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Ventilation strategies and children's perception of the indoor environment in Swedish primary school classrooms

Natalia Giraldo Vasquez [a,*], Gabriel Bekö [a,b,c], Pawel Wargocki [a], Blanka Cabovska [d], Despoina Teli [d], Jan-Olof Dalenbäck [d], Lars Ekberg [d,e], Theofanis Psomas [d], Sarka Langer [d,f]

[a] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark, Lyngby, 2800, Denmark
[b] Healthy and Sustainable Built Environment Research Centre, Ajman University, Ajman P.O. Box 346, United Arab Emirates
[c] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, Kaunas, Lithuania
[d] Chalmers University of Technology, Department of Architecture and Civil Engineering, Division of Building Services Engineering, SE-412 96 Göteborg, Sweden
[e] CIT Energy Management AB, SE- 412 88 Göteborg, Sweden
[f] IVL Swedish Environmental Research Institute, Environmental Chemistry, SE-400 14 Göteborg, Sweden

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ABSTRACT

This study explored the relationship between children's subjective perception of indoor environmental quality in classrooms, measured thermal and air quality factors, and the type of ventilation. Environmental data were collected in 45 classrooms in 23 primary schools in Sweden during the heating season. Schools with three types of ventilation were recruited: natural or exhaust ventilation (category A), balanced supply-exhaust with constant air volume (category B), and balanced supply-exhaust with variable air volume or demand-controlled ventilation (category C). 796 children (8–14 years of age) answered a questionnaire about their perception of the classroom's indoor environment. Based on ten dichotomous questions, the children's overall perceptions and subjective well-being was scored ("Individual score") from worst (0) to best (10) perception. A Perception Index (PI) was calculated as the arithmetic mean of the Individual scores from all children in a given classroom. We did not find statistically significant differences in the Individual scores or PI between the three ventilation categories. However, the PI of classrooms with ventilation category A, which also had lower ventilation rates and higher concentrations of pollutants, was noticeably lower than that in classrooms with ventilation category B or C. Correlations between the PI and most of the measured environmental parameters or the individual questions about perception were weak and not significant. The PI may be improved by including factors not considered in this study, such as those related to acoustic and lighting conditions.

1. Introduction

The impact the indoor environment of school classrooms can have on the academic performance of students has received considerable attention [1–3]. Nevertheless, most studies have focused on the effects of indoor air and/or thermal environment [4–9]. Studies investigating the impact of all four indoor environmental domains, namely thermal, air quality, light, and acoustics, are rare [10]. While the effects of at least one indoor environmental domain on academic performance is often examined, children's perceptions of the indoor environmental quality of the classroom are less explored [11,12]. In order to collect data on subjective assessments, survey tools must be adapted to the children's age [13]. Lampi et al. [14] concluded that children's self-reported perceptions of indoor air quality, obtained from a self-administered questionnaire, were as reliable as those from questionnaires administered and partly answered by their parents [14].

Field studies have shown that the most critical environmental disturbances in classrooms are noise, high temperatures, and poor air quality [15,16]. Zhang et al. [17] identified six clusters into which children would fit according to their specific needs regarding the classroom's indoor environment. Indoor temperature and noise were the most valued aspects of the indoor environment. On the other hand, Finelly et al. [18] found that observed indoor air problems and poor teacher-student relationship were significant predictors of poor

* Corresponding author.
E-mail address: natgir@dtu.dk (N.G. Vasquez).

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subjective indoor air quality (IAQ). However, in schools without observed indoor air problems, school-related stress was associated with poor subjective IAQ. The authors concluded that in buildings without observed indoor air problems, the psychosocial environment influences subjective IAQ more strongly than in buildings with such problems.

Although building characteristics are closely related to the quality of the indoor environment, other aspects, such as the pedagogical model [19] and sense of control [20], appeared to affect the perception of the IEQ. In their study with 1300 children between 8 and 12 years of age, Bluyssen et al. [19] found that the school's educational model was related to the reported health and perceived comfort. Schools with more flexible pedagogical models were rated better by the children than traditional schools. Furthermore, the perception of a poor relationship with the teacher also predicted poor IAQ perception [18]. Besides, the perception of having control over windows, thermostats and blinds improved the students' perception of the IAQ [20]. However, a study concluded that pupils had a better perception of the indoor environment in classrooms with automatically operable windows and exhaust fans than those with either only manual windows, only automatically operable windows, or only mechanical ventilation [21].

The type of ventilation used in the classroom can affect the indoor air and the thermal environment. Sadrizadeh et al. [22] identified that most educational buildings worldwide use natural ventilation, except in Nordic countries where mechanical and hybrid ventilation are routinely used. Researchers in this region have examined the impact of the type of ventilation system on IAQ and children's perceptions. For example, in Wargocki et al. [23] increasing the air supply rate in classrooms led to improved performance of the children and to the indoor air quality being perceived as more acceptable and fresher. Additionally, apart from temperature and supply flow rate, thermal comfort is also influenced by the ventilation strategy [24]. Thermal satisfaction increased with stratum ventilation under warmer conditions (from 24 °C to 27 °C). In a follow-up field study with around 1500 pupils, the subjective indoor air quality assessment was improved after implementing a retrofit of the ventilation system and better lighting [25]. A poorer assessment was associated with higher CO_2 concentrations (indicator of lower ventilation and generally poorer IAQ) and among children with allergies. More recently, Korsavi et al. [26] found that the perception of air quality in naturally ventilated classrooms was associated with CO_2 concentration during the warm season and with CO_2 concentration and operative temperature in the cold season. Overall, the study showed that the air quality was better when the children felt cooler and preferred to feel that way. In their preliminary results, Toftum and Clausen [27] showed that airing the classrooms improved the perceived air quality, although children felt cool since the intervention took place during autumn/winter in Denmark.

Studies on children's perceptions of the indoor environmental quality combined with comprehensive measurements of indoor air quality and thermal comfort in classrooms are limited. This study explores the subjective perception of the indoor environmental quality among school children and the relationship with the type of ventilation, environmental measurements, as well as the Indoor Discomfort Index (IDI) and the Indoor Air Pollution Index (IAPI) previously determined for the same school classrooms [28]. The objective of the study was to develop an index describing the indoor environmental quality of classrooms based on few simple questions related to the children's perception.

2. Methodology

This research collected environmental and subjective data through a field study in primary school classrooms in Sweden. Data were collected during the heating season from February to early April 2019 and from October 2019 to March 2020, right before the start of the COVID-19 pandemic. The study included measurements of indoor climate parameters and air pollutants, and a questionnaire survey on the perception of indoor environment in the classrooms administered to the children. A schematic flow chart of the methodological approach of the study is shown in the Supporting Information (Figure SI.1).

2.1. Study population and classroom selection

Twenty-three school buildings located in Gothenburg on the southwestern coast of Sweden were selected to participate in this study. Most of the selected schools were located in urban areas, i.e. in the city center or in the city's residential areas (Figure SI2). Two schools were located in rural areas but near main traffic roads. The buildings were classified according to the type of ventilation system to the following categories: A) natural and/or exhaust ventilation, B) mechanical ventilation with constant air volume (CAV), and C) mechanical ventilation with variable air volume (VAV). The schools were built between 1889 and 2016. The oldest schools had mostly category A ventilation system. During the past two decades, mechanical ventilation systems have been installed in some older school buildings. Two classrooms in each school building were surveyed, except for one building, where only one classroom was available. Thus, environmental measurements were performed in 45 classrooms, while data from the questionnaires was obtained from 44 classrooms. The classrooms were mainly on the building's ground or first floor and were occupied approximately 6.5 h per day: from 08:00 to 14:30. Pictures of some of the studied school buildings and classrooms are shown in the SI (Figure SI3 to Figure SI6). Table 1 indicates the number of classrooms in each ventilation category. Table 2 summarizes some classroom features relevant to this study. Further details about the schools can be found in Cabovská et al. [28].

