pathogen and CO_2 exposure by means of numerical flow simulation (CFD)
- Comparison of a total of seven options:
  - 3 cases with mixed ventilation
  - . 4 with displacement ventilation
- Modelling of a mobile air purifier in pure recirculation mode
- Classroom occupancy was varied between 24 and 12 children + one teacher
  - in the process one child exhaled virus-laden particles
  - Effectiveness of the measures was examined after 45 min

Important findings / results:

- Air exchange rate is not a measure of effectiveness of measures if exposure risk is from a single pollutant source
- Breathing zone is ventilated with only 20% efficiency
  - Exposed pathogen concentration 5 times higher than expected with corresponding air exchange rate
- Increased concentration around the environment of the emitting person
- Efficiency of mixed ventilation significantly higher than that of displacement ventilation
  - Effectiveness of air purifier with regard to particles similar to mixed ventilation, CO2 concentration however unacceptable



MV-A-1
Mittlerer Luftqualitätsindex im Atembereich, Position 1

0.80	0.98	0.59	0.64	0.79	0.91
1.19	1.23	0.68	0.57	0.94	0.58
1.59	1.49	0.51	0.61	0.57	0.74
1.74	1.60	0.42	0.54	0.23	
		0.89			

Min	0.23	Mean	0.87	Max	1.74
		Std	0.41		

Abbildung A7: Lokaler Luftqualitätsindex 1 m über dem Boden und mittlerer Luftqualitätsindex im Atembereich, MV-A-1, Position des infektiösen Schulkinds 1

Figure 33: Local air exchange index 1m above the ground and mean air quality index in the breathing zone.

Comments:

- Investigation focuses on distribution of virus-laden air
- No measurements, only simulation

Titel	Pilotprojekt: Experimentelle Untersuchung zum Infektionsrisiko in Klassenräumen in Stuttgarter Schulen
Autors	Lukas Siebler; Torben Rathje; Maurizio Calandri; Matthias Eydner; Ulrich Vogt; Tobias Henzler; Prof. Dr.-Ing. Konstantinos Stergiaropoulos
Year	2021
Reference	[67]

Short summary and approach:

- Indoor air quality survey of classrooms at ten schools in the city of Stuttgart
- Objective: To assess the risk of infection during classes and identify appropriate countermeasures (window ventilation, air handling units, mobile air purifiers)
- Evaluation is performed by quantitative measurements of substance dispersion with personal dummies in combination with the evaluation of relevant studies on airborne infection dispersion

Important findings / results:

- Window Ventilation:
  - Ventilation strategy 20/5/20 and 10/2.5/10 can significantly reduce infection risk
  - Shock ventilation better than continuous tilt ventilation
  - Ventilation during breaks is mandatory

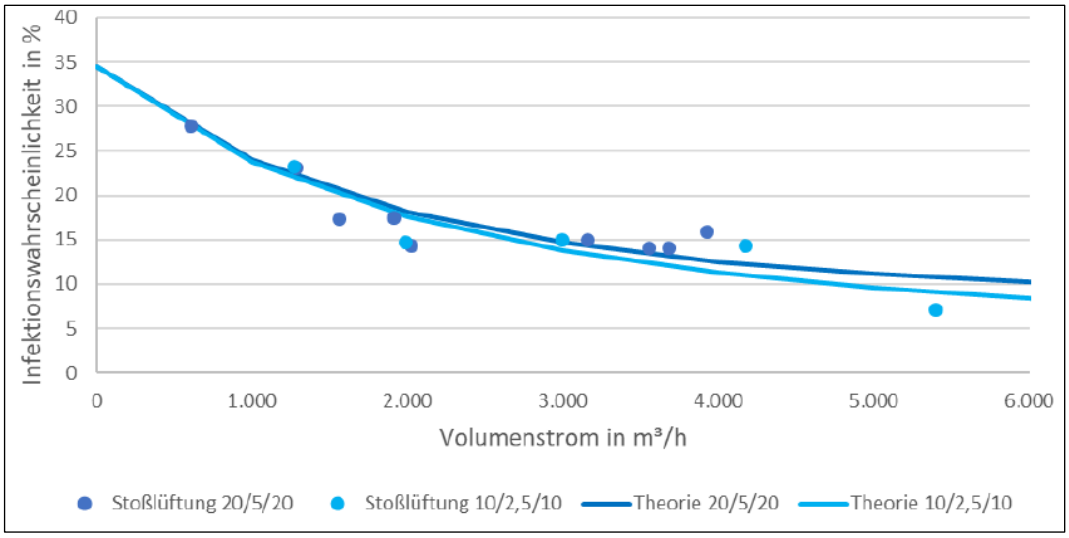


Figure 34: Probability of infection as a function of the volume flow rate during shock ventilation

- Air purifiers
  - Air purification devices in combination with window ventilation has a positive effect on infection incidence
  - Reduction of aerosol concentration is improved by LRG, but ventilation is still necessary as there is no CO2 or moisture removal
  - Drafts detectable even at low volume flows
- Air Handling Units:
  - Classrooms with RLT system show lower risk of infection compared to window ventilation
  - Similar draught risk as LRG (but cross-section can be enlarged)

- Window ventilation not mandatory (pauses are sufficient for the air handling unit to restore the initial state).

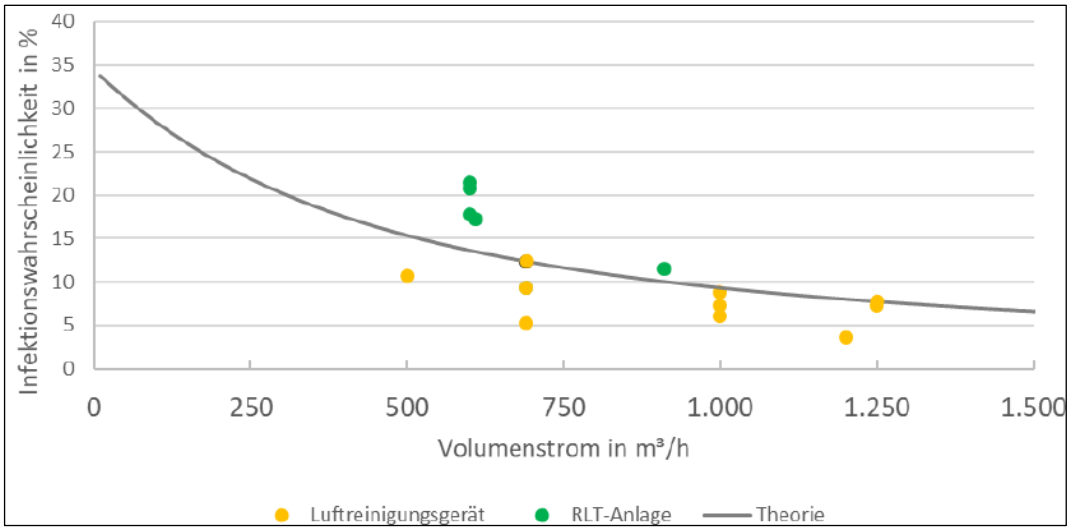


Figure 35: Probability of infection as a function of the mechanically conveyed volume flow

Comments:

- Very detailed study on the risk of infection in classrooms in relation to the way the air is exchanged

Titel	Research-based recommendations for achieving high indoor environmental quality in classrooms to promote learning
Autors	Pawel Wargocki; David P. Wyon
Year	2021
Reference	[68]

Short summary and approach:

- set of recommendations for main components of indoor environmental quality in classrooms:
  - Thermal environment
  - Indoor air quality (and ventilation)
  - Acoustic environment
  - Visual environment
- this set is compared with current recommendation and requirements regarding classroom environments

Important findings / results:

- ensure that windows can be opened
- keep CO_2 below 900 ppm at all times
- provide CO_2 sensors

Building regulations (BR18)		
CO_2 concentration	≤1000	ppm
Ventilation (sum of per person and per floor area)	≥5 ≥0.35	L/s per person L/s per m^2 floor area
Temperature	20-24 23-26	°C (during the heating season) °C (outside the heating season)
Noise (from outdoors)	≤33 ≤46 ≤52	dB(A) with closed windows dB(A) with open windows (roads) dB(A) with open windows (train tracks)
Noise (from building technical installations)	≤30	dB(A)
Reverberation time	<0.6	s (frequency 125-4000 Hz)
View out		windows to allow a view out and sun protection
Daylight	10 ≥300	% glass area in relation to the floor area lux for at least half of the relevant floor area and at least half of daylit hours
Artificial light	≥500 19	Lux Unified glare rating

