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The impact of climate change on cognitive performance of children in English school stock: A simulation study

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ABSTRACT

Children in England spend around 30% of their time in schools to gain knowledge and skills. Climate change could impact schools' thermal environments and children's learning performance by impairing their cognitive ability. This study presents an evaluation approach to investigating and quantifying climate change's impact on the cognitive performance of children across English school stocks. The study also evaluates the potential of possible strategies for mitigating the impacts of climate change. The results show that future climates are projected to increase cognitive performance loss of children in school archetypes representative of school stocks, with variations based on regional climate characteristics. Increasing ventilation rates proves to be an effective means of reducing cognitive performance loss, while its effectiveness diminishes as outdoor temperatures rise in the future. Thus, the introduction of air conditioning becomes a potentially more beneficial strategy, despite the associated increase in cooling energy demand. Moreover, higher ventilation rates in air-conditioned classrooms can further improve children's cognitive performance. The use of cognitive performance loss as a Key Performance Indicator (KPI) allows for better communication and understanding of climate change risks faced by schools among building and non-building experts. The proposed evaluation approach remains adjustable and can be continuously updated and enhanced as new insights from psychological research emerge.

1. Introduction

School buildings constitute a significant portion of the non-residential building stock. As the second most important environment for children after their homes, schools account for approximately 30% of their time [1]. Given that children are still in the developmental stage both physically and mentally, they are more sensitive to changes in indoor environment compared to adults [2]. However, even in developed countries, existing school buildings often fail to provide satisfactory IEQ (Indoor Environmental Quality) [2]. High occupancy density and insufficient ventilation lead to problems such as overheating and poor air quality in the classrooms [3–5]. Additionally, with the projected global temperature increases of 1–1.5 °C by 2040 and 1.5–3.5 °C by 2080 [6], there is a potential risk of worsening school classroom environments due to future climate warming. Thus, enhancing the schools' ability to resist the effects of climate change is an increasingly important topic.

The concept of climate resilience has gained widespread attention around the world in recent years [7]. Building' climate resilience refers to the ability of buildings to provide satisfactory indoor conditions regardless of external climates [8]. In the context of schools, climate resilience encompasses not only providing thermal comfort and good indoor air quality in classrooms, but also ensuring the health, well-being and performance of children under changing climates [9,10]. Achieving these goals in schools poses a complex and challenging task from the building design and engineering perspective [11].

1.1. Climate resilience and adaptation of English schools

There are more than 9 million children in English schools, including 16,786 primary schools and 3473 secondary schools [12]. English schools are mostly free running (naturally ventilated) during non-heating seasons while mechanical ventilation systems and air conditioners are rarely present today. The lack of resilience to external

Abbreviations: KPI, Key Performance Indicator; PDSP, Property Data Survey Programme; PMV, Predicted Mean Vote; PPD, Predicted Percentage of Dissatisfied; HDD, Heating Degree-Day; CIBSE, Chartered Institution of Building Services Engineering; TRYs, Test Reference Years; DSYs, Design Summer Years; HVAC, Heating, Ventilation, and Air Conditioning.

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climates is a major issue shared by most existing school buildings in the UK [13]. As many existing school buildings may last 40 years or more, it is crucial to understand the climate resilience of the schools at the stock level.

Several studies have been conducted to assess the impact of climate change on the indoor environment of building stock through building stock modelling [14–17]. Building stock modelling is a technique that allows for the examination of a large number of buildings and evaluate their performance by using energy or IEQ-related indicators [18]. Due to data scarcity and technical limitations in many regions and countries, these studies often rely on archetype-based approaches for stock modelling and simulation [19]. Archetype-based approaches involve dividing the building stock into different categories and developing multiple thermal models to represent the average characteristics of each category. The performance of these archetype models is then simulated to characterize the overall performance of the buildings within each category or of the entire building stocks. However, relevant studies have primarily focused on residential building stocks and pay limited attention to school building stocks. Thus, this study aims to address this research gap by focusing on school building stocks.

In addition, past research has also investigated the potential of climate adaptation strategies for building stock [20–22]. Ventilative cooling has been used as one of the climate adaptation strategies to mitigate the effects of climate change and improve the climate resilience of buildings [22]. Air conditioning is another type of adaptation strategy and in the future may become more prevalent in the UK [23], but expanded use of air conditioning is expected to inadvertently lead to increased energy consumption [24]. Currently, there is limited research available on climate adaptation strategies for school building stock. Building simulation techniques can provide a relatively rapid estimate and assessment of the effectiveness of different adaptation strategies [25].

1.2. Methods of assessing school building environment

Most studies assess school building thermal environment by using traditional evaluation indicators. For example, to evaluate thermal environment, studies often make use of the thermal comfort models and metrics, including in-the-moment metrics (e.g. Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD)), or long-term assessment metric (e.g. overheating risks) [26]. However, there exists a range of limitations if only considering the thermal comfort of the children in schools. One main limitation is that children may differ from adults in terms of their perception of indoor thermal environment [27]. It has been reported that children prefer lower indoor temperatures compared to adults [5,28], suggesting that existing adult-based thermal comfort metrics may not be applicable to children [29]. Although children generally have better learning performance in a thermally comfortable environment than in a thermally uncomfortable environment, the classroom temperature range which meets thermal comfort requirements may not guarantee good learning performance of children in the classrooms [30]. Due to the primary function of schools in providing environments conducive to learning, traditional evaluation indicators related to IEQ, such as thermal comfort, air quality, lighting levels, and noise levels, need to be complemented with indicators of children's performance [31].

Despite psychological studies aiming to derive the relationship between indoor environmental quality (IEQ) parameters and performance/productivity in educational or office buildings, only a few studies utilized such relationship to evaluate and guide the design of indoor environment [32–34]. Furthermore, none of these studies have specifically focused on the impact of changing climates on cognitive performance of children in their classrooms. Current UK school building standards do not incorporate cognitive performance as an indicator for evaluating and benchmarking classroom environments. Therefore, in order to incorporate the concept of occupant-centric building design into building standards, it is essential to establish a connection between psychological research findings and building design practice [35]. The development and applications of relevant evaluation approaches and indicators play a crucial role in this endeavour [36].

1.3. Aim and objectives

By using cognitive performance loss as the KPI, this study introduces a novel approach to quantifying the effects of climate change on children in English school stock in order to characterize its climate resilience. The study also investigates the potential of different adaptation strategies to improve schools' climate resilience during non-heating school days (from May to September and excludes holidays). The objectives of this study are as follows:

(1) to examine how current and future climate affects cognitive performance of children in schools across England.
(2) to investigate the potential of ventilative cooling to mitigate the effects of climate change on cognitive performance.
(3) to investigate the impact of different cooling-set point temperatures for air conditioning on cognitive performance and calculate the corresponding cooling demand of schools.

2. Cognitive performance as a function of indoor temperature and ventilation rate

Children's learning performance in classrooms has received continuous attention from educational and phycological researchers. Research reveals cognitive ability, personality and psychological health can affect children's learning achievement, while cognitive performance is often considered as the most stable predictor [37]. Since cognitive ability is involved in the future development of a child [38], many schools begin to attach importance to the cultivation of children's cognitive ability, rather than just imparting knowledge and skills [39]. Cognitive ability refers to the brain's ability to process, store and extract information, utilizing various cognitive skills, such as attention, memory, perception and reasoning [40]. Cognitive performance is typically measured by having participants complete a series of cognitive tasks based on paper or computerized tests in laboratory conditions or classrooms [41].