2.2. Environmental measurements and indexes

The measured parameters included indoor air temperature, relative humidity (RH); concentrations of carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), total volatile organic compounds (TVOC), C1 – C10 aldehydes (formaldehyde to decanal) and particulate matter (PM10 and PM2.5). Detailed descriptions of the measurement strategy, sampling, analytical techniques, and instrumentation are presented elsewhere [28]. Briefly, the measurements were launched on Monday morning after installation of the measurement equipment before the children entered the classroom and ceased on Friday afternoon after the children left the classroom. Indoor air temperature, RH and concentrations of CO_2 were monitored using a Wöhler CDL210 (Wöhler Technik GmbH, Bad Wünnenberg, Germany) with a 2-min time resolution. Particles (PM_{10} and $PM_{2.5}$) were measured using a TSI DustTrak DRX model 8533 optical particle counter (TSI Inc., Shoreview, Minnesota, USA) with a time resolution of 10 min. Air change rate (ACR) was calculated from the exponential, first order decay curves of CO_2 concentration vs. time, once the children left the classrooms for breaks or at the end of the school day. The method follows the standard procedure to determine air change rate by means of a tracer gas decay method, assuming that the classroom is a single zone with uniform CO_2 concentration [29,30]. It is standard procedure to keep the classroom doors closed and locked between and after classes. Therefore, the effect of potential interzonal transfer of air on the calculated air change rates is considered minimal. The corresponding ventilation rates required by the Swedish Work Environment Authority (7 L/s per person + 0.35 L/s per m^2) can be

Table 1
Number of buildings and classrooms for each ventilation category.

Ventilation category and ventilation strategy		No. buildings	No. of classrooms
A	Natural ventilation, exhaust ventilation, automated window opening	7	14[a]
B	Balanced supply-exhaust with constant air volume	8	15
C	Balanced supply-exhaust with variable air volume or demand-controlled ventilation	8	16

a Subjective assessments were not collected in one of the classrooms.

Table 2
Descriptive statistics for the studied classrooms.

Ventilation category		No. children	Construction year	Area (m^2)	Volume (m^3)	Area/ child (m^2)	Vol/ child (m^3)
A	Min.	17.0	1889	40.0	137.4	1.7	6.1
	Max.	30.0	1952	75.8	259.8	4.0	13.7
	Mean	21.8	–	55.9	191.3	2.7	9.2
	SD	3.5	25	10.0	33.3	0.7	2.2
B	Min.	16.0	1889	42.7	132.5	1.8	5.4
	Max.	25.0	2013	65.5	229.8	4.0	13.5
	Mean	21.3	–	58.5	175.5	2.8	8.5
	SD	3.3	40	6.5	28.6	0.7	2.3
C	Min.	15.0	1947	43.5	128.7	2.0	5.7
	Max.	30.0	2016	60.1	187.2	3.8	11.6
	Mean	20.6	–	54.3	156.9	2.7	7.8
	SD	3.8	28	5.8	17.0	0.6	1.6

found for each classroom in Cabovská et al. [28]. The design ventilation rates at the time of construction of the schools were not available.

The indoor air pollutants were sampled using passive/diffusive samplers and analyzed by appropriate techniques. The samplers for NO_2 and ozone are described by Ferm and Rodhe [31]. Their concentrations were analyzed by wet chemical techniques using a spectrophotometric method (NO_2) and ion chromatography (O_3). C1-C10 straight chain aldehydes (from formaldehyde to decanal) were sampled using DSD-DNPH Aldehyde Diffusive Sampling Devices (Supelco, Bellefonte, PA) and analyzed by high performance liquid chromatography/UV detection following solvent extraction. Volatile organic compounds (VOCs) were passively sampled on Tenax TA (Perkin-Elmer) adsorbent tubes that were thermally desorbed into a gas chromatograph and identified and quantified by a mass selective detector. The VOCs were evaluated as total VOC (TVOC), a sum of all individual compounds eluting between n-hexane and hexadecane (C6 to C16) and quantified as toluene equivalent concentrations.

The results obtained from the passive sampling (NO_2, ozone, formaldehyde, TVOC) are the concentrations integrated over the whole sampling week ("weekly average"). Temperature, RH, CO_2 and particles from the time-resolved measurements were aggregated into weekly averages and weekly averages for occupied hours; referred to as "occupied time average".

The Indoor Air Pollution Index (IAPI) proposed by Sofuoglu and Moschandreas [32] was calculated to characterize the air pollution conditions in the classrooms by aggregating the concentrations of the individual gaseous and particulate indoor air pollutants into one parameter, using weekly averages only, for consistency of the sampling period. The index relates the observed concentrations of air pollutants to the range of the observed values and to respective demarcation values, which are the recommended IAQ guideline values. The Indoor Discomfort Index (IDI) aggregates the observed temperature and relative humidity using averages during occupied time. These indexes are unitless and have values between 0 (best IAQ or comfort) and 10 (worst IAQ or comfort).

The Odor Index (OI) expresses the intensity of odors caused by aldehydes present in the air. Concentrations of aldehydes with detection frequency >90% and low odor threshold were used to create an Odor Index for each classroom. The index is a sum of odor ratios (OR) for formaldehyde, acetaldehyde, propanal, pentanal, hexanal, heptanal, octanal, nonanal and decanal. The odor ratio is the ratio of the measured concentration of each compound to the respective odor thresholds reported by Nagata [33], Equation (1). The odor thresholds of the substances are presented in the Supporting Information, Table SI.1. An OI within the range from 0 to 15 has been proposed to characterize ambient odors [34].

$$OI = \sum_{i=1}^{n} \frac{Ci}{Odor\ thresholdi} \quad \text{Eq. 1}$$

Measurements of the lighting and acoustic conditions were not performed.

2.3. Questionnaire

A questionnaire used in earlier studies was adapted to the target age group. The questionnaire, administered by the researchers one time during the measurement week, was filled during a regular 45-min class, most often on Wednesdays during morning. It contained 25 questions grouped into six sections. Section I contained three general information questions (Q1 to Q3) asking about the children's sex, age, and whether they suffer from asthma or hay fever. In section II, the children were asked about their currently worn clothing (Q5) and the health status on the day of the survey (Q4), i.e., whether they felt healthy or sick due to cold, running nose or cough. Section III contained one question about the children's activity half an hour before filling the questionnaire (Q6). Section IV addressed the children's perception at the time of filling the questionnaire. Children were asked about their thermal sensation using a 7-point Likert scale (Q7), their thermal preference through a 3-point Likert scale (Q8; colder, unchanged, warmer) and the perception of the air quality using a 3-point semantic differential scale (Q9; good/fresh, OK, bad/stuffy). Section V asked about the children's perception of the overall classroom environment ("usually") through five questions (Q10a to Q10e). Using 3-point scales (not at all – little – very much), children were asked about the classroom a) being too cold, b) being too warm, c) having bad smells, d) having disturbing noise and e) being poorly lit (too bright or too dim). Finally, in section VI, children were asked how they usually feel in the classroom, i.e., their subjective well-being (Q11a to Q11e). Using 3-point semantic differential scales (smiley faces; sad, neutral, happy), they assessed a) mood (feeling good to bad), b) alertness (alert to tired), c) concentration (can to cannot focus), d) desire to work, and e) headache. The full version of the questionnaire, translated to English, is presented in the Appendix. This paper focuses on the analyses of questions Q7, Q8, Q9, Q10 and Q11.

2.4. Scoring of children's perceptions: Perception Index

The answers to the questions were transformed into dichotomous variables using binary code. A positive condition was assigned a value of 1, negative condition a value of 0. For instance, in question Q10a "In the classroom, I usually find it is too cold", the answer "Not at all" was considered as positive (value "1"). The answers "Little" and "Very much" were labeled as "0". In this study, we grouped neutral answers in the same category as the negative assessments (value of 0). While a neutral assessment does not necessarily translate into a negative perception or feeling, neutral votes could encompass a certain degree of non-positive subjective evaluation. Table 3 presents the questions used for scoring children's perceptions, the possible answers, and the corresponding dichotomous variable.

Each child's perception of indoor environmental quality was expressed through an individual score of perceived indoor environmental quality. This is the sum of the values of the dichotomo us variables created from the answers of the 10 sub-questions under questions Q10 and Q11. The individual score is thus a value between 0 and 10, where 10 represents the most positive assessment. For example, a child voting positively ("Not at all" or happy smiley face) in 8 out of 10 questions had an individual score of 8. Finally, the 'Perception Index' of a given classroom is the arithmetic mean of the individual scores for children in the given classroom. All the questions have the same weight in the final score. Children with missing answers in any of the included questions were excluded.

2.5. Statistical approach

Differences in the individual scores between the classrooms' ventilation category and the children's health status (Q4) and reported

Table 3
Transformation of the answers into a dichotomous variable.