The Danish Working Environment Authority		
CO_2 concentration	≤1000 ≤2000	ppm (recommended) ppm (maximum allowable)
Formaldehyde	≤0.15	mg/m^3
Temperature	20-22 18 25	°C (recommended) °C (minimum) °C (maximum unless heatwave)
Relative humidity	25-60	%
Air velocity	≤0.15	m/s
Light	200-500	Lux

Comments:

- short summary report of research evidence on achieving high indoor environmental quality

9.3 Residential Buildings

Titel	Observatory on indoor air quality – national survey: indoor air quality in French dwellings
Autors	Séverine Kirchner, Jean-Francois Arenes, Christian Cochet, Mickael Derbez, Cédric Duboudin, Patrick Elias, Anthony Gregoire, Béatrice Jédor, Jean-Paul Lucas, Nathalie Pasquier, Michèle Pigneret, Olivier Ramalho
Year	2007
Reference	[28]

Short summary and approach:

- Status quo analysis of indoor air quality in French dwellings (start 2003, end 2005)
- Measuring investigation in 570 houses which representative of the 24 million houses in continental metropolitan France
- More than 30 parameters (chemical, biological and physical) have been measured during one week in serval rooms in dwellings

Important findings / results

- VOCs
  - Aldehydes are among the most frequent and most concentrated compounds in dwellings.
  - Hydrocarbons are frequent, two of them are observed in all dwellings (toluene and m/p xylene).
  - Glycol ethers are not very frequent.
- CO
  - In great majority, the CO concentrations are next to zero in different places.
- Biological pollutants
  - Concentrations of cat and dog allergens are below the limit of quantification in 50% of the dwellings.
  - Concentration of dust mite allergens are below 1,6 µg/g in 50% of the dwellings.
- Physical pollutants
  - In 50% of the dwellings concentrations in particles are greater than 19,1 µg/m³ for $PM_{2,5}$ and than 31,3 µg/m³ fpr PM_{10}
  - Radon concentrations are below 31 Bq/m³ in bedrooms and 33 Bq/m³ in other rooms in 50% of the dwellings.
- Parameters of comfort
  - Temperature is below 21°C in 50% of the dwellings.
  - Relative humidity is below 49% in 50% of the dwellings.
  - The average CO2 concentration over a week exceeds 756 ppm in 50% of the dwellings.

Comments

Extensive measurement analysis for indoor air quality in French dwellings. Good practical benchmarks. No correlation between indoor air quality and well-being.

Titel	Lüftung 3.0 - Bewohnergesundheit und Raumluftqualität in neu errichteten, energieeffizienten Wohnhäusern
Autors	Tappler, P.; Hutter, H.P.; Ringer, W.; Munoz-Czerny, U.; Damberger, B. Twrdik, F.; Torghele, K.; Kundi, M.; Wanka, A.; Wallner, P.; Wurm, G.
Year	2014
Reference	[29]

Short summary and approach:

- Investigation of the influence of indoor air quality on the well-being and (residential) satisfaction of residents of single and multi-family houses with and without a room ventilation system
- Testing of houses and flats with room ventilation systems in comparison to buildings with only window ventilation
- Analysis of the change in terms of well-being and health, perceived indoor climate and (residential) satisfaction after one year of use
- Method: Measurements and survey
- Analysis of ventilation on the well-being of people
- Analysis for conditions with and without ventilation systems
- Detection of differences between different types of homes

Important findings / results

- No significant changes in the health status of the individuals were detected within the year
- VOC concentrations in the properties with a domestic ventilation system were significantly lower on average on both measurement dates than in the properties with only window ventilation
- The VOC concentration was reduced by 80% within a year in buildings with a room ventilation system and buildings with window ventilation
- Ventilation type (with or without a room ventilation system) had a highly significant influence on the VOC concentration in the indoor air and with exclusive window ventilation frequent exceedance of guideline values
- The median CO2 concentration for buildings with a room ventilation system was 1,360 ppm, for buildings with only window ventilation it was 1,830 ppm
- significant correlation between CO2 concentration and the impression of stale air can be shown

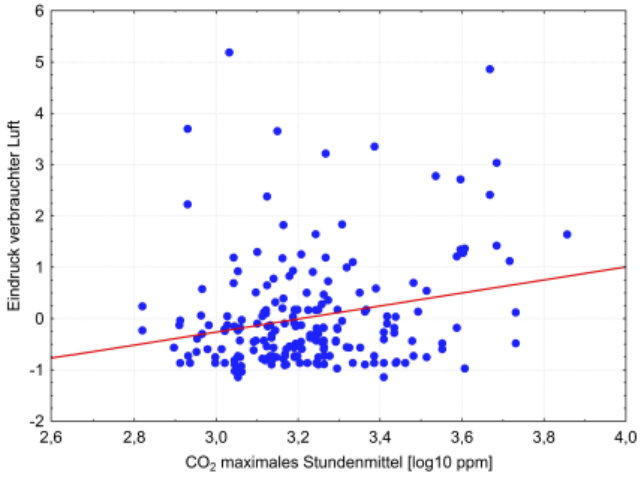


Figure 36: Summary of the maximum hourly average CO_2 value in the interior and the impression of stale air at the second measuring point M2

Comments

- Study contains no information on the performance of the individuals
- Comprehensive field analysis based on two measurement dates. There was approx. 1 year between the measurement dates. Analysis of physical and chemical parameters as well as a user survey. Clear correlations are detectable in places, especially in the reduction of the VOC concentration and in the comparative use of domestic ventilation systems and window ventilation.

Titel	Indoor air quality, thermal comfort and daylight - ANALYSIS OF RESIDENTIAL BUILDING REGULATIONS IN EIGHT EU MEMBER STATE
Autors	Sara Kunkel, Eleni Kontonasiou, Aleksandra Arcipowska, Francesco Mariottini, Bogdan Atanasiu
Year	2015
Reference	[27]

Focus of the study / methods

- Compilation of various parameters with regard to indoor air quality, thermal comfort, daylight requirements and compliance and control for European countries:
  - Brussels-capital region
  - Denmark
  - France
  - Germany
  - Italy
  - Poland
  - Sweden
  - UK (England & Wales)

Important findings / results

- Indoor air quality is recognised as an important aspect of the building codes in all focus countries of this survey
- Ventilation is included in the building regulations of all surveyed states
- In Denmark, France, Sweden and Brussels-Capital Region (BE), there are clear minimum requirements, while in Germany, Italy, Poland and the UK there is only a recommendation for minimum ventilation rates. The indicators for minimum ventilation rates vary from one country to another and are generally different from EU standards

Table 1 - Ventilation standards in dwellings (Source: BPIE based on feedback from country experts)

Country and Standard Reference	Whole Building Ventilation Rates	Living Room	Bedroom	Kitchen	Bathroom + WC	WC only
Brussels (NBN D 50-001)	3.6 m³/(h·m²) floor surface area	Minimum 75 m³/h (limited to 150 m³/h	Minimum 25m³/h (limited to 72m³/h)	Open kitchen Minimum 75 m³/h (exhaust)	Minimum 50 m³/hour (limited to 75 m³/h	Minimum 25 m³/h
Denmark (BR10)	Min. 0.3 l/s·m² (supply)	Min. 0.3 l/(s·m²) (supply)		20 l/s (exhaust)	15 l/s (exhaust)	10 l/s (exhaust)
France (Arrêté 24.03.82)	10-135 m³/h (depending on room number and ventilation system)			Continuous: 20 – 45 m³/h		Minimum 15 m³/h
Germany (DIN 1946-6)	15-285 m³/h (details see chapter)			45m³/h (nominal exhaust flow)	45 m³/h (nominal exhaust flow)	25 m³/h (nominal exhaust flow)
Italy (Legislative Decree 192/2005, UNI EN 15251)	Naturally ventilated: 0.3 – 0.6 vol/h	0.011 m³/s per person for an occupancy level of 0.04 persons/m²			4 vol/h	
Poland (Art 149 (1) – Journal of Laws 2002 No. 75, item. 690, as amended and PN-B-03430:1983/ Az3:2000)	20 m³/h for each permanent occupant should be calculated according to the Polish standard but not less than 20 m³/h	20 -30 m³/h for each permanent occupant (for public buildings) For flats, it is a summary of flow from all rooms		30 m³/h to 70 m³/h without windows	50 m³/h	30 m³/h
Sweden (BFS2014:13 – BBR21)	Supply: min 0.35 l/(s·m²) floor area					
UK (Approved Document F)	13-29 l/s (depending on bedrooms)			13-60 l/s (extract)	8-15 l/s (extract)	6 l/s (extract)
EN 15251	0.35 – 0.49 l/ (s·m²)	0.6 – 1.4 l/(s·m²)		14-28 l/s	10-20 l/s	7-14 l/s

Requirement **Recommendation** **European standard**

Comments

- Good overview and comparison of the key data for the countries analysed. No statements on correlations between air quality and well-being.