Some studies attempted to create a quantitative relationship between IEQ indicators and children's cognitive performance. While these studies do not make a clear distinction between human performance, cognitive performance, learning performance and productivity, accuracy and reaction time (speed) are two main dimensions used for demonstrating the outcomes of cognitive tasks [42]. Generally speaking, a higher accuracy and lower reaction time indicate superior cognitive performance [27].

2.1. Cognitive performance and indoor temperature

The influence of indoor temperature on human performance, particularly in the context of schoolwork and office work has become an area of interest in indoor environmental research community [9]. A common ground is made that indoor thermal environments have an impact on the performance of schoolwork and office work. Previous studies have reported different findings regarding the effects of indoor temperature on occupants. Some studies have found an inverted U-shaped relationship, indicating that there is an optimal temperature at which occupants perform best, while lower or higher temperatures lead to relatively poorer performance [40]. On the other hand, other studies have reported an extended U-shaped relationship, suggesting that there is a range of temperatures within which occupants' performance remains stable, rather than a single optimal temperature. Beyond this range, cognitive performance decreases rapidly due to the limitations of thermal adaptability [43]. However, due to methodological inconsistency and potential confounders, it is still difficult to drive a generalized relationship between indoor temperature and cognitive performance [38]. Some studies (Ref. [28,44]) reviewed the previous publications and carried out a meta-analysis of their findings, in order to develop a synthesized function that considers various findings within a specific temperature range. Despite these efforts, limitations still exist and further research is needed to fully understand the complex relationship between indoor temperature and cognitive performance.

2.2. Cognitive performance and ventilation rate

In addition to indoor temperature, ventilation rate is also an important factor that affects the cognitive performance of children [9,38,45]. Past research suggests low ventilation rate in classrooms is associated with higher levels of air pollutants and poor Indoor Air Quality (IAQ), which can negatively impact children's attention, vigilance and memory [2,46–48]. Two studies [49,50] investigated the effect of IAQ and ventilation rates on children's performance in the UK schools. In these studies, children participated in cognitive tests in their classrooms and CO2 levels (as an indicator of ventilation) were monitored by using in-situ direct measurements. The study findings show that a high level of CO2 adversely affects learning performance. When raising ventilation rates from 1 l/s per person to about 8 l/s per person, the surveyed students showed significantly faster and more accurate responses for cognitive tests. It is noted that the main effect of ventilation rate on cognitive performance is usually examined in temperature-controlled indoor spaces in previous studies, for the purpose of isolating the influence of ventilation from temperature effects. In real-world environment, ventilation may affect children's performance by altering the thermal environment, as especially in free-running schools where introducing outdoor air may have a noticeable effect on indoor temperatures.

3. Methodology

To quantify the impact of climate change on the cognitive performance of children across English school stock, we first developed and selected school stock models to be simulated (Section 3.1). Then we utilized weather files developed by the Chartered Institution of Building Services Engineers (CIBSE) as inputs for dynamic simulation (Section 3.2). Then assumptions were made regarding the non-geometric parameters of the school building models (Section 3.3). To calculate cognitive performance from the dynamic simulation results, we employed an appropriate function established from previous research (Section 3.4). The workflow of the methodology is also presented in Fig. 1.

3.1. School model development

The school building models used in this study were developed based on a novel stock-modelling framework - Data-Driven Engine for Archetype Models of Schools (DREAMS). Readers can refer to Schwartz et al. [51] for the detailed workflow of model development). Briefly, DREAMS utilized PDSP data from the Property Data Survey Programme (PDSP) and Display Energy Certificate (DEC) to acquire information on the thermal characteristics of school buildings. Based on the initial data analysis, a set of 'seed' models was then developed. These are thermal models representing schools built in five construction ages based on the PDSP record: pre-1919, inter-war, 1945–1966, 1967–1976, post-1976. Each construction age was associated with a typical school's built form and typical building fabric characteristics. The thermal properties of the seed models have been stored in the form of Energyplus Input Data Files (*. idf). By considering different construction types (single- or multi-block school), the internal environment (natural or mechanical ventilation) and climate regions, the school stocks were classified into

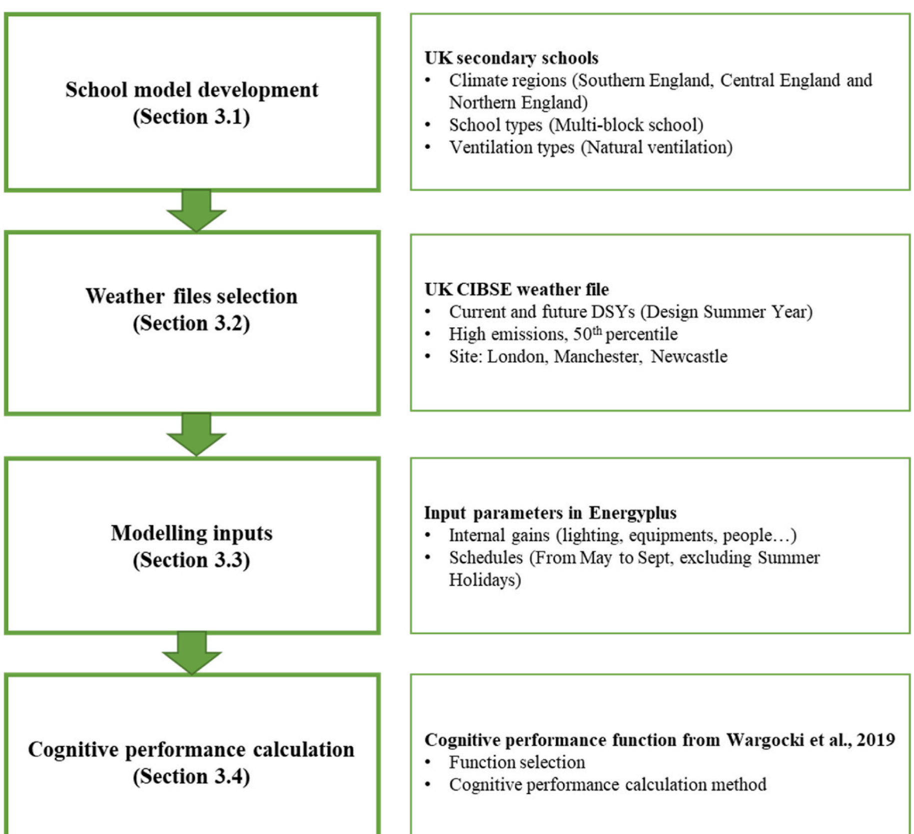

Fig. 1. An overview of the study design.

different archetypes (Fig. 2). A Python script was developed to automatically read the 'seed' models and modify the relevant inputs to generate archetype models (Fig. 3), which represent the unique characteristics of each school archetype.

Using the DREAMS framework, this study focused on secondary schools across England. The climate regions in the UK are based on the Heating Degree-Day (HDD) regions defined in the Chartered Institution of Building Services Engineers (CIBSE) methodology (See Figure A1 in the Appendix) [52]. In this study, England was divided into three major climate regions and in each major region, the schools located in one climate region were selected as representatives, namely:

(1) Southern England (HDD18 °C < 2000), represented by Thames Valley climate region.
(2) Central England (2000 < HDD18 °C < 2200), represented by West Pennines climate region.
(3) Northern England (HDD18 °C > 2200), represented by Borders climate region.

In each region, only the schools with multiple blocks and those that are naturally ventilated were modelled, simulated and analyzed, as they account for the largest proportion of secondary school types surveyed in PDSP (95%). Schools with multiple blocks have two building entities: a main building, representing the largest building in a school, and an additional building, representing an aggregation of the floor area of the rest of the buildings in the school.