Questions	Answers as in the questionnaire (Dichotomous variable)
Q10 - In the classroom, I usually find… (perceptions)	Not at all **(1)** Little + Very much **(0)**
Q10a - It is too cold.	
Q10b - It is too warm.	
Q10c - It smells badly.	
Q10d - There is disturbing noise.	
Q10e - There is poor light (bight or dim).	
Q11 - In the classroom, I usually feel like… (subjective well-being)	☺ (1)
Q11a - I feel good/I feel bad.	
Q11b - I am alert/I am tired.	😐+
Q11c - I can focus/I cannot focus.	
Q11d - I want to work/I don't feel like working.	☹ (0)
Q11e - I have no headache/I have a headache.	

allergies (asthma/hay fever, Q3) were tested using independent tests. The differences in the Perception Index between groups stratified by health status (healthy vs. sick) and allergies (asthma or hay fever vs. no allergies), as well as the differences in the Perception Index between ventilation categories were tested using independent tests. Non-parametric tests such as Wilcoxon rank-sum and Kruskal-Wallis tests were used when the normality of data distribution was violated according to the Shapiro-Wilk test of normality [35]. For all analyses, the statistical significance level was $p < .05$. Cohen's (d) benchmarks were used to interpret effect sizes as follows: from ±0.1 to ±0.29 represent a small effect, from ±0.3 to ±0.49 is a medium effect and from ±0.5 to ±1 is a large effect [35,36]. Statistical analyses were performed in R-studio [37], for the graphical exploration was used Tableau Desktop software [38].

Spearman's rank correlation test (two-tailed) was used to look for correlations between the pupil's subjective responses, measured environmental parameters and calculated indexes. The correlations were run at classroom level; for each question in the questionnaire, the means of the transformed dichotomous variables across all children in the classroom were used.

3. Results

3.1. Study population and objective measurements

A total of 919 children, of which 52% were females, answered the survey. The age of the children ranged from 8 to 14 years. In classrooms with ventilation category A, slightly more children reported having asthma or hay fever and slightly more reported being sick on the day of the survey than in the other two categories (Table 4). Children across the three ventilation categories wore clothing with nearly identical clo value.

Classrooms with ventilation category A had lower air change rates and higher CO_2 concentrations than classrooms with ventilation category B and C (Table 5). Although classrooms with ventilation category B had slightly lower indoor temperatures (two classrooms had slightly lower temperatures than the minimum recommended 20 °C in the winter), most classrooms complied with the recommended indoor temperature [39]. Relative humidity (RH) was somewhat low across the three ventilation categories, although on average within the recommended level. The lowest average RH was above the minimum recommended level (25%) only among classrooms with ventilation category C. The highest average RH (around 60%) was registered in a classroom with ventilation category A. Monthly mean outdoor temperatures and RH are presented in the Supporting Information, Figure SI.7. During the month of the measurements in the schools, the mean ambient temperature and RH (± standard deviation) were 5.5 ± 1.4 °C and 82 ± 5%, respectively [40]. Particulate matter (PM_{10} and $PM_{2.5}$) during the occupied time was also higher in classrooms with ventilation category A; the mean and median of the average concentrations in this category were above the recommended target of 15 μg/m^3 for $PM_{2.5}$ (24-h mean) [41]. The Indoor Discomfort Index (IDI) and Indoor Air Pollution Index (IAPI) are a good representation of the environmental conditions in the classrooms. As reported by Cabovská et al. [28], there were no significant differences in the thermal environment between the ventilation categories as described by the Indoor Discomfort Index (IDI). However, the indoor air quality as described by the Indoor Air Pollution Index (IAPI) was significantly lower in classrooms with ventilation category A (higher IAPI). The Odor Index was also lower in classrooms with ventilation category B, where concentrations of aldehydes were significantly lower than in classrooms category A ($p < .05$).

3.2. Subjective assessments

Fig. 1 presents children's thermal sensation, thermal preference, and air quality perception at the time of the survey. Fewer children in category C classrooms felt thermally comfortable (68.2% feeling neutral, slightly warm, or slight cold, compared to 84.5% in category A and 80.6% in category B). More pupils in classrooms with ventilation category C felt cold, warm, very cold, very warm (31.8%) than their peers in the other classrooms (Category A = 15.5%; Category B = 19.4%). More children in these classrooms preferred a warmer environment (41.9%) than in classrooms with ventilation categories A (23.5%) and B (27.5%), which could be the effect of the slightly lower operative temperature in category C classrooms. Reflecting this, the relationship between ventilation category and thermal preference was significant ($\chi^2 = 20.4$, df = 4, $p < .001$). Regardless of the ventilation category, most children perceived the air quality as neutral ("OK", neither fresh nor stuffy). The air was perceived as stuffy by the same proportion of pupils in the three types of classrooms. However, more children in classrooms with ventilation category C assessed the air quality as good or fresh (27.8%) than in classrooms with category A (20.2%) and B (17.3%).

Fig. 2 contains a summary of the results of the five statements in question Q10 in the questionnaire used to assess the perception of the indoor environment and stratified by the ventilation category of the classrooms. Across the three ventilation categories, around 55% of the children perceived the classroom as usually little or very cold. While 64% of the children in category A classrooms found the environment usually warm, only about 50% of those in category B and C classrooms did the same. Is worth to notice that some children answered both: the classroom is too warm and too cold. The perception of noise seemed to be similar in all classrooms. Only between 30% (category A and C) and 35% (category B) of the children indicated that the classrooms did not have a disturbing noise. Most pupils perceived the classrooms as a little

Table 4
Gender distribution, reported allergies (asthma/hay fever), and health status on the day of survey by ventilation category.

			Q3-Asthma/hay fever			Q4-Health status			Q5-Clo value
Ventilation category	No. of children	Females	I do not have	I have	NA	Healthy	Sick	NA	Mean (SD)
A	282	52%	80%	16%	4%	65%	33%	3%	0.68 (0.14)
B	319	54%	84%	12%	4%	74%	21%	4%	0.68 (0.15)
C	318	51%	85%	8%	6%	76%	20%	4%	0.70 (0.17)

Table 5
Summary of the measured environmental parameters and calculated indexes by ventilation category (average of all classrooms).

		Ventilation category A (n = 14)					Ventilation category B (n = 15)					Ventilation category C (n = 16)				
		Mean	Median	Max	Min	IQR	Mean	Median	Max	Min	IQR	Mean	Median	Max	Min	IQR
Indoor Environment	Air change rate (ACR), h^{-1}	1.4	1.3	3.5	0.3	1.1	3.3	3.5	4.3	2.3	0.8	3.7	3.7	5.1	1.9	1.3
	L/s per child	3.6	3.0	6.7	0.8	2.4	7.7	6.6	13.4	5.0	3.0	7.9	7.7	11.3	4.4	4.8
	NO_2 all week ($\mu g/m^3$)	8.9	9.0	14.9	2.9	4.4	14.5	11.4	32.3	9.0	3.8	9.7	8.3	20.1	3.9	2.8
	Ozone all week ($\mu g/m^3$)	7.8	4.5	18.2	4.5	5.9	14.3	10.3	55.6	4.5	5.0	16.7	18.7	35.5	4.5	10.5
	Formaldehyde all week ($\mu g/m^3$)	14.2	12.2	26.9	7.4	4.9	7.9	6.8	16.1	1.7	5.9	10.6	9.3	20.1	5.2	4.9
	TVOC all week ($\mu g/m^3$)	192	155	590	43	88	124	118	206	35	53	126	101	293	57	43
	PM_{10} occupied time ($\mu g/m^3$)	34.4	32.5	51.0	15.0	20.5	19.3	20.0	27.0	11.0	9.0	15.9	15.5	33.0	8.0	9.5
	$PM_{2.5}$ occupied time ($\mu g/m^3$)	20.7	21.5	29.0	10.0	8.5	11.4	12.0	16.0	7.0	4.0	9.8	9.0	22.0	5.0	6.0
	CO_2 occupied time (ppm)	1136	1112	1628	600	572	661	676	763	547	75	640	634	801	538	108
	CO_2 occupied time 95-%ile (ppm)	1839	1839	2671	736	619	900	917	1098	710	137	841	848	1012	673	163
	Temperature occupied time (°C)	21.6	21.5	24.0	20.1	1.8	21.1	20.9	23.6	19.4	1.6	21.1	20.9	22.2	19.8	1.0
	Temperature during the survey (°C)	21.7	21.7	23.5	20.0	1.5	21.3	21.0	23.5	19.6	2.1	21.1	21.1	22.1	19.2	1.3
	Operative Temp. during the survey (°C)	22.2	22.2	24.2	20.4	1.3	21.6	21.2	25.7	19.2	2.6	21.0	20.9	22.8	19.3	1.0
	RH occupied time (%)	38	37	57	21	8	32	34	42	20	8	34	35	45	27	8
	RH during the survey (%)	40	40	61	24	6	37	39	46	19	8	36	36	45	26	8
Indexes	IDI	3.0	3.0	4.7	1.4	1.4	3.4	3.0	5.8	1.9	1.3	2.7	2.5	3.9	0.9	1.7
	IAPI	6.0	6.0	6.8	5.1	1.1	4.9	4.9	6.4	3.8	1.4	4.7	4.7	5.8	3.0	1.0
	Odor index	271	292	461	110	100	164	169	311	28	101	256	241	499	140	130

IQR = Interquartile Range.

noisy. Bad smells and disturbing lighting conditions appeared not to be a major problem in the classrooms. Classrooms with ventilation type B had slightly better lighting conditions, although this is expected to be unrelated to the ventilation category.