Titel	Relationships between socioeconomic and lifestyle factors and indoor air quality in French dwellings
Autors	Brown, T.; Dassonville, C.; Derbez, M.; Ramalho, O.; Kirchner, S.; Crump, D.; Mandin, M.
Year	2015
Reference	[30]

Focus of the study / methods

- The study focuses on indoor air quality (IAQ) and its impact on health, particularly the interrelationship between socioeconomic status (SES) factors, environmental exposure, and health outcomes.
- Socioeconomic status is determined by social or cultural factors, education, income, and assets. The study examines how SES factors indirectly influence exposure to indoor contaminants and directly affect health outcomes.

Short summary and approach

- The study explores the complex relationship between SES, indoor pollutant exposure, and health outcomes.
- It analyzes household behaviors, such as chemical product usage, and their association with SES factors.
- The research uses data from a nationwide survey in France conducted between 2003 and 2005 to investigate the influence of socioeconomic and lifestyle factors on indoor air pollutant levels.

Important findings / results

- Wealthier households had higher formaldehyde, acetaldehyde, and perchloroethylene levels but lower BTEX concentrations.
- Occupant activities and building characteristics also influenced indoor air quality significantly.
- Formaldehyde levels were linked to absolute humidity and dwelling construction date.
- Smoking contributed to higher acetaldehyde and PM2.5 levels and a positive fungal contamination index.
- Identifying sources and factors affecting indoor pollutants is crucial for risk assessment and policy development.

Comments

- This paper investigates the relationship between socio-economic factors, occupant behaviors, and building characteristics in influencing indoor air quality, emphasizing the need for comprehensive risk assessment and targeted interventions to improve indoor environmental health.

Titel	Indoor environmental quality in French dwellings and building characteristics
Autors	Langer, S.; Ramalho, O.; Derbez, M.; Riberon, J.; Kirchner, S.; Mandin, C.
Year	2016
Reference	[31]

Focus of the study / methods

- The study aimed to assess indoor environmental quality in 567 residences in mainland France, considering parameters such as temperature, humidity, CO2 levels, various indoor air pollutants, and their correlations with building characteristics.
- It sought to identify significant predictors of indoor air quality, with a particular emphasis on factors like air exchange rates (AER), specific humidity differences, outdoor pollutant concentrations, smoking, attached garages, and building characteristics such as construction period and ventilation systems.

Short summary and approach

- This national survey conducted in mainland France between 2003 and 2005 focused on indoor environmental quality in 567 residences. Several parameters were measured, including temperature, relative humidity, CO2 levels, as well as various indoor air pollutants like volatile organic compounds (VOCs), aldehydes, and particulate matter (PM10 and PM2.5). The study aimed to understand the correlations between these indoor environmental factors and various building characteristics.

Important findings / results

- The median nighttime AER for all dwellings surveyed was 0,44 h^{-1}. Apartments had a slightly higher AER (median 0,49 h^{-1}) compared to single-family houses (median 0,41 h^{-1}).
- Formaldehyde concentrations were approximately 30% higher in dwellings built after 1990 compared to older ones. They were also higher in dwellings with mechanical ventilation systems and in buildings made of concrete.
- VOC concentrations varied depending on various building characteristics.
- The season in which sampling occurred had a significant impact on indoor climate parameters and air pollutant concentrations, often more so than building characteristics.
- Multivariate linear regression models revealed that the difference in specific humidity between indoor and outdoor environments (a proxy for the number of occupants and their indoor activities) remained a significant predictor for most gaseous and particulate air pollutants. Other strong predictors included outdoor pollutant concentrations, smoking, the presence of an attached garage, and AER.

Comments

- In summary, this study investigated indoor environmental quality in residences across France, focusing on various parameters and their correlation with building characteristics. The findings

highlighted the importance of factors like AER, specific humidity, and outdoor pollution levels in determining indoor air quality.

Titel	Perceived indoor air quality and its relationship to air pollutants in French dwellings
Autors	Langer, S.; Ramalho, O.; Le Ponner, E.; Derbez, M.; Kirchner, S.; Mandin, C.
Year	2017
Reference	[69]

Short summary and approach

- The study focused on evaluating the Perception of Indoor Air Quality (PIAQ) in 567 French dwellings.
- It combined PIAQ assessments with measurements of gaseous and particulate indoor air pollutants (PM10 and PM2.5) and indoor climate parameters.
- PIAQ was assessed using a nine-grade scale by both the dwelling occupants and the inspectors who conducted the air quality measurements.
- The study examined differences in PIAQ perceptions between occupants and inspectors and explored associations between PIAQ and indoor air pollutant concentrations.
- Multivariate models were used to account for confounding factors, including building and personal characteristics.

Important findings / results

- Occupants tended to perceive the air quality in their homes as more pleasant than the inspectors did.

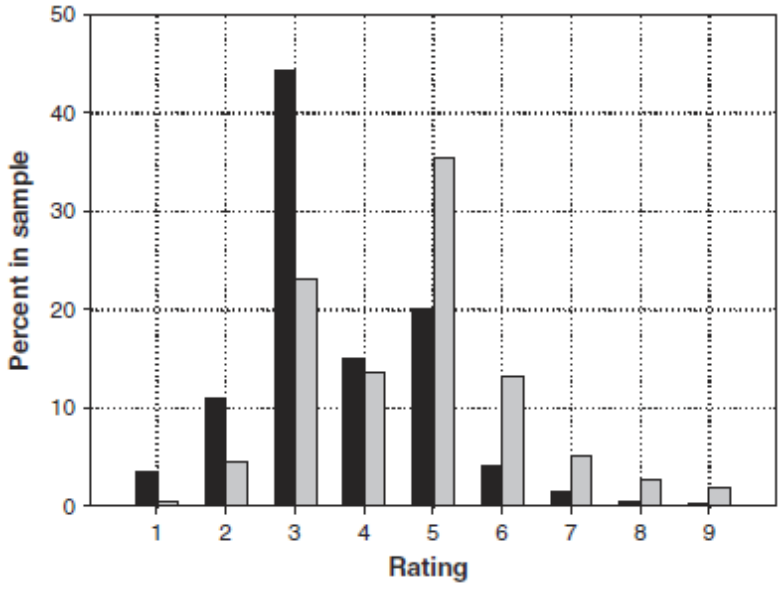


Figure 37: Distribution of the perceived air quality by the occupants and the inspectors from (1) extremely pleasant to (9) extremely unpleasant (bars: black – occupants / gray - inspectors)

- Inspectors perceived air quality as more unpleasant in dwellings where residents smoked indoors.
- Significant associations between PIAQ and indoor air pollutant concentrations were observed for both inspectors and, to a lesser extent, occupants.
- When confounding parameters were introduced into multivariate models, tenure status and occupation of occupants were identified as the primary factors influencing their PIAQ.

- For inspectors, perceived air quality was affected by the presence of smokers, seasonal variations, the type of ventilation system, retrofitting activities, and the concentrations of acetaldehyde and acrolein.

Comments

- This study underscores the divergence in PIAQ perceptions between occupants and inspectors, with smoking habits playing a significant role in inspectors' assessments. Additionally, it highlights the influence of various factors, such as building characteristics and indoor pollutant levels, on PIAQ. Understanding these perceptions can help in addressing indoor air quality concerns effectively.