The simulated results generated by the school archetype models have been validated against measured energy data [51], exhibiting deviations in the range of 4–12% for different construction ages of schools. The accuracy of the models' predictions for indoor temperature and IAQ has also been confirmed in Grassie et al. [53]. These validation efforts serve as crucial evidence supporting the robustness and reliability of the school models.

The schools within built each construction age share the same main built-up characteristics among three regions as shown in Table 1. The average floor area, numbers of floors and % of windows and doors of regional-specific school archetypes are shown in Table 2.

3.2. Weather files

Climate data is the key input for assessing building performance by dynamic simulation. The weather files chosen for this study were derived from CIBSE weather data sets, which are the standardized weather data in the building industry in the UK. The CIBSE published Test Reference Years (TRYs) and Design Summer Years (DSYs) weather data periodically for 13 sites within England and Wales [54]. Current TRYs and DSYs were developed based on historic weather records from 1984 to 2013. UK CIBSE is also in collaboration with UK Climate Impacts Programme (UKCIP) to provide future TRYs and DSYs for three climate periods (2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100)).

In this study, DSY was selected to represent a year with warm but not extreme summer, as it is typically used for modelling the risks of climate change in indoor environment. The current and future DSYs of three sites: London, Manchester and Newcastle were chosen as representatives of Southern, Central and Northern England. It is noted that current DSYs were used in this study as the baseline weather conditions. 2020s DSYs were considered as the future projections despite being in 2023 at the time of writing, because the future weather files encompass uncertainties in the climate projection models. The uncertainties of future DSYs for each climatic period are represented by three carbon emissions scenarios (Low, Medium, High) and three percentiles (10th,50th,90th) [55]. This study adopted the strategy suggested in Ref. [56] to select weather files for future-proofing buildings against climate change. Hence, High emission scenarios and the 50th percentile (central estimate) were selected.

3.3. Modelling inputs

Hour-by-hour multi-zone simulations of school archetype models were conducted in EnergyPlus v8.9. Key input parameters were determined as follows (Table 3).

(1) The classrooms are occupied by children from 9am to 4pm (excluding 12am-1pm as lunch break), Monday to Friday; The school days between May and September follow the typical UK school calendar [57].
(2) The internal load from people, lights and equipment was assumed as per 2018 version BB101 Building Bulletin 101 (Guidelines on ventilation, thermal comfort, and indoor air quality in schools) [58].
(3) For the purpose of suggesting criteria for school building standards, this study assumed fixed air change rates of 5l/s-person for each school model during school hours (equivalent to daily average of 1500 ppm CO_2, which is the minimum requirement in naturally ventilated schools specified in BB101 [58]).

3.4. Cognitive performance calculation

To quantify the impact of climate change on cognitive performance of children in their classrooms, it is important to establish a suitable cognitive performance function that can calculate the cognitive performance level based on simulated indoor temperatures from Energyplus. In this study, the cognitive performance function was derived from a meta-analysis study by Ref. [28]. The meta-analysis included the findings of 10 field or laboratory studies that investigated primary and secondary school children in temperate climates. These studies provided measured data on the relationship between indoor temperature and cognitive performance. The individual findings from these studies were then used to fit a linear regression function that describes the quantitative relationship between indoor temperature and cognitive performance. The cognitive performance function can be expressed as follows:

$$RP_t = 0.2269\,t^2 - 13.441\,t + 277.84 \tag{1}$$

Where t represents the indoor temperature, and RP_t represents relative performance at a specific temperature. According to Wargocki et al.

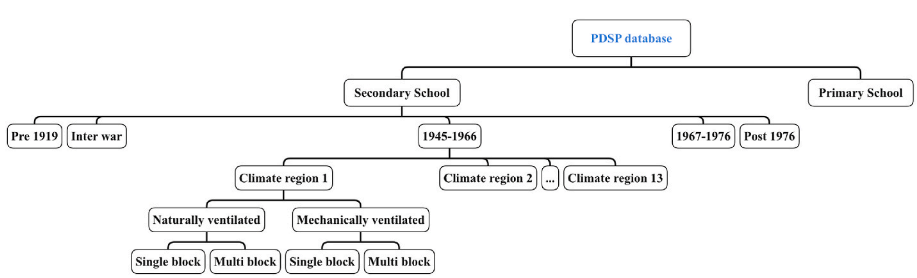

Fig. 2. The classification of school archetypes.

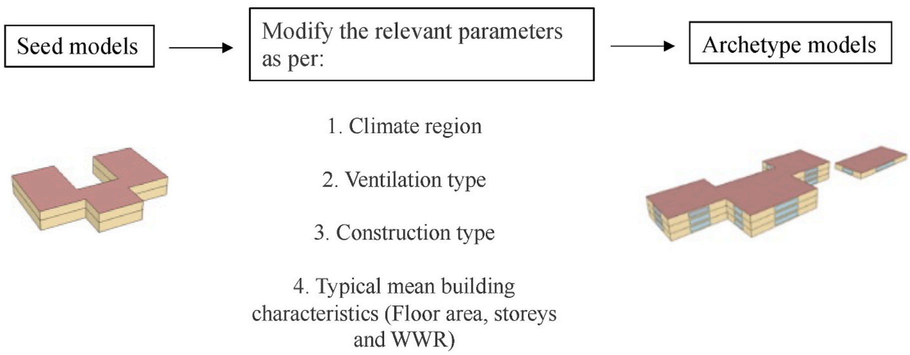

Fig. 3. The school archetype models developed from the 'seed' models.

Table 1
The build-up characteristics of school archetype models.

Construction age	U-value of Ground floor (W/m^2-K)	U-value of External floor (W/m^2-K)	U-value of Roof (W/m^2-K)	U-value of Windows (W/m^2-K)	Other characteristics
Pre-1919	1.5	1.9	3.0	5.7	The original building has an attic space with tiled roof
Inter-war	1.5	1.9	3.0	5.7	The original building has an attic space with tiled roof
1945–1966	1.4	1.8	2.0	5.7	
1967–1976	1.4	1.0	1.3	5.7	
Post 1976	0.82	0.85	0.63	5.7	

[28], Equation (1) is valid between 20 °C and 28 °C and is only applicable to children between 9 and 18 years old. The performance at the temperature of 20 °C was used as a reference, and performance at that temperature was set to 100% based on Wargocki and Wyon [2]. For any temperature higher than 20 °C, the variation in performance is calculated using the relationship described by Equation (1). However, due to a lack of empirical evidence, it is assumed that cognitive performance remains at 100% for temperatures below 20 °C. Wargocki et al., also suggested that performance does not further reduce at temperatures exceeding 28 °C. Consequently, cognitive performance at temperatures above 28 °C is considered to be the same as the cognitive performance at 28 °C in this study.

Additionally, Cognitive Performance Loss (CPL) serve as the KPI to assess the negative impact of warming climate on cognitive performance, which is calculated by Equation (2):

$$CPLt = 100\% - RPt \tag{2}$$

CPLt represents the difference between the reference performance level (100%) and the cognitive performance level calculated by Equation (1).

4. Results

In the result section, we start by exploring the effects of both current and future climates on school archetypes, aiming to understand how changing climate affects the cognitive performance of children in their schools. We first examine the impacts of current climate on school archetypes (Section 4.1), and shift our focus to the impact of future climate on school archetypes (Section 4.2), Then, we investigate the adaptation

Table 3
Modelling parameters assumed in Energyplus models.