The results of the five statements in question Q11 used to survey the children's subjective well-being are summarized in Fig. 3. Most children reported not having a headache and feeling usually good in the classroom. Slightly more children in classrooms with ventilation categories B and C reported the latter (72.6% and 70.7%, respectively, in comparison with 62.5% in category A). Slightly fewer children in classrooms with ventilation category A (48.9%) than in the other classrooms (~55%) reported that they could focus, and more children in category C classrooms felt they wanted to work (56.6% vs. about 45% in category A and B classrooms). Most pupils felt neutral about being alert/tired, although the fraction of those who felt alert was lowest in category A classrooms (26.1%), highest in category C classrooms (41.2%).

We found a significant association between thermal preference, the feeling of alertness ($\chi^2 = 11.2$, df = 4, p = .02, Fig. 4a), and desire to work ($\chi^2 = 13.3$, df = 4, p = .009, Fig. 4b). Among children who preferred a "colder" thermal environment, only 28.6% felt "alert," while 47% and 41.6% of those who preferred the thermal environment to remain "as it is now" or "warmer", respectively, reported being "alert". Most children who preferred the thermal environment to remain "as it is now" or to be "warmer" felt that they wanted to work (~60%), while only 44.4% of children who preferred a "colder" thermal environment were motivated to work.

3.3. Individual scores of perceived indoor environmental quality

Individual scores of perceived indoor environmental quality were calculated for 796 children who answered all ten questions in sections V and VI of the questionnaire (Q10 and Q11).

The individual scores were stratified by health status on the day of filling the questionnaire (Q4; healthy vs. sick). The distribution of the individual scores was non-normal in the group of healthy children (n = 582; p < .0001) as well as in the group of those children that reported feeling sick (n = 188; p < .0001]. The non-parametrical Wilcoxon-Mann-Whitney test (two-tailed) for independent samples indicated that the individual scores were significantly higher in the group of healthy children (median = 6.00, SD = 2.22) than in the group of sick children (median = 4.00, SD = 2.15) (p < .0001, Fig. 5a). However, the effect size showed a moderate association between the children's health status and their score (d = −0.30).

The individual scores were also stratified by children's reports of having asthma or hay fever (Q3). The distribution of the individual scores was non-normal in both groups (without asthma n = 663, $p <$ .0001; with asthma n = 101, p = .01). Children without asthma/hay fever had significantly higher scores (median = 5.00, SD = 2.31) than those that suffered from any of those conditions (median = 4.00, SD = 2.17) ($p <$ .001, Fig. 5b). However, the effect size showed a weak association between the variables ($d = -0.14$).

The individual scores of children feeling both healthy on the day of the questionnaire and not suffering from asthma/hay fever (n = 498) were stratified by classroom ventilation type (Table 6). Since the assumption of normal distribution was violated in the three groups, the non-parametric Kruskal-Wallis test (one-tailed) for independent samples was used to look for differences in the individual scores between ventilation types. Children in classrooms with ventilation category B and C had slightly higher individual scores than those with ventilation category A (Fig. 5c). However, these differences were not statistically significant (p = .38).

3.4. Perception Index

Fig. 6 presents each classroom's Perception Index, grouped by ventilation category. The Perception Index for the classrooms was

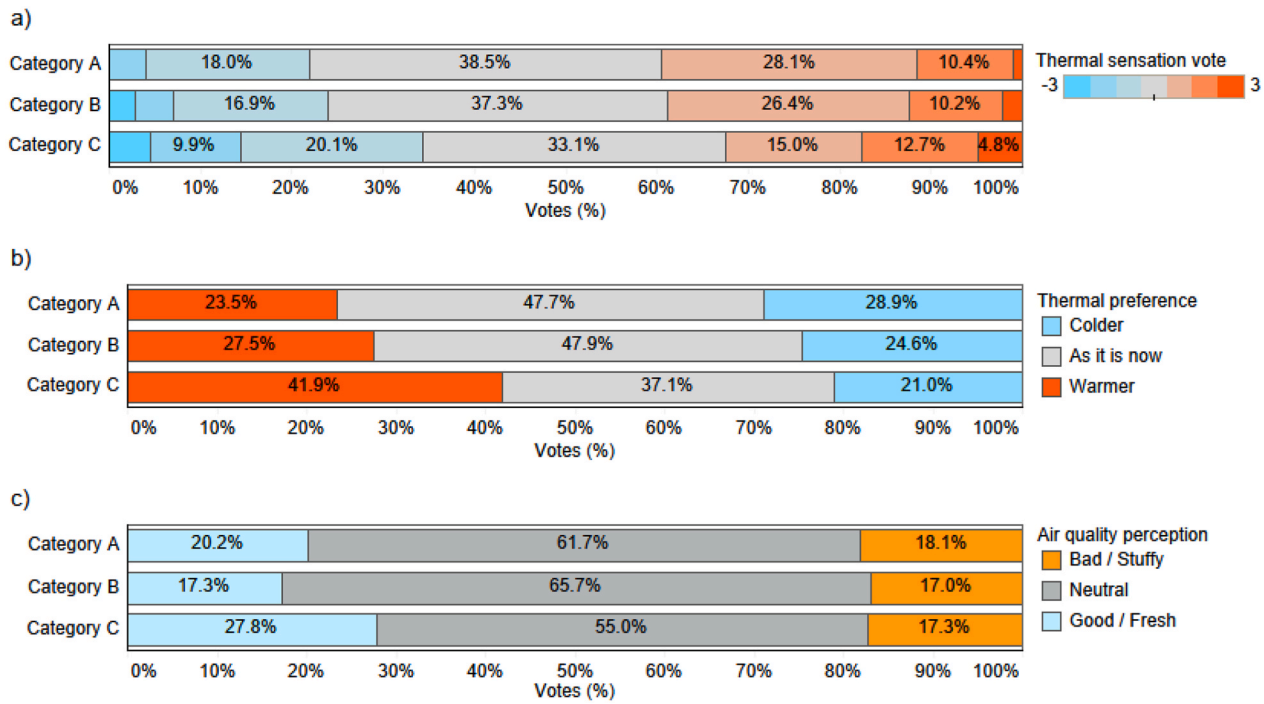

Fig. 1. Thermal sensation vote (a), thermal preference (b), and air quality perception (c) by ventilation category.