Titel	Indoor environment of sleeping rooms and sleep quality – a research on the influence of carbon dioxide levels on sleep quality in an intervention study
Autors	van Ruitenbeek, A.M.
Year	2016
Reference	[32]

Short summary and approach

- The study examined the indoor environmental quality of bedrooms, specifically focusing on indoor air quality indicated by carbon dioxide (CO2) levels and its impact on sleep quality.
- The study aimed to establish a threshold level of CO2 at which sleep quality starts to deteriorate and explored different methods for measuring sleep quality.
- Data was collected from 17 single rooms, with measurements taken over five days for two scenarios: 1) with open windows or doors and 2) with closed windows and doors.
- Subjects were initially selected based on building type and later through a selection questionnaire.
- Data collection included CO2 levels, temperature, background noise, relative humidity, qualitative sleep quality questionnaires, sleep diaries, quantitative sleep quality measurements using a Sensewear Armband, and movement detection with a flex sensor.
- Statistical analysis using SPSS included Pearson and Spearman correlations and linear regression analysis to establish univariate and multivariate correlations.

Important findings / results

- Average CO2 levels were 731 ppm for the open window condition and 1147 ppm for the closed window condition.
- Depth of sleep, as measured by the questionnaire, was significantly different between the two conditions, with lower CO2 levels and higher temperature correlating with deeper sleep.
- Sensewear Armband data indicated that lower CO2 levels and higher temperatures were associated with fewer awakenings (improved sleep efficiency).
- Sleep depth and efficiency were lower when CO2 levels exceeded 800 ppm, with more awakenings observed.
- The study suggested using an opened door setup over an opened window setup for future research and maintaining consistent building characteristics for all subjects.

Comments

- This study sheds light on the relationship between indoor CO2 levels, temperature, and sleep quality, highlighting the importance of proper ventilation for better sleep. The findings offer valuable insights for designing bedrooms to promote healthy sleep environments.

Titel	On the economics of health in homes
Autors	Ayden, E.; Eichholtz, P.; Kok, N.; Palacios, J.
Year	2018
Reference	[33]

Short summary and approach

- The study explores the relationship between home maintenance and occupant health.
- It utilizes a longitudinal dataset of approximately 25,000 German households to investigate how poorly maintained homes may impact the health of occupants.
- The analysis takes into account socio-economic status and lifestyle choices that affect health.
- The study examines the self-reported health issues of individuals living in poorly maintained homes.
- It also considers the impact of housing quality on healthcare demand, measured by the number of visits to the doctor.
- The authors identify significant variations in the detrimental effects of poor housing quality on healthcare demand across different age groups.

Important findings / results

- Individuals residing in poorly maintained homes tend to report a higher number of health problems.
- After controlling for relevant factors, these individuals experience an 11-percent increase in healthcare demand, as reflected in doctor visits.
- Among age groups over 64 years, occupants of homes in need of major renovation visit the doctor approximately 30 percent more frequently compared to those living in well-maintained homes.
- Homeowners and tenants are equally likely to move out of poorly maintained homes, but homeowners are more likely to renovate their homes, leaving tenants exposed to adverse housing conditions.

Comments

- This study highlights the importance of home maintenance for occupant health and healthcare demand, particularly among older age groups. It underscores the potential health consequences of living in poorly maintained homes and the role of homeowners and landlords in addressing housing quality issues.

9.4 Others

Titel	Behaglichkeit und Wohnluftqualität
Autors	Kristin Lenz
Year	2005
Reference	[70]

Short summary and approach:

- Indoor air analysis of interior spaces
- The focus is on the effect of materials and construction methods on the indoor climate and thus comfort
- Various materials were tested for moisture buffering behaviour and outdoor tests were carried out in residential buildings (masonry construction, timber construction)
- Temperature and humidity conditions were investigated

Important findings / results:

- Comfort and air quality in living spaces are heavily dependent on hygrothermal conditions
- Wall construction:
    - Strong fluctuations in temperature and humidity in spring/fall
    - Overheating in summer
    - In winter, humidity is in a non-critical range
    - The humidity remains within the comfort range, as room furnishings release stored humidity when the temperature rises (e.g., heating)
    - Low temperature fluctuation is due to the storage capacity of the building materials

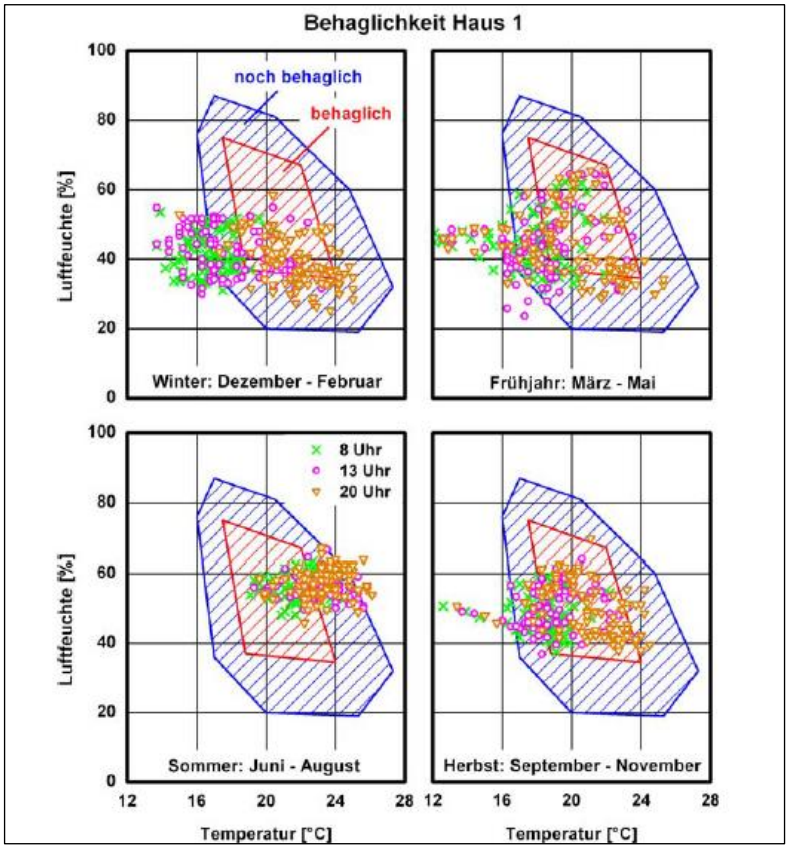


Figure 38: Temperature and relative humidity - building 1

- Timber construction
    - Maximum values in the heating period from 20 to 22 °C
    - Minimum values rarely fall below 18 °C
    - Humidity level is generally lower
    - Generally lower fluctuations between maxima and minima, reason: better insulation

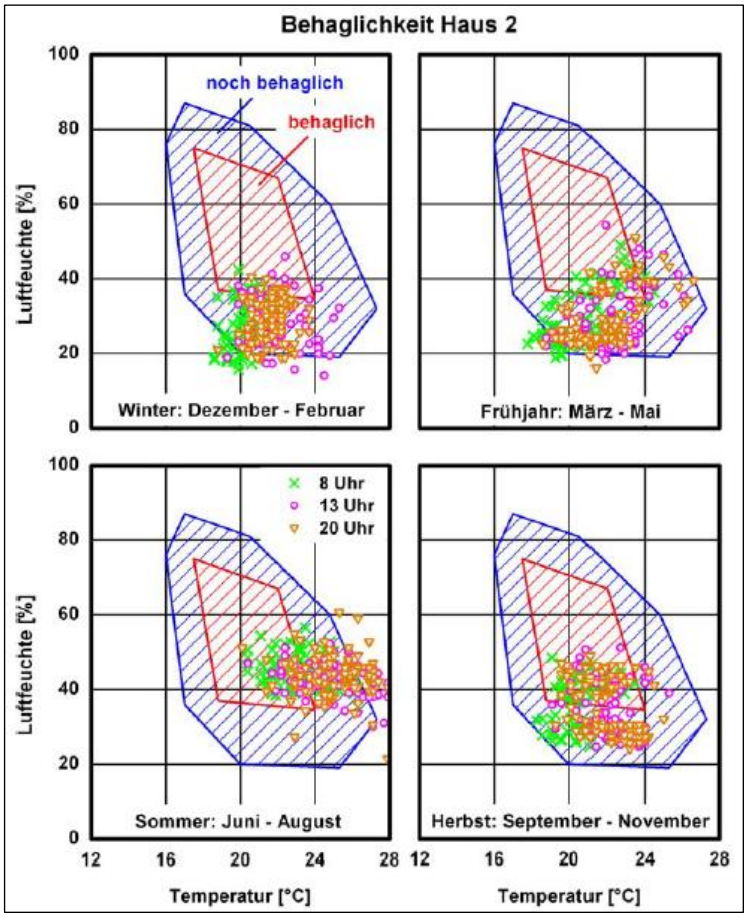


Figure 39: Temperature and relative humidity - building 2

- In general, humidity and temperature depend on many influencing factors - > no general statements can be derived