Parameters	Schedule/Value	
Occupancy	09:00–16:00 0.58ppl/m^2	Set to 0 during lunch hour
Lighting	09:00–16:00 7.2W/m^2	
Equipment	09:00–16:00 10W/m^2	
Ventilation rate	09:00–16:00 5l/s-person	

Table 2
The average floor area, numbers of floors and % of windows and doors of regional-specific school archetypes.

Construction age	Number of schools	Main buildings			Additional buildings		
		Floor area (m^2)	Number of floors	% of windows and doors	Floor area (m^2)	Number of floors	% of windows and doors
Thames Valley (N = 1760)							
Pre-1919	443	2963	3	25	3157	3	35
Inter-war	207	3757	2	29	2729	3	40
1945–1966	427	4750	2	28	2412	2	35
1967–1976	445	4148	3	25	3163	2	28
Post 1976	238	6212	2	28	1291	2	28
West Pennines (N = 1498)							
Pre-1919	353	2675	2	25	4019	2	34
Inter-war	121	5338	2	25	1756	2	31
1945–1966	302	6028	2	25	1843	2	26
1967–1976	494	5465	2	26	2171	2	27
Post 1976	228	5522	2	35	1511	2	23
Borders (N = 121)							
Pre-1919	26	2496	3	30	1041	2	23
Inter-war	11	2878	2	27	2146	2	22
1945–1966	36	3960	2	29	768	2	23
1967–1976	40	3281	2	25	363	1	18
Post 1976	8	6080	3	15	2484	2	23

strategies for mitigating the climate change impact on schools, including ventilative cooling (Section 4.3) and air conditioning (Section 4.4.1). The combined effects of these two strategies on schools are also explored (Section 4.4.2).

4.1. The impact of current climates on school archetypes

The cognitive performance loss of children during non-heating school days in current climate scenarios was investigated. Table 4, Table 5 and Table 6 show the median and interquartile of hourly CPLs of children on different floors of school buildings in Southern England, Central and Northern England.

The results indicate that the schools in the warmer climate (London) experience CPLs with medians ranging between 19.6% and 20.4% during non-heating school days, which is generally higher than those in the cooler climates (Manchester and Newcastle). For schools in Southern England, the median CPLs on the top floors are generally higher than or equal to that on the lower floors, which may be explained by the heat from the lower floors rising to the top floors. For schools in Central England and Northern England, different phenomena were observed in the building built in different construction ages. Specifically, the median and interquartile CPLs on the top floor are lower in the original buildings in pre-1919 and inter-war schools. This is because the exclusion of summer holidays results in relatively lower outdoor temperatures during the remaining periods of non-heating seasons (See Table A1 in the Appendix). For these two schools, the top floors, with their poorly insulated attics, experience significant heat loss during this period, leading to lower indoor temperatures and therefore better cognitive performance. As the top floors of these buildings have poorly insulated attic, large amounts of heat loss from the roof lead to lower indoor temperature and therefore better cognitive performance. In 1945–1966, 1967–1976, and post-1976 schools, the median and interquartile CPLs on the top floors are higher, as their relatively good thermal roof insulation leads to lower heat loss from the roof.

We also conducted a significant difference test (Kruskal-Wallis test) on the CPL distribution on different floors in each school (Table 7). The results show even though there exist differences in CPLs between floors within a school, they do not reach a statistically significant value ($P \geq 0.05$). Therefore, during the non-heating school days, the impact of an outdoor climate on CPLs for each school archetype is similar regardless of the school's floor.

4.2. The impact of future climates on school archetypes

Fig. 4 illustrates the distribution of hourly CPLs of children in each school archetype in current and future DSYs. The hourly CPLs of each school was calculated by averaging hourly CPLs of every floor within a school. The four boxplots of each archetype become successively flatter, and the median lines become higher as it progresses from 'current' to '2080s', which demonstrates that overall CPL will increase over the 21st century in all archetypes. In Southern England schools, most values of hourly CPLs in 2080s are close to the upper limit, indicating that in 2080s, children will suffer from 20.6% CPLs in most hours during the non-heating school days. Children in Central and Northern England schools have relatively better cognitive performance in 2020s while they will be more significantly reduced by future climatic conditions.

Kruskal-Wallis test was also conducted for the school archetypes in each region in current and three future climatic periods, and the P-values are shown in Table 8. The testing result shows different school archetypes at each region do not reach significant differences in CPLs in all DSYs (P value > 0.05), which means construction age may not be the main predictor for CPL of children in schools.

The overall CPLs of children by climate regions were explored by aggregating the hourly CPLs of five school archetypes in each region. To be more specific, there are 5 school archetypes in each region, and the study calculated hourly CPL for a total of 528 h. Therefore, there are

Table 4
Median and interquartile of hourly CPLs (%) in Southern England schools during non-heating school days.

	Pre-1919			Inter-war			1945–1966			1967–1976			Post 1976		
	Floor	Median	Inter- quartile	Floor	Median	Inter- quartile	Floor	Median	Inter- quartile	Floor	Median	Inter- quartile	Floor	Median	Inter- quartile
ORI	Ground	19.4	15.6–20.6	Ground	19.4	15.7–20.6	Ground	19.5	15.9–20.6	Ground	19.7	16.0–20.6	Ground	19.7	16.5–20.6
	1st	20.0	16.5–20.6	Top	20.3	16.1–20.6	Top	20.6	17.5–20.6	1st	20.3	16.7–20.6	Top	20.3	16.9–20.6
	Top	20.3	16.1–20.6							Top	20.6	17.3–20.6			
ADD	Ground	19.8	16.1–20.6	Ground	20.0	16.5–20.6	Ground	19.8	16.3–20.6	Ground	19.6	16.1–20.6	Ground	20.1	16.9–20.6
	1st	20.5	17.1–20.6	1st	20.6	17.6–20.6	Top	20.6	17.8–20.6	Top	20.6	17.2–20.6	Top	20.6	17.4–20.6
	Top	20.6	18.1–20.6	Top	20.6	18.5–20.6									

Table 5
Median and interquartile of hourly CPLs (%) in Central England schools during non-heating school days.

	Pre-1919			Inter-war			1945–1966			1967–1976			Post 1976		
	Floor	Median	Inter- quartile	Floor	Median	Inter- quartile	Floor	Median	Inter-quartile	Floor	Median	Inter-quartile	Floor	Median	Inter-quartile
ORI	Ground	13.6	9.3–17.1	Ground	13.5	9.4–16.7	Ground	13.6	9.5–17.2	Ground	14.1	9.8–17.7	Ground	14.7	10.5–18.1
	Top	12.8	7.0–17.4	Top	12.7	7.2–17.2	Top	14.2	9.4–18.5	Top	14.4	9.5–18.5	Top	15.1	10.3–18.7
ADD	Ground	14.0	9.8–17.5	Ground	14.2	9.8–17.7	Ground	14.0	9.6–17.4	Ground	14.4	10.0–17.9	Ground	14.2	9.8–17.8
	Top	15.3	10.1–19.5	Top	15.3	9.9–19.6	Top	14.3	9.4–18.6	Top	14.5	9.7–18.6	Top	14.6	9.6–18.4

Table 6
Median and interquartile of hourly CPLs (%) in Northern England schools during non-heating school days.