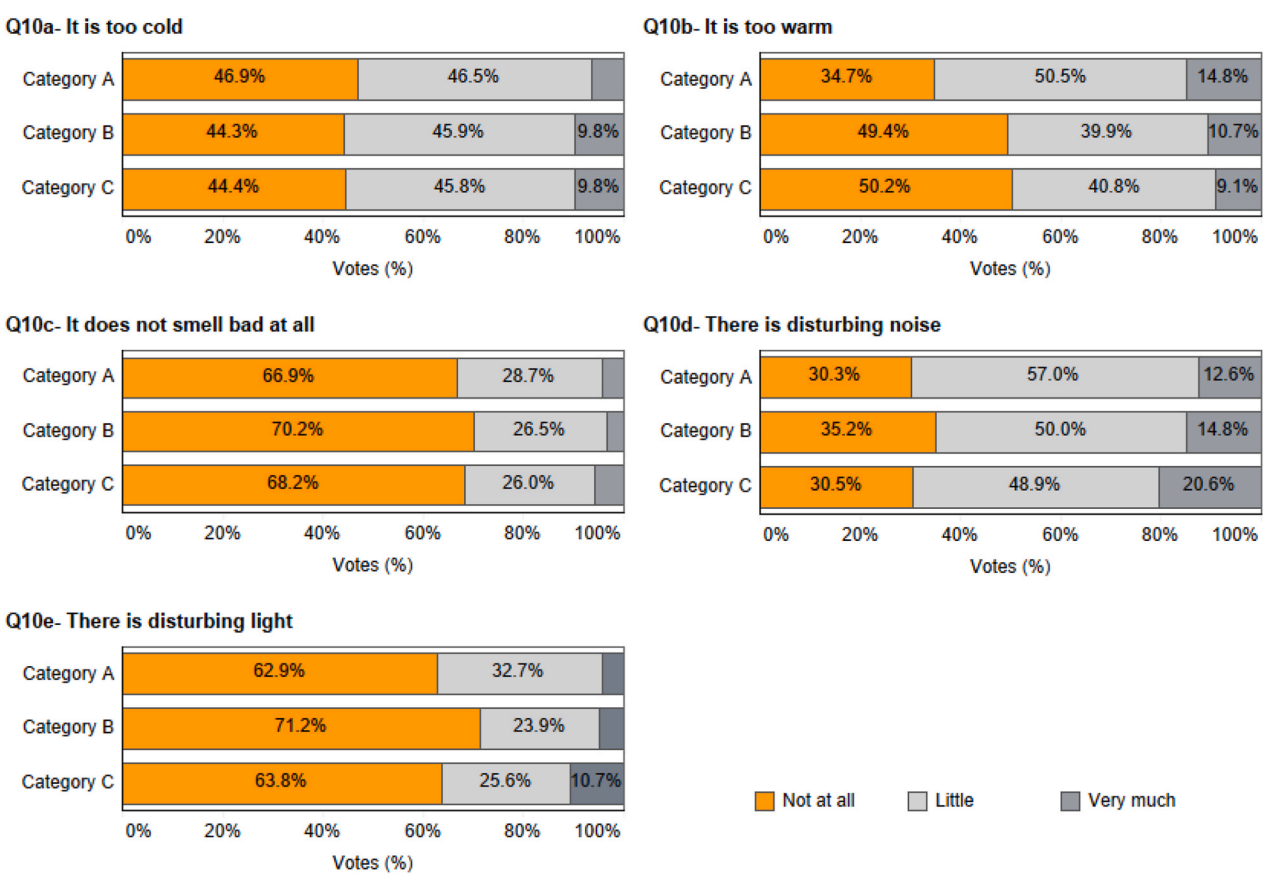

Fig. 2. Perception of the indoor environment: Summary of responses to the statements in question Q10 of the questionnaire ("In the classroom, I usually find …").

calculated separately using all children (n = 770) and children feeling healthy on the day of the survey (n = 582) (Fig. 7a); the individual scores from 26 children who did not answer the question about health status were removed from the dataset. The distribution of the Perception Index was normal with all children (p = .08) as well as with healthy children only (p = .06). Thus, a parametric independent t-test was used

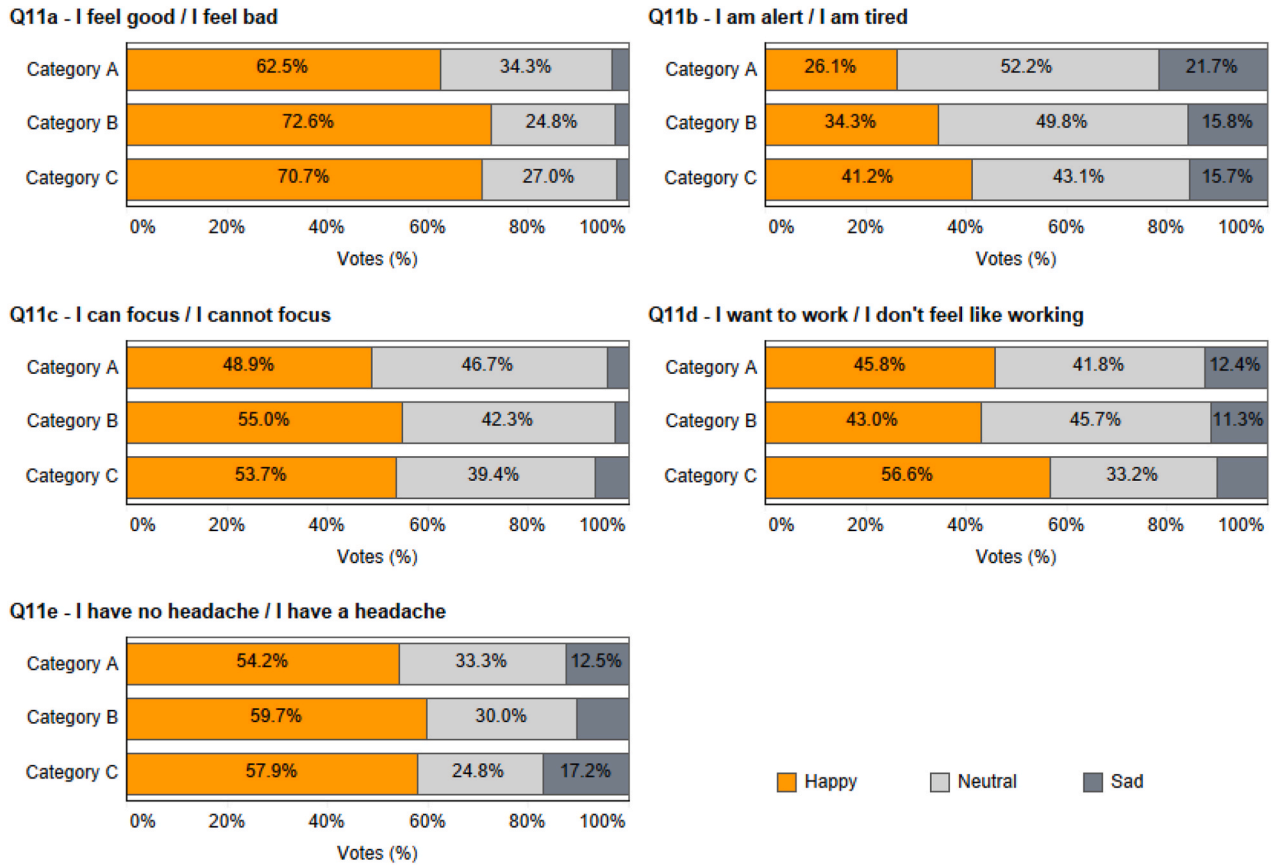

Fig. 3. Subjective well-being votes: Summary of responses to the five statements in question Q11 of the questionnaire ("In the classroom, I usually feel like …"). The responses used semantic differentials with icons (smiley faces corresponding to being happy, neutral, or sad).

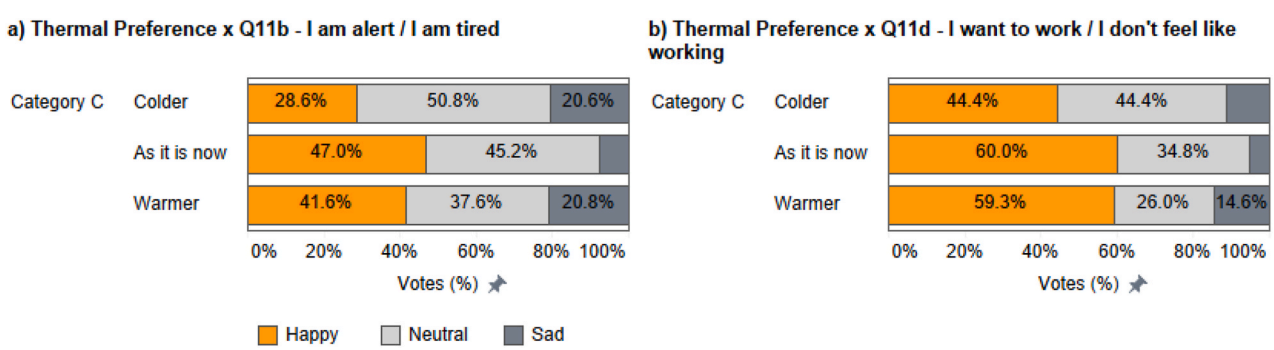

Fig. 4. Thermal preference of children in classrooms with ventilation category C and their alertness (a) and desire to work (b).

to test the differences between the groups. The Perception Index was higher for healthy children (mean = 5.66, SD = 0.82) than for all children (mean = 5.20, SD = 0.88). This difference was, however, not statistically significant (p = .06). Therefore, the inclusion of children feeling sick on the day of the survey did not influence the Perception Index of a given classroom.