Comments:

- Study is limited to two examples and analyses humidity and temperature

Titel	Leitfaden für die Innenraumhygiene in Schulgebäuden
Autors	Moriske, Heins-Jörg; Szewzyk, Regine
Year	2008
Reference	[71]

Short summary and approach:

- Guide provides assistance in the operation and renovation of school buildings to provide the best possible air quality
- The suffering thread is divided into 5 parts:
  - A: Hygiene requirements in practical school operations
  - B: Indoor air pollution in schools
  - C: Structural and indoor climate requirements
  - D: Procedures in cases of complaint
  - E: Remediation guidelines and procedures
- Guidelines primarily relate to classrooms and common rooms in school buildings

Important findings / results:

- Part A:
  - The school grounds must be favourably located in terms of emission control
  - The classrooms must be of a sufficient size
  - Windows or other ventilation options must be permitted
  - Cleaning must comply with DIN 77400
  - Ventilation system is required if the school is in an unfavourable location
- Part B:
  - Important air pollutants are: Carbon dioxide, carbon monoxide, nitrogen dioxide, ozone
  - There are also volatile organic compounds (VOCs), which are harmful. These occur during renovation work.
  - Guide values:

Tabelle 2. Leitwerte für die Kohlendioxid-Konzentrationen in der Innenraumluft (Ad-hoc-AG 2008)

Co_2-Konzentration [ppm]	Hygenische Bwertung	Empfehlung
< 1000	Hygnienisch unbedenklich	▶ Keine weiteren Maßnahmen
1000–2000	Hygnienisch auffällig	▶ Lüftungsmaßnahmen intensivieren (Außenluftvolumenstrom bzw. Luftwechsel erhöhen ▶ Lüftungsverhalten überprüfen und verbessern
> 2000	Hygnienisch inakzeptabel	▶ Belüftbarkeit des Raumes prüfen ▶ ggf. weitgehende Maßnahmen prüfen

- Part C:
  - The building materials to be used are specified in the EC Construction Products Directive (Directive 89/106/EEC)
  - The air supplied by mechanical ventilation should consist of 100% fresh air without the addition of recirculated air

Comments:

- Very comprehensive guide

Titel	Long term monitoring of residential heat recovery ventilation with ground heat exchange
Autors	Bart Cremers
Year	2012
Reference	[72]

Short summary and approach:

- Results of a full year monitoring of a zero-energy residential building are reported.
- The building is built to passive house standards and has photovoltaic panels, a heat pump with a vertical bore hole.
- Fresh air is provided by a recovery unit, the heat is recovered from the indoor air
- The ventilation system is monitored.
- Comfort is measured by the CO_2-concentration. (Threshold living rooms: 800 ppm, bedrooms: 1000 ppm)

Important findings / results:

- During the day CO_2-levels are close to natural background: 400 ppm. At night they range from 800-1000 ppm.
- When threshold from 1000 ppm is exceeded, the ventilation increased automatically
- From mid-April on, the CO_2 levels are lower due window ventilation by residences
- The CO_2-levels during night are higher in the children's bedroom due to the door being closed.
- The uncomfortable level of 1200 ppm is rarely exceeded.

Comments:

- Not relevant to the task at hand

Titel	Sanitary aspects of domestic ventilation systems: an in situ study
Autors	Kristin Lenz
Year	2005
Refernce	[73]

Short summary and approach:

- The paper analysis the impact of the accumulation of micro-organisms within ventilation systems, especially in ducts, the filters and on controllable supply grids.
- Five exhaust ventilation systems and twenty-eight balanced ventilation systems were evaluated

Important findings / results:

- Outdoor air quality has a major influence of the supplied and indoor air, especially the mold load.
- Human activity and indoor environment have a higher impact on indoor bacterial load
- Exhaust ventilation systems hardly alter the quality of the supplied air-> indoor micro bacterial load is dependent on outdoor air quality.
- Balanced ventilation systems are capable of reducing the mold load, and to lesser extent bacterial load
- Effectiveness of filtration is largely dependent on quality of the filters

Comments:

Titel	The effect of enthalpy recovery ventilation on the residential indoor climate
Autors	Bart Cremers
Year	2014
Reference	[74]

Short summary and approach:

- The paper deals with an enthalpy recovery unit for ventilation systems. The ERV recovers energy in terms of both temperature and moisture
- Two systems are compared over an eight-day period. The systems are:
  - Heat recovery ventilation
  - Enthalpy recovery ventilation

Important findings / results:

- The absolute recovered humidity with ERV is about 1-2 g/kg with a humidity recovery efficiency of 65%
- ERV brings the indoor relative humidity up to 10% higher than HRV

Comments:

Titel	The effect of CO2 on the nocturnal restlessness of an Alzheimer patient
Autors	Bart Cremers
Year	2015
Reference	[75]

Short summary and approach:

- The paper documents the effect of CO_2 on the nocturnal restlessness of an Alzheimer patient
- During a period of one month, CO_2-levels in the bedroom of the patient were recorded.
- The behavior of the patient was observed and recorded by the partner

Important findings / results:

- At levels between 750-880 ppm restlessness was absent
- Above these values, restlessness emerged in symptoms like humming, teeth grinding, apnea and sometimes panic.
- Intervention by the partner by opening the window decreased the CO_2-concentration and lead to a more restful sleep

Comments:

- This paper deals with just one patient

Titel	Ventilation effectiveness comparison between extract ventilation and balanced ventilation in a scale model
Autors	Bart Cremers
Year	2015
Reference	[76]

Short summary and approach:

- The study deals with the effectiveness of different ventilation models
- The difference between extract and balanced ventilation is usually described by the heat recovery but there I also a difference in ventilation effectiveness
- A scale model is used to compare both types
- The ventilation effectiveness is measured in time it takes for smoke to be completely extracted from rooms

Important findings / results:

- In undisturbed systems the cleaning time for rooms is independent of the ventilation system
- In disturbed systems (open window) the cleaning is slower for designs without heat recovery, the cleaning time with heat recovery doesn't change.
- Systems with heat recovery operate independent from ventilation influences

Comments:

Titel	Monitoring the energy- & IAQ performance of residential ventilation systems
Autors	Rob van Holsteijn; William Li
Year	2015
Reference	[77]

Short summary and approach:

- The study deals with indoor air quality performance and energy characteristics of ten different mechanical ventilation solutions.
- Over a year 62 residential dwellings were monitored
- Monitoring through:
  - Sensor of occupancy
  - CO_2 sensor
  - Relative humidity
  - Air temperature
  - Power consumption

Important findings / results:

- There are big differences in CO_2-excess in the air between the different compared systems
- This is due to the fact that some systems have mechanical components for aur exchange in every habituated room
- These systems due suffer from higher noise in these rooms
- The figure below shows the different systems and the CO_2 excess that is produced

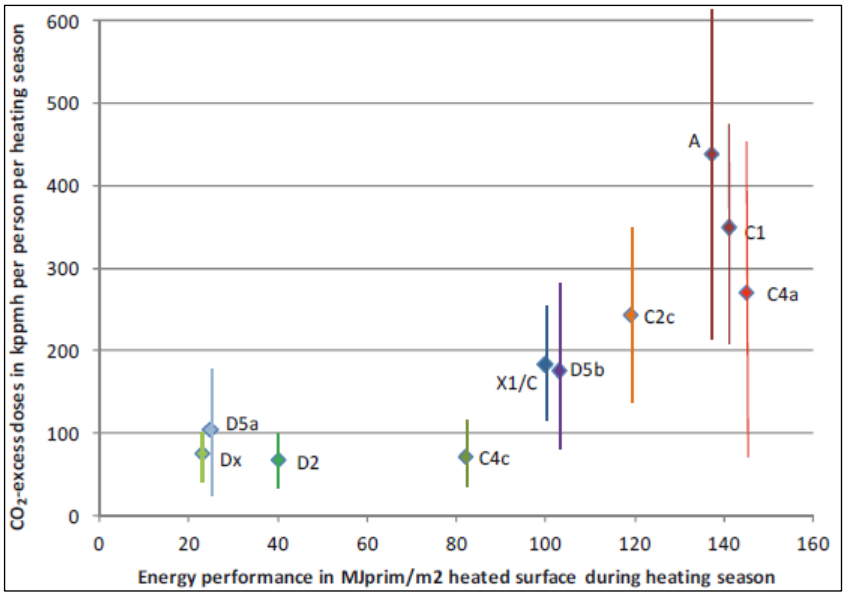


Figure 40: Ventilation system averages and standard deviation on CO_2-excess dose and energy performance

Comments:

Titel	Aktuelle Aspekte zur Lufthygiene in Schulen
Autors	Mario Hopf, Katrin Flohrs
Year	2015
Reference	[78]

Short summary and approach:

- The text deals with a current consideration of air hygiene in schools
- Proper ventilation is crucial for the health and cognitive performance of pupils and teachers. The introduction of a "ventilation traffic light" was evaluated as useful and could improve ventilation in schools.