	Pre-1919			Inter-war			1945–1966			1967–1976			Post 1976		
	Floor	Median	Inter-quartile	Floor	Median	Inter- quartile	Floor	Median	Inter-quartile	Floor	Median	Inter-quartile	Floor	Median	Inter-quartile
ORI	Ground	11.9	6.4–15.6	Ground	11.9	6.6–15.4	Ground	12.0	6.7–15.6	Ground	12.3	6.6–16.0	Ground	11.4	5.9–15.1
	1st	12.4	6.1–16.4	Top	11.2	5.2–15.7	Top	12.5	6.8–17.1	Top	12.4	6.5–16.9	1st	11.5	5.4–15.6
	Top	11.3	4.9–16.0										Top	11.8	5.8–16.0
ADD	Ground	11.8	6.4–15.6	Ground	11.6	6.4–15.3	Ground	11.9	6.4–15.7	Ground	12.0	6.4–16.5	Ground	12.1	6.7–15.7
	Top	12.8	6.5–17.9	Top	13.0	6.6–17.8	Top	12.2	6.2–17.0				Top	12.4	6.5–16.5

Table 7
P-values of K–W test for each school by floors.

Region	Construction age				
	Pre-1919	Inter-war	1945–1966	1967–1976	Post 1976
Southern England (London)	0.18	0.12	0.95	0.97	0.92
Central England (Manchester)	0.13	0.06	0.74	0.47	0.48
(Northern England) Newcastle	0.08	0.05	0.94	0.81	0.43

528*5 h to be aggregated. Since there are no regulations or guidelines that categorie the levels of CPLs, a categorisation was proposed to better compare and visualise the overall CPLs in the following analyses, as shown in the following.

(1) No loss: when the hourly cognitive performance loss is equal to 0%.
(2) No significant loss: when the hourly cognitive performance loss is between 0% and 5%.
(3) Moderate loss: when hourly cognitive performance loss is between 5 and 20%.
(4) Severe loss: when hourly cognitive performance loss is above 20%.

Fig. 5 the frequency distributions of all school hours in the three regions in current and future climates. The results indicate that outdoor climates have different impacts on schools at the regional level. Schools in Southern England have minimal hours categorized as 'no loss' and 'no significant loss' in current and future climates. There are around 51.0% of hours in which children experience severe CPL in current climates, and the hours categorized as 'severe loss' rise to 81.6% in 2080s climates, both of which are much higher than those in the other two regions. For Central England schools, the majority of hours (78.6%) fall under the category of 'moderate loss' in both future climatic periods. However, due to an increase in hours with severe CPLs (38.1%), the frequency of hours at 'moderate loss,' 'no significant loss,' and 'no loss' will decrease under climate change. For Northern England schools, 11.3% of hours experience 'no loss,' while only 7.5% of hours are classified as 'severe loss' in current climate. As the climate warms, the percentage of hours with 'severe loss' is projected to rise to 26.1%, while the percentages of hours categorized as 'no loss' (1.6%) and 'no significant loss' (7.7%) decrease in the 2080s.

4.3. Ventilative cooling to mitigate climate change impact

This section examines the impact of increased ventilation rates in classrooms on cognitive performance. Two ventilation rates were evaluated, in comparison with the baseline ventilation rate (5l/s-p).

(1) 8l/s-p: The ventilation rate that schools should have the capacity to reach by mechanical ventilation, in order to maintain CO2 concentrations at less than 1000 ppm or as per BB101 [58].
(2) 15l/s-p: Maximum ventilation rate that has a statistically significant effect on cognitive performance (with 95% CI) [59].

Both ventilation rates were maintained at a constant level across all school archetype models during occupancy. it is important to note that the impact of higher ventilation rates on indoor air quality was taken into account when calculating cognitive performance loss in this study. Based on the relationship between ventilation rate and cognitive performance derived from Ref. [60], the relative cognitive performance (speed) at a given ventilation rate was calculated by Equation (3):

$$RP_{IAQ} = 0.0086 * VR + 0.9368 \quad (3)$$

In Equation (3), RP_{IAQ} *is* the Relative Performance modified by the

Table 8
Results of K–W test for schools in each region in current, 2020s, 2050s and 2080s DSYs.

Region	Climatic period			
	Current	2020s	2050s	2080s
Southern England (London)	0.22	0.16	0.30	0.60
Central England (Manchester)	0.09	0.12	0.09	0.26
Northern England (Newcastle)	0.20	0.41	0.35	0.28

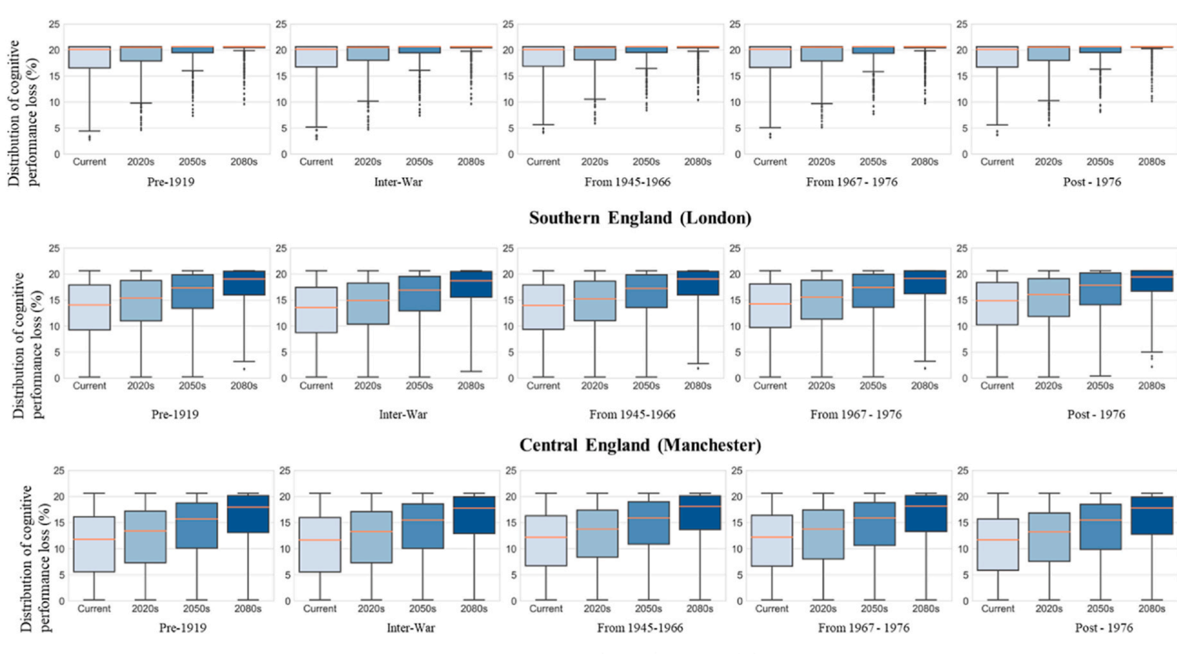

Fig. 4. Cognitive performance loss of children in school archetypes in Southern England, Central and Northern England.