The Perception Index was also compared for all children (n = 764) and children not having asthma/hay fever (n = 663); 32 children who did not answer the question about asthma/hay fever were removed. The Perception Index for both groups had a normal distribution (all children p = .08, without asthma/hay fever, p = .36). The Perception Index was slightly higher when removing children with asthma/hay fever (mean = 5.39, SD = 0.89) than for all children (mean = 5.26, SD = 0.87). The difference was not significant (p = .47). Thus, the inclusion of children with asthma/hay fever did not have a meaningful effect on the Perception Index of a given classroom.

Since health status and allergies did not influence the Perception Index, the individual score of all children was used to calculate and compare the Perception Index between ventilation types. Such comparison was constrained by the small sample size (number of classrooms) in each group (Table 7). The assumption of normal distribution was violated for ventilation category A (p = .047). Therefore, the non-parametric Kruskal-Wallis test (one-tailed) for independent samples was used. No significant differences in the Perception Index were found between the three ventilation categories (p = .11). Post-hoc tests (one-tailed) did not find statistically significant differences in the Perception Index. However, the comparison between classrooms with ventilation category A and C showed that the observed difference between the ranks (9.38) is close to the critical difference (9.40); therefore, it could be inferred that pupils in classrooms with ventilation category C perceived the indoor environment as better than their peers in classrooms with ventilation category A.

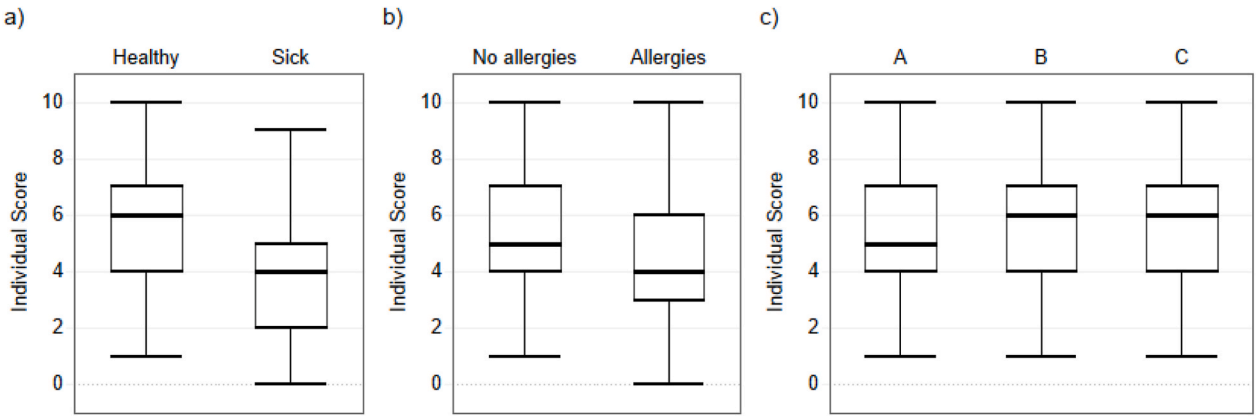

Fig. 5. Individual scores by a) Health status: healthy vs. sick children, b) Allergies: asthma/hay fever vs. no asthma/hay fever and c) Ventilation Category (only healthy, non-asthmatic children). The bottom and the top of the boxes represent 25th (Q1) and 75th (Q3) percentiles and the band near the middle of the box is the median. The length of the whiskers is 1.5 times the IQR of the upper and lower quartiles.

Table 6
Individual scores of perceived indoor environmental quality for the three ventilation categories.

							Post-hoc test (one-tailed)			
Ventilation Category	No. of children	Mean	Median	SE	SD	Kruskal-Wallis mean rank	Comparison	Observed diff.	Critical diff.	Difference($p < .05$)
A	134	5.47	5.00	0.19	2.16	234.96				
B	180	5.75	6.00	0.17	2.28	255.97	A-B	21.01	32.18	False
C	184	5.73	6.00	0.16	2.14	253.75	A-C	18.78	32.03	False

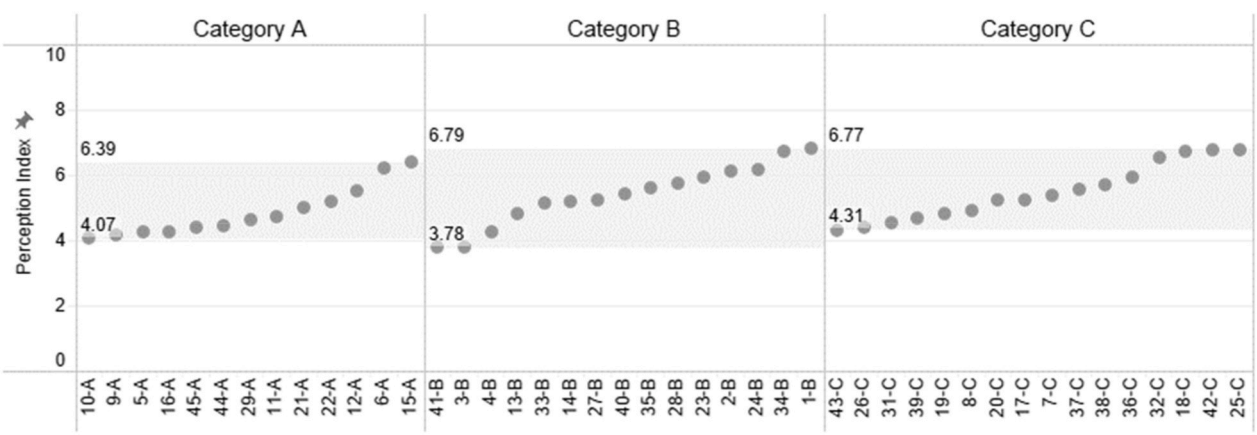

Fig. 6. Perception Index of the 44 classrooms. The values indicate the maximum and minimum index values for each ventilation type.

3.5. Relationship between measurements, questionnaire responses and indoor environmental indices

Table 8 contains the results of the correlations between the measured indoor environmental parameters, the calculated indexes and questions Q7 (thermal comfort), Q8 (thermal preference), Q9 (air quality), Q10 (perceptions) and Q11 (subjective well-being). Since lighting and acoustic measurements were not conducted, questions Q10d and Q10e were excluded from these analyses.

We did not find significant correlations between questions Q10a ("It is too cold"), Q10c ("It smells badly"), Q11c ("I can/I cannot focus"), Q11d ("I want to work/don't feel like working") and Q11e ("I have no headache/I have a headache") and any of the relevant environmental parameters and calculated indexes. Most of the significant correlations ($p < .05$) had a moderate effect size (indicated in blue in the table). We did not find a significant association between the Perception Index and temperature or relative humidity. The Perception Index was only correlated with concentrations of particles and with ACR. Classrooms with lower particle concentrations and higher ACR had higher Perception Index, which indicates more positive perceptions and subjective well-being. ACR was moderately and positively correlated with feeling good (Q11a) and being alert (Q11b); CO_2 concentrations were not correlated with these subjective assessments. Thermal sensation (Q7), and the perception of the classroom being too warm (Q10b) showed a moderate correlation with the Indoor Air Pollution Index (IAPI) and the concentrations of particles, which themselves strongly correlated with IAPI [28] (both positive correlations for Q7, negative for Q10b). Question Q9 related to the perception of the air quality was negatively correlated with particle levels. Questions Q7 and Q8 strongly correlated with temperature. Thermal sensation (Q7) moderately negatively correlated with the Indoor Discomfort Index (IDI), which reflects temperature and RH. The Odor Index was found not to be correlated with the perception of the air quality (Q9) or with the presence of smells in the classroom (Q10c). It correlated negatively with the perception of the classroom being too warm (Q10b) and with concentrations of NO_2, positively with temperature, and the concentrations of formaldehyde, particles and CO_2.