Important findings / results:

- The air quality in classrooms has a significant impact on the health and performance of pupils and teachers.
- Investigations in Saxony and other federal states indicate considerable hygiene deficiencies in schools, particularly with regard to increased carbon dioxide concentrations, fine dust pollution, mould problems and volatile organic compounds (VOCs).
- The investigations showed that many rooms did not meet the recommended target values for the FOV sum concentration, and in some cases air concentrations of health concern were measured, which required measures to combat the causes.
- Ventilation deficits have often been identified as the main cause of the accumulation of pollutants in rooms.
- The introduction of a "ventilation traffic light" in schools, which indicates ventilation deficits, shows gradual progress towards better air quality.
- Current recommendations emphasize the importance of maintaining a carbon dioxide concentration of 1000 ppm or less in classrooms to ensure health and performance.
- Window ventilation remains the dominant method in schools and tools such as the "ventilation traffic light" are used to support ventilation management.

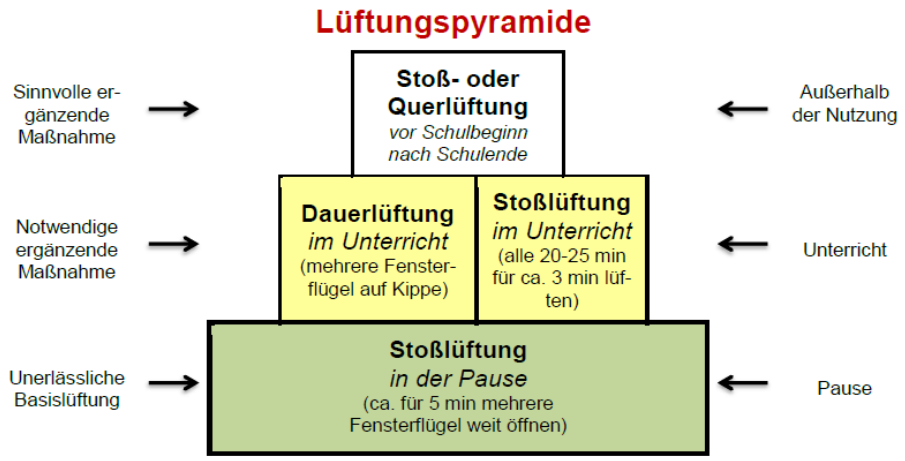


Figure 41: Ventilation pyramid

Comments:

Titel	Anforderungen an Lüftungskonzeptionen in Gebäuden Teil I: Bildungseinrichtungen
Autors	Eva Anlauft et. al
Year	2017
Reference	[79]

Short summary and approach:

- The work deals with airspace requirements in educational institutions
- The focus here is on calculating the CO2 level in the air

Important findings / results:

- The quality of indoor air in educational facilities affects the health and well-being of pupils, teachers and other users who spend long periods of time in the rooms.
- In addition to sufficient ventilation, low-emission building products and furnishings are necessary to make indoor air safe for health.
- The CO_2 content of the air serves as an indicator of indoor air quality. A value of 1,000 ppm CO2 over the duration of a teaching unit (typically 45 minutes) should not be exceeded.
- Window ventilation alone is often not enough to maintain the required air quality all year round.
- A detailed ventilation concept that provides for demand-controlled technical ventilation is required. This concept should be included in the planning and subsequent use.
- The recommended solution is "hybrid ventilation", a combination of mechanical basic ventilation and additional ventilation via windows as required. This improves user acceptance and makes it possible to reduce the outside air volume flow through free ventilation.

Comments:

Titel	A study of Indoor Air Quality in Refurbished Museum Building
Autors	Syahrun Neizam Mohd Dzullkiflli, Abd Halid Abdullah, Lee Yee Yong, Abdul Mutalib Leman, Samiullah Sohu
Year	2018
Reference	[80]

Short summary and approach:

- The paper addresses the issue of indoor air quality (IAQ), which is becoming a significant health concern as people spend about 90% of their time indoors.
- The study focuses on IAQ in museum buildings in Malaysia, particularly the Melaka Sultanate Palace Museum and the History and Ethnography Museum.
- IAQ measurements were conducted over six days, examining gaseous pollutants (nitrogen dioxide, sulfur dioxide, and carbon dioxide) and fine particulate matter (PM2.5) using specific IAQ equipment.

Important findings / results:

- The results indicated that the distance of buildings from roadways had a significant impact on indoor environmental levels, especially for nitrogen dioxide, sulfur dioxide, and particulate matter. Only sulfur dioxide did not exceed acceptable TLV compared to the other IAQ pollutants.
- CO2 concentrations exceeded the acceptable TLV during specific periods, particularly on weekends, and were influenced by visitor numbers.
- The study emphasizes the importance of IAQ assessment in maintaining a healthy environment in museums, especially when refurbishing historical buildings.

Comments:

Titel	2019 Novel Coronavirus (COVID-19) Pandemic: Built Environment Considerations To Reduce Transmission
Autors	Leslie Dietz, Patrick F. Horve, David A. Coll, Mark Fretz, Jonathan A. Eisen, Kevin Van Den Wymelenberg
Year	2020
Refrence	[81]

Short summary and approach:

- The paper deals with the transmissibility of the Sars-Cov-2 Virus inside build environment

Important findings / results:

- Individuals can either be infected directly or indirectly with the Corona Virus
    - By indirect transmission the virus is first deposited on a surface before it comes into contact with a second person
- Data shows that the virus survives longest at a relative humidity of 40% on plastic surfaces (half-life median= 15,9 h) and shortest in aerosol form (half-life median= 2,74 h)
    - Copper: 3,4 h
    - Cardboard: 8,45 h
    - Steel: 13,1 h
- At the publishing date there has been no infection documented from contact with a surface
- The virus has been observed in aerolized particles in a spectrum of sizes, including 0,25 to 0,5 µm.
- High efficiency filtration techniques are required to reduce the transmission potential because enhanced building HVAC operational practices can also reduce the potential for spread of SARS-CoV-2.

Comments:

Titel	Seasonality of Respiratory Viral Infections
Autors	Miyu Moriyama, Walter J. Hugentobler, Akiko Iwasaki
Year	2020
Reference	[82]

Short summary and approach:

- The review deals with the evidence of how outdoor and indoor climate links to the seasonality of viral respiratory infections

Important findings / results:

- Local weather conditions have a negligible impact on the transmissibility of infections
- The overwhelming majority of transmissions occur indoors
- Therefore, indoor air climate and air change rates, modulated by outdoor seasonal conditions are key drivers of seasonal patterns in epidemiology
- Viruses usually have a season in which they are most transmissible
- Three categories can be classified
    - Winter viruses
    - All-year viruses
    - summer viruses
- Relative humidity affects all transmission ways but has the most pronounced effect on airborne transmission
- The stability of winter viruses is enhanced at low relative humidity
- The stability of summer and all-year viruses is enhanced at higher relative humidity
- Viral transmission was generally more efficient at 5°C compared to 20°C. Of note, 5°C ambient air temperature allowed 50% transmission even under 80%
-

Climate/season	Outdoor absolute humidity	Indoor relative humidity (%)	Respiratory virus stability	Proportion of droplet nuclei	Viability of respiratory viruses	Predominant transmission
Tropical	High	60–100	High	Low	High	Fomite, direct and indirect contact
Temperate: spring, fall	Intermediate	40–60	Low	Low	Low	All transmission ways possible
Temperate: winter	Low	10–40	High	High	High	Predominantly airborne

Figure 42: Droplet transmission under different relative humidity conditions

Comments:

- Medical review, no comment on ventilation systems

Titel	The resulting CO2 levels and the heating/cooling consumption of apartments with balanced ventilation versus window ventilation
Autors	Bart Cremers
Year	2021
Reference	[83]