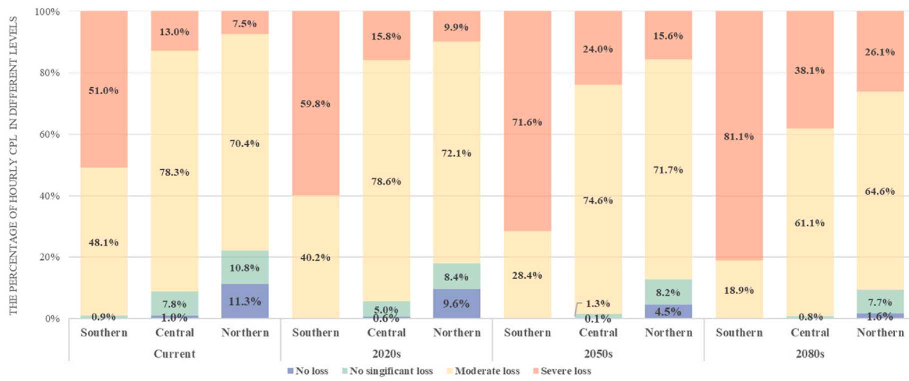

Fig. 5. The frequency distributions of hourly CPLs within different levels in English schools per region.

change in indoor air quality due to ventilation rate, and *VR* is ventilation rate. The values of RP_{IAQ} were determined to be 0.98, 1.01, and 1.07 at ventilation rates of 5, 8, and 15 l/s-p, respectively. A modifying coefficient (α) was then determined to represent the ratio between cognitive performance at the given ventilation rates (8 and 15 l/s-p) and that at 5 l/s-p. Subsequently, it was assumed that the hourly cognitive performance loss due to temperature could be adjusted using the modifying coefficient (α), as follows:

$$\mathrm{CPL}_{t+\mathrm{IAQ}} = \mathrm{CPL}_t/\alpha \tag{4}$$

In Equation (4), CPL_{t+IAQ} represents the hourly cognitive performance loss by temperature and air quality at a given ventilation rate. The coefficient α is equal to 1.03 at 8l/s-p and 1.09 at 15l/s-p.

As the regional climate is the main factor leading to CPLs difference as shown in Section 4.1, CPLs of schools for each region were aggregated and the impacts of different ventilation rates on CPLs were evaluated and compared at the regional level in subsequent analyses. Figs. 6 and 7 present the distribution of hourly CPLs within different levels in schools across all regions at ventilation rates of 8 and 15 l/s-p, respectively. Furthermore, Table 9 displays the median CPLs per region under future DSYs. Notably, all CPLs categorized as 'severe loss' will be eliminated in the future at both ventilation rates. Within each climatic period, increasing the ventilation rates has demonstrated positive impacts on schools, resulting in a higher proportion of hours with CPLs categorized as 'no loss' and 'no significant loss' at 15 l/s-p compared to 8 l/s-p. However, cognitive median CPLs at higher ventilation rates rise and the difference in median CPLs between the baseline and a higher ventilation rate diminishes across all regions over the future climatic periods. For instance, in Southern England schools, the median CPLs increase from 14.1% in 2020s to 18.0% in 2080s when the ventilation rate is set at 15 l/s-p. In Central England schools, the median CPLs rise from 1.9% to 10.0%, while in Northern England schools, they increase from 0.0% to 7.1%. This implies that in 2020s, higher ventilation rates prove to be more effective in improving cognitive performance, but their impact weakens in the 2050s and 2080s due to the rising outdoor temperatures.

4.4. *Air conditioning to mitigate climate change impact*

4.4.1. *Impact of different cooling set-point*

This section examined the potential of set-point temperature control on the cognitive performance of children by introducing air conditioning. To ensure that the classrooms remain within satisfactory levels, CIBSE Guide A recommends the summer operative temperatures in teaching space should be kept from 21 °C to 25 °C. Therefore, 21 °C and 25 °C were chosen for the analyses. The air conditioning was assumed to operate when the classroom temperature is above the set-point during the occupied hours in all schools.

The impact of different set-point temperatures on cognitive performance is illustrated in Figs. 8 and 9, while Table 10 presents the median CPLs per region. When air conditioning is introduced, setting the temperature at 25 °C eliminates CPLs categorized as 'severe loss'. However, even with this improvement, the median CPLs in all regions during future climates remain considerably high, ranging from 13.5% to 16.4%. This suggests limited enhancements in cognitive performance throughout the entire duration of non-heating school days. In addition, setting the temperature at 21 °C demonstrates a significant improvement in cognitive performance. CPLs categorized as 'moderate loss' and 'severe loss' are eliminated, resulting in an average CPL decrease to 4.4% across all regions during all future climatic periods.

Table 10 also provides insight into the corresponding cooling loads

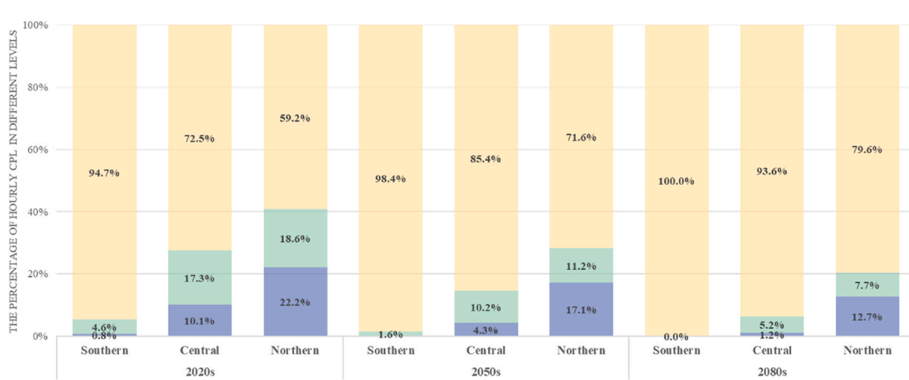

Fig. 6. The frequency distributions of hourly CPLs within different levels in English schools per region at ventilation rate of 8l/s-p.

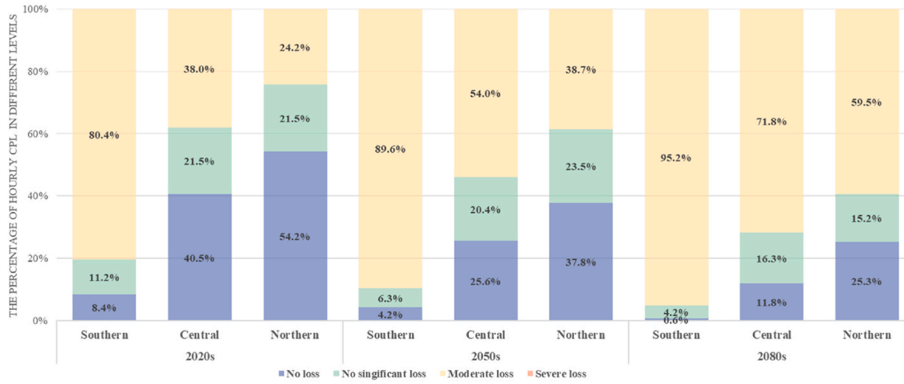

Fig. 7. The frequency distributions of hourly CPLs within different levels in English schools per region at ventilation rate of 15l/s-p.

Table 9
Median of CPL (%) in different ventilation rates per climate region.

		2020s			2050s			2080s		
		Base- line (5l/s-p)	8/s-p	15/s-p	Base- line (5l/s-p)	8/s-p	15/s-p	Base- line (5l/s-p)	8/s-p	15/s-p
Southern England (London)	**Median CPL (%)**	20.5	18.1	14.1	20.6	19.1	16.4	20.6	19.4	18.0
Central England (Manchester)	**Median CPL (%)**	15.4	9.7	1.9	17.3	12.6	5.8	19.1	15.4	10.0
Northern England (Newcastle)	**Median CPL (%)**	13.5	7.1	0.0	15.7	10.2	2.3	18.0	13.4	7.1

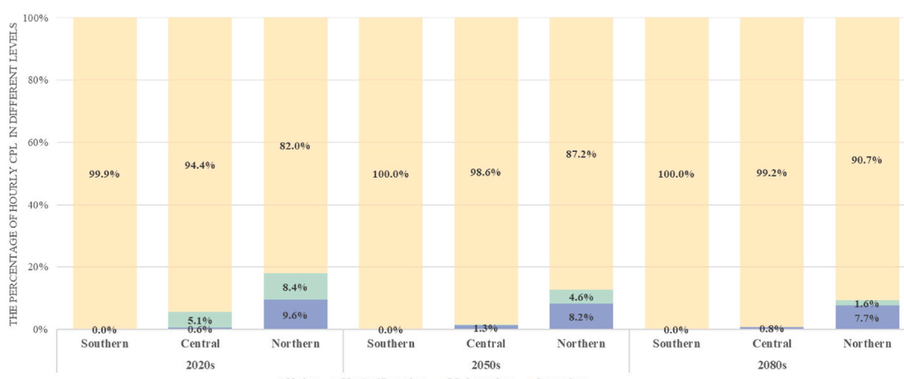

Fig. 8. The frequency distributions of hourly CPLs at different levels in England per region in current and future climates at set-point temperature of 25 °C.