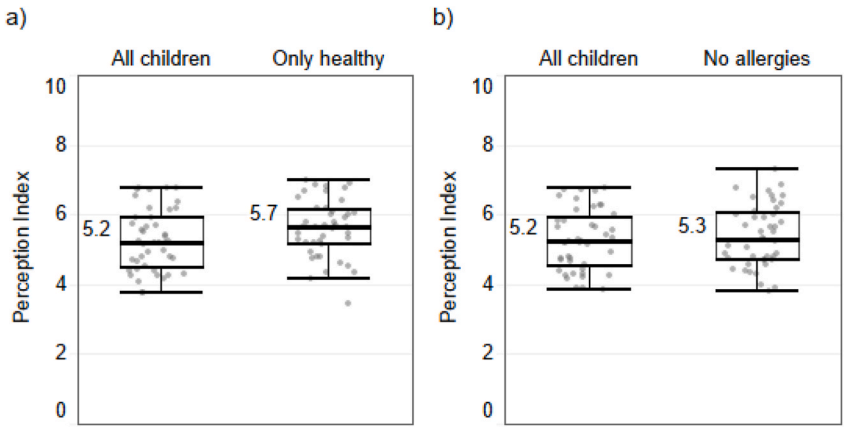

Fig. 7. Perception Index of the classrooms by a) Health status on the day of the survey b) Allergies (asthma/hay fever. The values indicate the medians. The bottom and the top of the boxes represent 25th (Q1) and 75th (Q3) percentiles and the band near the middle of the box is the median. The length of the whiskers is 1.5 times the IQR of the upper and lower quartiles.

Table 7
Perception Index for the three ventilation categories.

							Post-hoc test (one-tailed)			
Ventilation category	No. of classroom	Mean	Median	SE	SD	Kruskal-Wallis mean rank	Comparison	Observed diff.	Critical diff.	Difference ($p < .05$)
A	13	4.87	4.65	0.21	0.76	16.27				
B	15	5.38	5.42	0.24	0.94	24.53	A-B	8.26	9.54	False
C	16	5.47	5.30	0.22	0.86	25.65	A-C	9.38	9.40	False

4. Discussions

In the studied classrooms, Cabovská et al. [28] found that regardless of the ventilation system, indoor temperatures and relative humidity were rather similar and within the recommended ranges [39]. Small differences between the classroom categories were observed in operative temperature; the lowest were measured in category C classrooms. Around two-third of the children in these classrooms with balanced supply-exhaust ventilation with variable air volume or demand-controlled ventilation preferred to be either warmer (42%) or cooler (21%).

Although concentrations of most air pollutants were below the recommended limit values, classrooms with ventilation category A had poorer indoor air quality than classrooms with other ventilation categories. Their ventilation rates were lower, and the concentrations of formaldehyde, TVOC, CO_2 and PM were higher. Ozone and NO_2 concentrations were however lower. Classrooms with ventilation category A were in older, naturally ventilated buildings, while the other schools had balanced mechanical ventilation designed to meet the requirements set by the Swedish Work Environment Authority. Thus, ventilation in category A classrooms relied on window airing. However, our measurements were conducted during the heating season, when window opening is limited. Moreover, mechanical ventilation in Sweden operates with large fraction of outdoor air (up to 100%), with minimal recirculation.

On the other hand, most children across all classrooms perceived the air quality as neutral ("OK", neither good/fresh nor bad/stuffy). This may indicate that children may not fully understand the concept of air quality. Armijos Moya and Bluyssen [42] concluded that children participating in their study did not understand clearly the meaning of "stuffy air". In our study, consistently across all classroom types, relatively few children complained about the stuffiness of the air (below 20%). A slightly larger fraction of children in category C classrooms assessed the air quality as good or fresh (27.8%), compared to the other two categories. These results differ from the earlier findings in classrooms with natural ventilation [15,43] and hybrid ventilation [44]. In these studies, the CO_2 concentrations were higher than in the present study, and children's perceptions were worse.

The differences in perceptions (Q10) and subjective well-being (Q11) between the three classroom categories were small. However, a larger proportion of children in category A classrooms found the environment usually warm and fewer felt good or alert than in the other two types of classrooms. More children in category C classrooms indicated being alert and motivated to work, which could be linked with earlier findings that feeling slightly cool is optimal for learning and performance [45]. We speculate that those results in category C classrooms could be explained by how the VAV system operates [28]; it increases the airflow when the indoor temperature rises above 21 °C. However, further field studies need to be conducted to confirm whether the perception of increased alertness and motivation was due to the ventilation system or to other factors such as building features or children's socioeconomic background. ACR correlated with feeling good and feeling alert, while ventilation rates were higher in classrooms with category B and C ventilation. These results may indicate that although the differences in perceptions and subjective well-being between Swedish schools are relatively small, mechanical ventilation may lead to better perceived indoor environment and more satisfaction with it.

The weak and mostly non-significant correlations between the questionnaire data and the measured variables indicate that the children's perception of the indoor environment and the associated subjective well-being are not directly related to the measured pollutants. Only the perception of the thermal environment was clearly associated with the measured temperature. Particle concentrations were correlated with thermal sensation (Q7), thermal preference (Q8), perception of the air quality (Q9), feeling too warm (Q10b) and with the Perception Index. However, the correlations between particles and the various indicators of thermal comfort may have occurred by chance, and due to the fact that the various questions related to thermal environment were likely highly correlated.

We analyzed whether health status and allergies affect the assessment of environmental quality. The Individual score, which reflects the overall perception of the indoor environment and subjective well-being for each pupil, was lower for children reporting sickness on the day of the questionnaire or allergies in general. However, the Perception Index, which

Table 8
Correlations between the pupil's subjective assessments, the indoor environment parameters, and Indexes.

		Indexes		Indoor Environment	Questionnaire					
		Odor Index	Perception Index	ACR h-1	Q7 - Thermal sensation vote	Q8 - Thermal preference	Q9 - The air feels… (good/OK/bad)	Q10b - It is too warm	Q11a - I feel good/I feel bad	Q11b - I am alert/I am tired
Indoor Environment	Air change rate (ACR), h^{-1}	n.s	0.35	–	n.s	n.s	n.s	n.s	0.38	0.37
	NO_2 all week (μg/m^3)	−0.37	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	Formaldehyde all week (μg/m^3)	0.49	n.s	−0.44	n.s	n.s	n.s	n.s	n.s	n.s
	TVOC all week (μg/m^3)	n.s	n.s	n.s	0.32	n.s	n.s	n.s	n.s	n.s
	PM_{10} occupied time (μg/m^3)	0.38	−0.33	−0.38	0.43	−0.49	−0.43	−0.37	n.s	n.s
	$PM_{2.5}$ occupied time (μg/m^3)	0.37	−0.37	−0.47	0.36	−0.43	−0.36	−0.33	n.s	n.s
	Temperature occupied time (°C)	0.48	n.s	n.s	0.57*	−0.49	n.s	−0.51*	n.s	n.s
	RH occupied time (%)	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	CO_2 occupied time (ppm)	0.34	n.s	−0.70*	n.s	n.s	n.s	−0.31	n.s	n.s
	CO_2 occup. 95-% (ppm)	n.s	n.s	−0.68*	n.s	n.s	n.s	−0.30	n.s	n.s
	Temperature during the questionnaire (°C)	0.42	n.s	n.s	0.58*	−0.53*	n.s	−0.48	n.s	n.s
	RH during the questionnaire (%)	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s	n.s
	Operative temp. during the questionnaire (°C)	0.38	n.s	n.s	0.45	−0.47	n.s	−0.33	n.s	n.s
Indexes	IDI	n.s	n.s	n.s	−0.35	n.s	n.s	n.s	n.s	n.s
	IAPI	0.42	n.s	n.s	0.36	n.s	n.s	−0.34	n.s	n.s
	Odor index	–	n.s	n.s	n.s	n.s	n.s	−0.38	n.s	n.s
	n.s: not significant	Correlation coefficient effect size: ±0.3 to ±0.49 , "*" > ±0.5								

represents the overall perception of all children in a classroom, was not affected by health status or allergies. Regarding the differences in the overall perception between ventilation categories, no statistically significant differences in the Individual score or Perception Index were found. Yet, the Perception Index of classrooms with ventilation category A was noticeably lower than that for ventilation categories B and C. This is in line with the lower ventilation rates, generally higher concentrations of pollutants and higher IAPI observed in category A classrooms [28]. Although the Perception Index and the individual perception/subjective well-being questions did not correlate with the measured pollutants other than particles, other factors and elevated levels of pollutants other than the measured ones may be responsible for the lower perceived air quality in category A classrooms. It is also plausible that a stronger relationship between the measured pollutants and perception/subjective well-being would be observed at higher concentrations of the measured pollutants.