Short summary and approach:

- The study deals with the different CO2 levels of four apartments
  - two apartments were ventilated with a balanced ventilation system
  - The other apartments were ventilated by manual opening of windows
- The apartments were monitored over a period of one year
- CO2 sensors were installed in the living rooms and the bedrooms
- Space heating and cooling were investigated by the energy signature

Important findings / results:

- CO2-levels were lower in the apartments which were equipped with balanced ventilation in comparison to manually ventilated apartments.
- The percentage of hours exceeding 1000 ppm is below 1% of the year for apartments with balanced ventilation
- The percentage of hours exceeding 1000 ppm is 30-60% of the year for window ventilated apartments
- Balanced ventilation systems- including recovery brings higher indoor air quality but also a lower heating (-24%) and cooling use (-50%)

Comments:

Titel	Einfluss der Luftfeuchte auf den Menschen und seine Gesundheit
Autors	Felix Nienaber, Kai Rewitz, Paul Seiwert, Dirk Müller
Year	2021
Reference	[84]

Short summary and approach:

- Meta-study analysing the influence of humidity on human health
- Evaluation criteria are:
  - Comfort
  - Health
  - Influence on pathogens and pollutants

Important findings / results:

- It is difficult to specify a concrete target range for indoor humidity
- The influences of relative humidity must be considered individually for each criterion
- Low relative humidity levels lead to higher perceived air quality and a reduction in the proliferation of dust mites
- Maintaining medium relative humidity levels leads to a reduction in adverse effects on the eyes, skin and respiratory tract
- Humidity also has an influence on the inactivation of virus types:
  - Polioviruses are inactivated at low humidity levels,
  - Influenza viruses are inactivated at medium humidity levels,
  - Coronaviruses become inactive at medium to high relative humidity.
- High relative humidity reduces the suspension time of particles and aerosols
- However, high relative humidity leads to microbial growth and mould formation
- The recommendation of 40-60% relative humidity from the literature is consistent with the research results

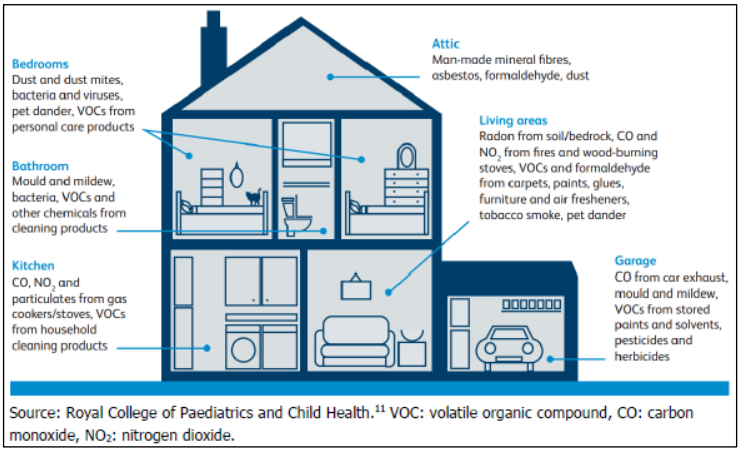
Comments:

9.5 VOC - Aspects

Titel	POSTbrief 54 Indoor Air Quality
Autors	Geroge Duffield, Sarah Bunn
Year	2023
Reference	[85]

Short summary and approach:

- Briefing for UK parliamentarians including information on health effects of poor indoor air quality such as:
- Health Risks from Indoor Air Pollutants: Exposure to indoor air pollutants, although less well characterized than outdoor pollution, is linked to various health issues, including heart disease, stroke, cancers, dementia, respiratory illnesses, and cognitive decline. The composition of indoor air varies significantly due to different sources and occupant behaviours, making causal associations challenging to quantify.
- Vulnerable Populations: Certain demographics, including children, the elderly, pregnant women, and those with pre-existing health conditions, are more susceptible to the negative effects of indoor air pollution. Socioeconomic status and ethnicity also play roles in exposure levels and health impacts.
- Diversity of Indoor Environments: People are exposed to a wide range of pollutants in various indoor settings such as homes, schools, and workplaces. Factors like housing quality, location, and indoor activities influence exposure levels.
- Economic and Healthcare Burden: Poor indoor air quality significantly impacts healthcare services and the economy, with costs related to illnesses and lost productivity. Estimates suggest substantial societal costs due to air pollution, including indoor pollution.
- Importance of Ventilation: Good ventilation is crucial in mitigating the effects of indoor air pollution, particularly highlighted during the COVID-19 pandemic. Improving indoor air quality through effective ventilation can reduce the risk of bioaerosol exposure and contribute to healthier indoor environments.
- Sources of indoor air pollutants:



Source: Royal College of Paediatrics and Child Health.[11] VOC: volatile organic compound, CO: carbon monoxide, NO_2: nitrogen dioxide.

Figure 43: Sources of indoor pollution in a home

Important findings / results:

- The authors suggest the following interventions to improve indoor air quality:

- Government and Multi-level Stakeholder Engagement: A collaborative approach is needed due to the complexity of indoor air quality, involving multiple government departments, local authorities, and stakeholders from various sectors. There's a call for increased government coordination, local authority oversight, and funding to address these issues comprehensively.
- Holistic Approach and Evidence Base Strengthening: It's vital to consider the interplay between different indoor environmental factors like air quality, lighting, and temperature. Enhancing the indoor air quality evidence base requires addressing gaps in research, such as airflow dynamics, pollutant sources, and long-term monitoring.
- Public Awareness and Climate Change Considerations: Public awareness of indoor air quality is limited, and there's a need for better information dissemination. Climate change and net-zero policies can impact indoor air quality, necessitating alignment between climate, net-zero, and air quality policies to reduce unintended negative effects.

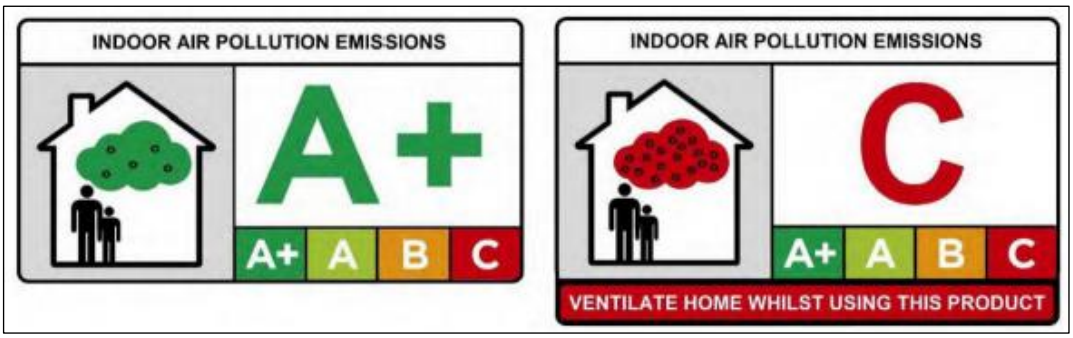


Figure 44: Mock-up of potential VOC Product labels - adapted from a French system.

- Specific Interventions for Source Control and Ventilation: Interventions should include source control of pollutants, effective ventilation strategies, and the use of air-cleaning devices. Correct installation and maintenance of ventilation systems are essential, alongside legislative and technological solutions to control sources of indoor pollution.
- Policy and Regulatory Opportunities: Legislative changes can drive healthier occupant choices and reduce pollutants in public and private spaces. Strategies should focus on areas like public spaces, workplaces, domestic burning, and building standards, considering the balance between legislative measures and personal choice.

Comments:

- The briefing highlights the multifaceted nature of addressing indoor air quality, emphasizing the need for comprehensive research, multi-level stakeholder collaboration, public awareness, and targeted interventions, while also considering the interplay between indoor air quality and broader issues like climate change and socioeconomic factors.

Titel	Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile-Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments
Autors	Allen, Joseph G., Piers MacNaughton, Usha Satish, Suresh Santanam, Jose Vallarino, and John D. Spengler
Year	2015
Reference	[57]

Short summary and approach:

- Simulation of indoor environmental quality (IEQ) conditions in "Green" and "Conventional" buildings
- Evaluation of the impacts on an objective measure of human performance: higher-order cognitive function
- 24 participants spent 6 full work days in an environmentally controlled office space, blinded to test conditions. They were exposed to high and low concentrations of VOCs on different days. In addition, ventilation rate and carbon dioxide levels have been changed artificially but independent of each other.