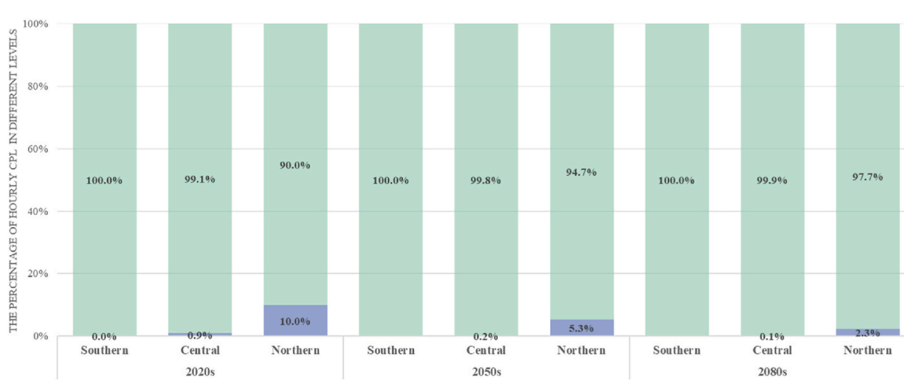

Fig. 9. The frequency distributions of hourly CPLs at different levels in England per region in current and future climates at set-point temperature of 21 °C.

of schools per region at the two set-point temperatures. The cooling load calculation weighted the total floor area of each school archetype within a region. It is expected that schools in all three regions set at 21 °C will have higher cooling loads compared to those set at 25 °C, indicating a greater demand for cooling over the future periods. The difference in cooling loads among schools in different regions is primarily influenced

Table 10
The CPL and cooling load of schools in England in changing climates per climate region.

		2020s			2050s			2080s		
		Base- line (no AC)	25 °C	21 °C	Base- line (no AC)	25 °C	21 °C	Base- line (no AC)	25 °C	21 °C
Southern England (London)	Median CPL (%)	20.5	16.4	4.4	20.6	16.4	4.4	20.6	16.4	4.4
	Cooling Load (kWh/ m^2)		19	39		25	46		33	54
Central England (Manchester)	Median CPL (%)	15.4	15.1	4.4	17.3	16.2	4.4	19.1	16.4	4.4
	Cooling Load (kWh/ m^2)		5	21		8	26		13	33
Northern England (Newcastle)	Median CPL (%)	13.5	13.5	4.4	15.7	15.5	4.4	18.0	16.4	4.4
	Cooling Load (kWh/ m^2)		3	15		5	19		9	25

by the outdoor climate. Southern England schools exhibit higher cooling loads compared to those in Central and Northern England. By the 2080s, the cooling loads are projected to reach 54 kWh/m^2 in Southern England schools and 25 kWh/m^2 in Northern England schools.

4.4.2. Increased ventilation rate in air-conditioned schools

Based on the results in Section 4.3 and 4.4.1, it can be found that a higher ventilation rate is able to improve overall cognitive performance by reducing indoor temperature and improving overall air quality for every hour, while air conditioning improves overall cognitive performance by controlling temperature and eliminating cognitive performance loss at a certain level and above. It is therefore reasonable to speculate that increased ventilation rate while air conditioner is operating may further reduce the risks of cognitive performance loss in the future.

Fig. 10 shows the impact of the increased ventilation rate (15l/s-p) on cognitive performance in air-conditioned schools. At 25 °C, increasing ventilation rate will reduce cognitive performance loss in all three regions, especially more significantly in Central England and Northern England schools. At 21 °C, an increased ventilation rate is less effective in reducing cognitive performance losses in all regions, because the average CPLs are relatively good at baseline ventilation rates.

Fig. 11 shows the impact of increased ventilation rate on cooling loads of air-conditioned schools. At 25 °C, an increased ventilation rate will reduce cooling loads due to outdoor cooler air being introduced to classrooms. At 21 °C, increasing ventilation rate will reduce cooling loads in Central and Northern England schools, while it has counter-effects on Southern England schools, which might be explained by the fact that outdoor air introduced to air-conditioned classrooms is generally warmer than indoor air, increasing the need for cooling energy.

5. Discussion

5.1. Main findings and policy implications

This study proposes an evaluation approach and KPI to investigate the climate resilience of school buildings through the lens of cognitive performance. By using cognitive performance loss (CPL) as the KPI, this study quantifies and compares the impact of climate change on English secondary school stock at different levels. The results indicate that future warming climates will significantly decrease cognitive performance of children when they are in schools during non-heating school days. Under the high emission scenario (DSY), schools in Southern England will have cognitive performance loss of more than 15% for all hours by 2050s. By 2080s, schools in all three regions in England will have very few hours of cognitive performance loss below 5%. The differences in cognitive performance among different schools are primarily due to regional climate characteristics. Outdoor climate impacts schools built in different construction ages similarly and also affects different floors within a school in a similar manner. Therefore, from the perspective of cognitive performance, the evaluation of classroom environment and climate adaptation strategies for schools can be conducted at a regional level.

This study also explores the potential of different ventilative cooling and air conditioning design parameters in enabling schools to adapt to future climates. Increasing ventilation rates in school buildings will effectively reduce the risks of cognitive performance loss of children and enhance climate resilience in the near future (2020s), while the effectiveness of higher ventilation rates decreases in the far future (2050s and 2080s) due to higher outdoor temperatures. These findings are consistent with the conclusions drawn from other studies that have examined the role of ventilative cooling in mitigating the impact of climate change on indoor environments. Hamdy et al. [22] conclude the potential of ventilative cooling on thermal comfort in Dutch housing stocks will

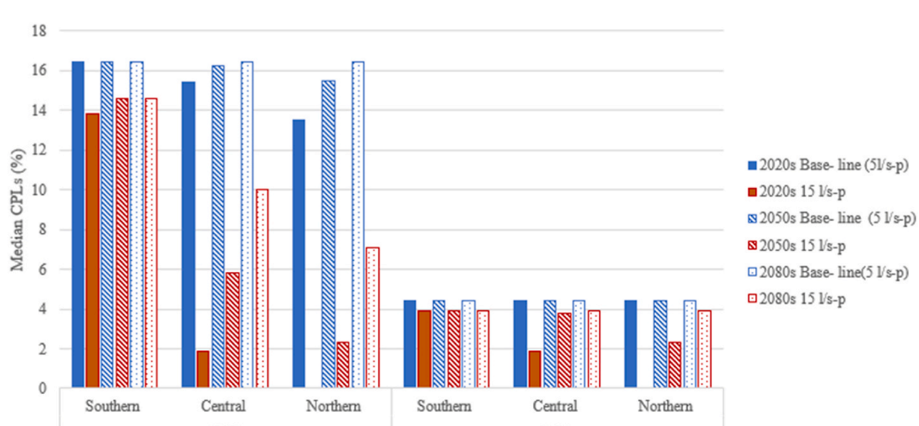

Fig. 10. The median CPLs (%) at baseline ventilation rate (5l/s-p) and 15l/s-p in air-conditioned schools in 2020s,2050 and 2080s.