This study has some limitations that should be considered in future research. Our results may have been also influenced by the type of questions used to develop the Perception Index. The ten questions referred to the children's perception and subjective well-being in general ("usually"), which relies on the children's recollection, instead of their momentary perception at the time of filling the questionnaire. Our questionnaire did not include a question about draught. Considering local discomfort due to draught would improve the PI and may identify further differences between classrooms with different ventilation systems. Moreover, our results may be influenced by small sample size. Even though a power analysis indicated that our sample size, in terms of number of children, was adequate (n = 936 needed), not all children answered all the questions in the survey, resulting in a reduced sample size (n = 796 in our study). Furthermore, the Perception Index was calculated at classroom level, for which the sample size was smaller (n = 44) than suggested by the power analysis (n = 240). The children's socioeconomic background and the pedagogical model of the schools might have had an impact on children's responses and their assessment of the indoor environment. Finally, using occupant-generated CO_2 to estimate classroom air change rates that reflect outdoor ventilation rates has its own limitations. Although we believe that the assumption of a classrooms with closed doors being a single zone with uniform CO_2 concentrations is solid, inaccuracies derived from possible interzonal airflows between the classrooms and the surrounding rooms cannot be entirely excluded [46–48].

Poor air quality is among children's main complaints when assessing their classroom environment [16,17]. However, the importance of the acoustic and lighting conditions should not be overlooked [19]. Although this study intended to develop an index to assess the indoor environment based on responses to a few questions, our questionnaire included only one question on acoustic and one on lighting conditions. Corresponding measurements were not made. The associations between the children's perception/subjective well-being and the acoustic and lighting conditions could therefore not be examined. Future studies should investigate more comprehensively the relationship between the actual indoor environmental quality in classrooms and its subjective assessment by the pupils.

5. Conclusions

Children's subjective assessment of the indoor environment in classrooms with three different ventilation systems was investigated. At individual level (Individual score), children healthy on the day of the survey and children who do not suffer from asthma/hay fever perceived the classroom's indoor environment as better than those who reported being sick and having allergies. However, since the Perception Index is the arithmetic mean of the individual scores of the children in each classroom, including children with self-reported sickness and allergies did not have a meaningful effect on the Perception Index. We did not find statistically significant differences in the Perception Index between classrooms with different ventilation categories. However, classrooms with natural ventilation, exhaust ventilation and automated window opening (ventilation category A) had a lower Perception Index than classrooms with balanced mechanical ventilation (ventilation category B and C). This may reflect the lower ventilation rates and higher concentrations of pollutants in the naturally ventilated classrooms. However, no correlations were found between most of the objectively measured parameters and the Perception Index or the majority of the individual questions about perception and subjective well-being that make up the index. Apart from the relationship between temperature and the perception of the thermal environment, the perception of the indoor environmental quality may depend on other factors than the ones measured in this study. The potential impact of acoustic conditions and lighting conditions on children's overall perception of the indoor environment in classrooms warrants further attention. This study contributes to our understanding of the link between the indoor environment and children's perception in classrooms, as well as to the development of an index for the overall assessment of the indoor environmental quality of classrooms based on children's perceptions.

CRediT authorship contribution statement

Natalia Giraldo Vasquez: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Gabriel Bekö:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Pawel Wargocki:** Writing – review & editing, Methodology, Conceptualization. **Blanka Cabovska:** Writing – review & editing, Investigation, Data curation. **Despoina Teli:** Writing – review & editing, Investigation. **Jan-Olof Dalenbäck:** Resources, Investigation, Funding acquisition. **Lars Ekberg:** Resources, Investigation. **Theofanis Psomas:** Writing – review & editing, Formal analysis. **Sarka Langer:** Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110450.

Appendix

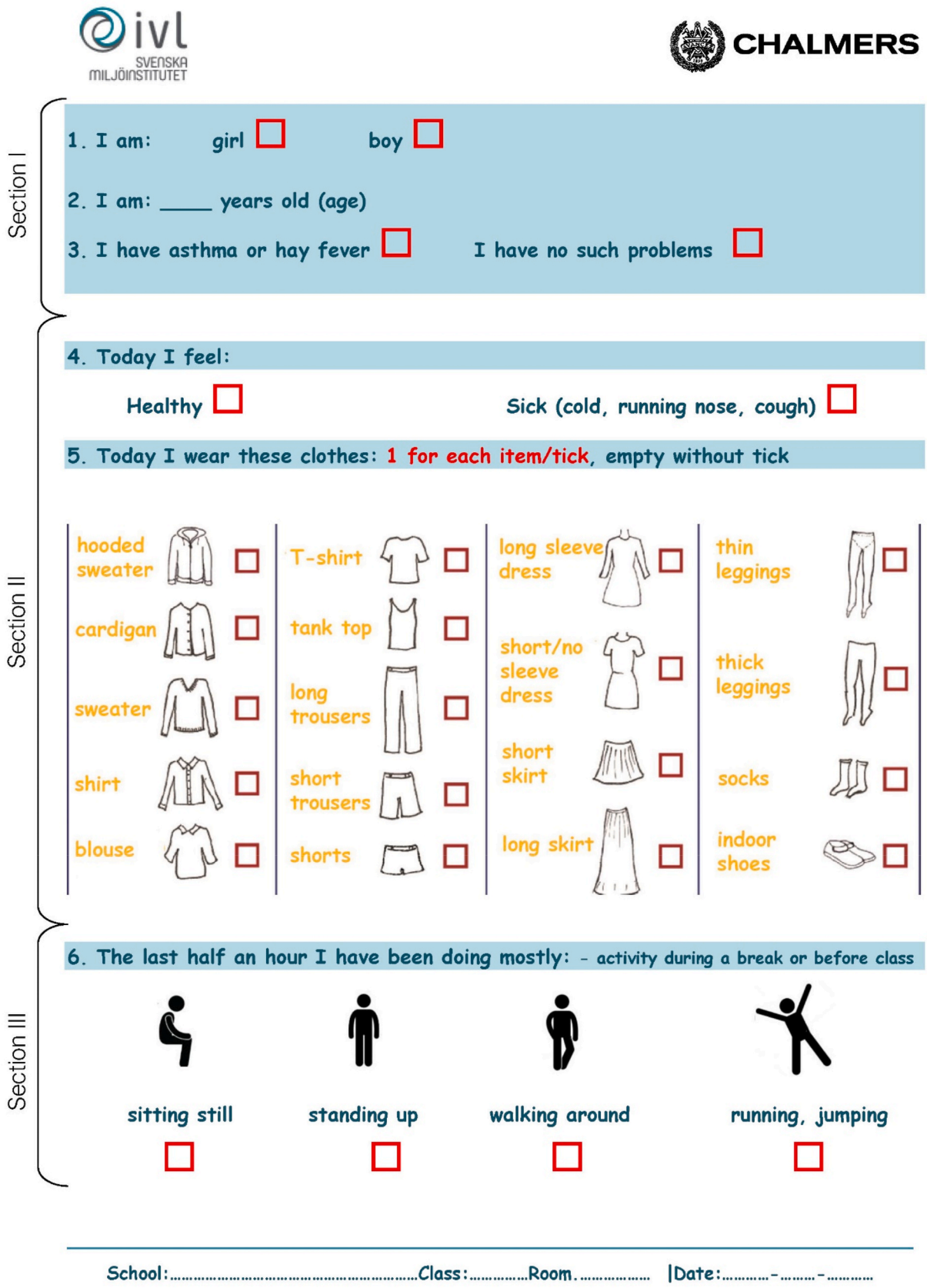

fig1

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CHALMERS

Section IV

7. How do you feel right now:

Very cold	Cold	Little cold	Neither cold or warm	Little warm	Warm	Very warm
-3	-2	-1	0	1	2	3

8. Right now I wish it were:

Colder ☐ as it is now ☐ Warmer ☐

9. Right now I think the air feels: corresponds to acceptance of air quality

Good (fresh) ☐ OK ☐ Bad (stuffy) ☐

Section V

10. In the classroom, I usually find that:

It is too cold	not at all ☐	little ☐	very much ☐
It is too warm	not at all ☐	little ☐	very much ☐
It smells badly	not at all ☐	little ☐	very much ☐
There is disturbing sound/noise	not at all ☐	little ☐	very much ☐
There is poor light (too bright or too little light)	not at all ☐	little ☐	very much ☐

Section VI

11. I usually feel like this in the classroom: Circle a face.

I feel god	🙂	😐	☹️	I feel bad
I am alert	🙂	😐	☹️	I am tired
I can focus/concentrate	🙂	😐	☹️	I cannot focus/concentrate
I want/have desire to work	🙂	😐	☹️	I do not feel like working
I have no headache	🙂	😐	☹️	I have a headache

Thank you so much!

fig2

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