Important findings / results:

- Cognitive scores were 61 % higher on days with lower concentration (Green building) and 101 % higher on days with additional ventilation (Green+ building) than on days with higher concentration (Conventional building)

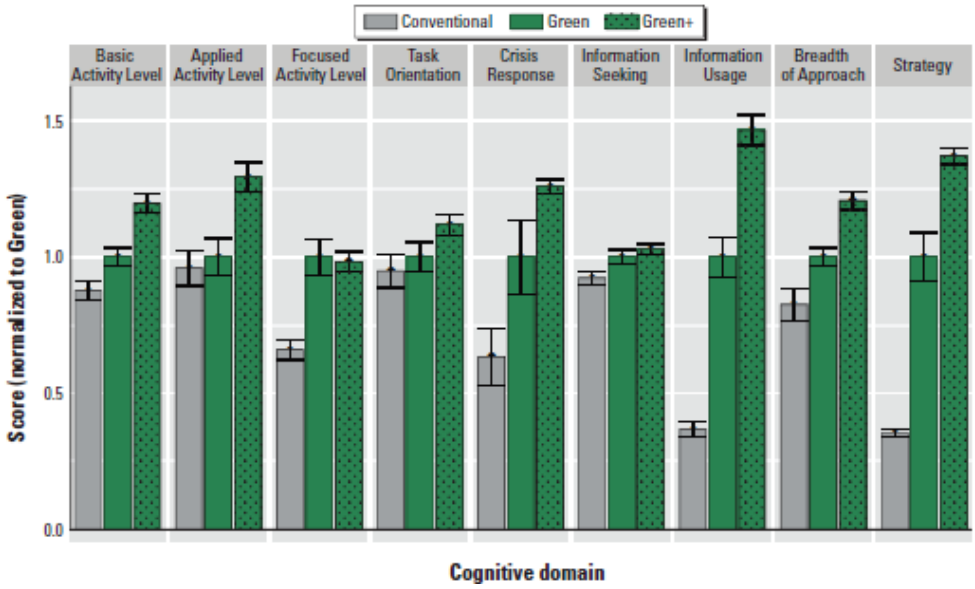


Figure 45: Average cognitive function scores and standard error bars by domain for the Conventional, Green, and two Green+ conditions, normalized to the Green condition by dividing all scores by the average score during the Green condition

- The findings have wide-ranging implications because this study was designed to reflect conditions that are commonly encountered every day in many indoor environments

Comments:

- The study shows, that VOCs have a significant impact on cognitive functions and should be equally considered as CO_2

Titel	Indoor Air Quality
Autors	Air Quality Expert Group
Year	2022
Reference	[86]

Short summary and approach:

- People spend 80-90% of their lives indoors, where air quality is influenced by both outdoor air ingress and indoor sources like building materials, combustion appliances, and consumer products. Indoor air pollutants include CO_2, bio-effluents, and biological aerosols like viruses.
- Key outdoor pollutants like PM2.5, NOx, and CO are also significant indoors, but indoor environments can have higher concentrations of volatile organic compounds (VOCs) and biological aerosols due to different sources and limited dispersion.
- The UK's National Atmospheric Emissions Inventory provides data on indoor emissions, notably VOCs. However, regulations and guidelines affecting indoor air quality, such as ventilation standards and product emission regulations, lack integration and comprehensive standards for acceptable indoor air pollutant concentrations.
- Unlike outdoor air quality, there is a lack of comprehensive data on indoor air quality trends in the UK. Research is fragmented, focusing on specific environments and pollutants, making it difficult to form a holistic view of indoor air quality trends.
- Predictive modelling of indoor air quality is limited due to uncertainties in emission sources and factors like ventilation, temperature, and occupant behaviours. This hampers efforts to estimate exposure and health effects or evaluate interventions.
- Potential interventions include reducing emissions from sources like solid fuel burners, improving building quality, and developing lower emission standards. The role of outdoor air quality improvements and the importance of ventilation, particularly highlighted during the COVID-19 pandemic, are also noted. Caution is advised regarding certain air cleaning technologies due to the risk of creating harmful secondary pollutants.

Important findings / results:

- A significant portion of VOCs in residential buildings come from products like cosmetics, toiletries, aerosols, and household products, with ethanol and butane being predominant emissions. Indoor VOC emissions are highly variable and influenced by factors like building materials, appliance types, and occupant behaviour. However, comprehensive quantification of these emissions is lacking, necessitating further research to develop detailed emission inventories for effective modelling and intervention planning.
- The current regulatory framework for VOCs is fragmented and sector-focused, lacking a holistic approach to managing indoor emissions. There is limited public awareness of VOC-emitting products due to inadequate product labelling, which could be a key area for improvement. Research is also needed to understand the transformation of VOC emissions into secondary pollutants through reactions with other chemicals like ozone, as these transformations can lead to the creation of harmful air pollutants not currently covered by existing inventories or guidelines.
- In the UK, indoor air pollution is becoming a more significant concern due to factors like increased building airtightness for energy efficiency, lifestyle changes leading to more time spent indoors, and a

lack of current data on pollution levels in various environments, necessitating updated research and policy responses.

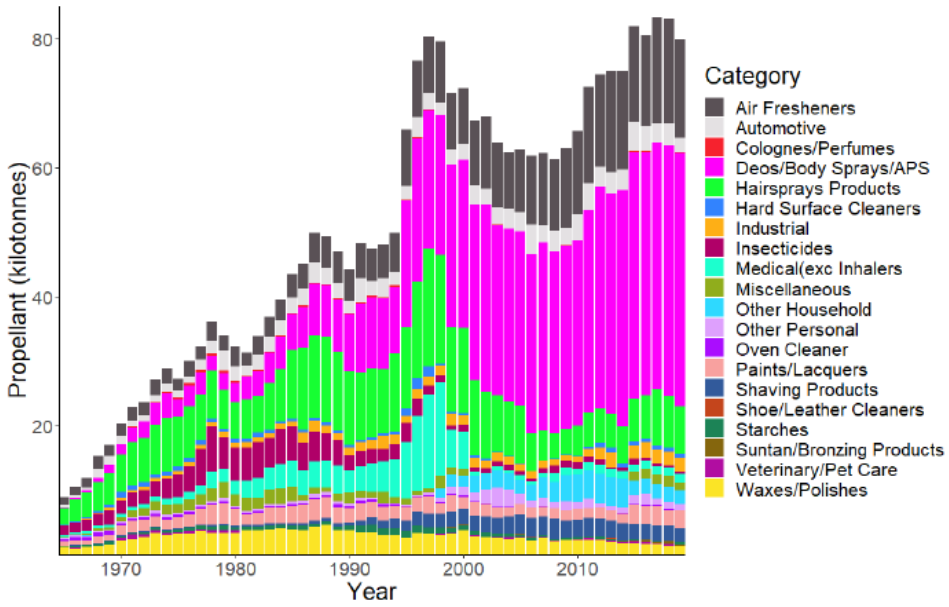


Figure 46: Propellant in kT for different sources

- The review highlights the need for a comprehensive national assessment of indoor air quality in the UK, addressing the heterogeneity of indoor environments and requiring new research strategies, calibrated instrumentation for diverse indoor pollutants, and multi-disciplinary approaches to understand and improve air quality across various indoor settings, while also considering non-inhalation exposure routes like dermal contact and ingestion.
- Enhance indoor air quality through increased ventilation, reduced emission sources, consistent application of existing regulations, and innovations to lower VOCs and SVOCs in products and building materials. Communication and education about indoor pollution and its mitigation are also key.
- Focus on holistic building designs that balance energy efficiency with air quality, and decarbonize heating and cooking methods. Establish enforceable indoor air quality standards, particularly in public spaces, and ensure cross-government collaboration and research prioritization to address indoor air pollution comprehensively.

Comments:

- The texts emphasize the growing significance and complexity of indoor air quality issues in the UK, highlighting the need for enhanced research, regulatory action, public awareness, and integrated approaches to mitigate pollution sources and improve air quality in various indoor environments.

Fachverband Gebäude-Klima e. V.
Hoferstraße 5
71636 Ludwigsburg
Telefon: +49 (0) 7141/25881-0
Telefax: +49 (0) 7141/25881-19
info@fgk.de
www.fgk.de

Fachverband
Gebäude-Klima e.V.