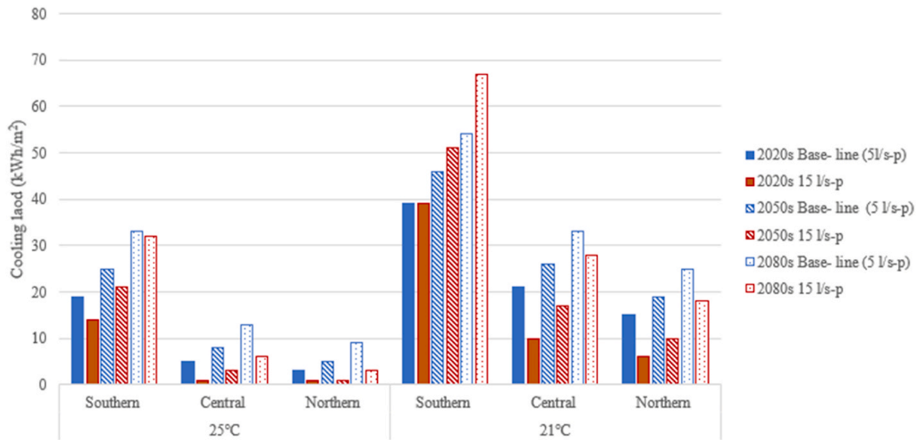

Fig. 11. The cooling load (kWh/m^2) at baseline ventilation rate (5l/s-p) and 15l/s-p in air-conditioned schools in 2020s,2050 and 2080s.

decrease until 2100. Dodoo and Gustavsson [61] point out for the time period 2090–2099, overheating still occurs for the precast-frame building in Sweden when increased ventilation rates is implemented. It is worth mentioning that his study assumes the feasibility of achieving the proposed ventilation rates in all schools. In practice, schools without mechanical ventilation may struggle to meet higher ventilation requirements (e.g., 15 l/s-p). The installation of hybrid ventilation or mechanical ventilation systems may be necessary, but the additional electricity consumption should be carefully assessed.

In 2050s and 2080s, active cooling such as air conditioning may need to be introduced to mitigate the impacts of warming climates on children. This study indicates whilst installing air-conditioners can provide benefits in terms of reducing cognitive performance loss, it will increase energy demand of schools. Moreover, the use of air conditioners will potentially impose additional environmental impacts, including greenhouse gas emissions and the UHI (Urban Heat Island) effect due to the released waste heat [62]. In addition, inadequate ventilation is often a concern in air-conditioned spaces with high occupancy density. This study suggests that increasing the ventilation rate in air-conditioned classrooms, can not only improve children's cognitive performance, but also reduce cooling energy demand in cooler climate regions such as Central and Northern England. In regions with higher outdoor temperatures such as Southern England, the use of adiabatic cooling, which increases the ventilation rate and reduces the flow temperature may be a viable solution [63]. It is important to note that the results of this study can be considered as an indicative guide of HVAC (Heating, Ventilation and Air Conditioning) designs for schools. The technological and economic feasibility of cooling systems needs to be evaluated on a case-by-case basis.

The study aims to provide quantitative insights to inform possible climate adaptation strategies for increasing climate resilience of the school building stock. Making the UK's schools stock more resilient to future climates requires the involvement of multiple stakeholders, including building experts, governments, educators, school teachers, and students. Indeed, climate resilience and adaptation have gained interest not only from building experts, but also from educationalists and policymakers in the education sector. However, stakeholders without building expertise may struggle to fully comprehend the outcomes of building performance assessments based on traditional engineering key performance indicators (e.g., indoor temperature, PMV index) and the implications of these outcomes for children's learning in the classroom [25]. Using cognitive performance loss as the KPI to describe the climate resilience of schools offers a means of using language that can be understood by non-building experts, facilitating the interpretation and communication of research findings to the intended audience. In addition to this, it may be necessary to establish benchmarks and standardized climate change risk assessment categories related to cognitive performance in schools. By categorizing schools based on their vulnerability to climate change, appropriate adaptation strategies can be developed and implemented to ensure the resilience of school buildings in the face of changing climatic conditions.

5.2. Limitations and future work

The cognitive performance function utilized in the study has certain limitations, as outlined in Wargocki et al. [28]. Specifically, the study employs temperature as a proxy for the thermal environment in establishing the relationship. Other factors such as humidity and air velocity, which are key determinants of occupant's thermal perception, are not taken into account due to data limitations. Furthermore, the function focuses solely on the relationship between temperature and cognitive performance in terms of speed, as there is insufficient data to include accuracy. It should be noted that the relationship derived by Ref. [28] is only applicable within the temperature range of 20 °C–28 °C. Therefore, further investigation is recommended to explore cognitive performance below 20 °C and above 28 °C to enhance the reliability of the results. In addition, the cognitive performance function does not account for individual difference, such as age, gender, skill level and emotional state, which may act as confounding factors mediating the effects of temperature on cognitive performance [42]. Future research could consider incorporating these factors to provide a more comprehensive understanding of the relationship.

In addition, cognitive performance was calculated based on the simulated indoor temperature on an hourly basis in this study. To provide an overview of cognitive performance over a specific time period, basic descriptive statistics such as the median and interquartile range were utilized to aggregate the hourly cognitive performance during non-heating school days. An underlying assumption is that the children's performance will change immediately with variations in indoor temperature. However, it should be acknowledged that the change in cognitive performance may not occur as frequently, as humans have the ability to adapt to thermal conditions. Moreover, these studies are typically conducted in controlled environments, and the applicability of the cognitive performance model in dynamic physical environments warrants further investigation [38]. To date, most experimental and field studies examining cognitive performance have employed a cross-sectional approach, and longitudinal studies have been recommended to better understand the association between long-term exposure to indoor temperature and cognitive performance [27].

This study also suggests that children still have cognitive performance loss in their schools over a number of hours when the indoor temperature is within the comfortable range (21 °C–25 °C). The ideal classroom environment should not impair cognitive performance while satisfying the thermal comfort of the children. An evaluation framework that takes into account both thermal comfort and cognitive performance of children is recommended for future work, so that school design requirements can be set from a more holistic view. This study considers the cognitive performance due to the change in indoor temperature and ventilation in a relatively simple way, because there is lack of empirical data on the combined effects of indoor temperature and ventilation rate on the cognitive performance of children [60]. It is worth further exploring the magnitude of improvement in cognitive performance change when classroom temperature and air quality change simultaneously. To explore such an effect, the authors found one study which investigates the combined effects of indoor temperature and air quality on university female children [64]. The influence of two or more indoor environmental variables on school children is recommended for future research.

Lastly, using building stock modelling and simulations to model cognitive performance introduces uncertainties. One uncertainty is that representative archetypes may not encompass heterogeneous school buildings stock, potentially limiting the generalizability of the findings. An ongoing research on the development of building-by-building school models can potentially account for this issue [65]. Additionally, simulation tools rely on assumptions and simplifications that may not fully replicate real-world conditions. Therefore, it is crucial to validate the cognitive performance results through field measurements in specific schools.

6. Conclusion

This study presents an evaluation approach to quantitatively assess the impact of climate change on the cognitive performance of children in their schools. The research focuses on English secondary schools and examines the cognitive performance loss of children under current and future climates. Cognitive performance loss serves as the KPI for evaluating school building stocks in different regions of England, namely Southern, Central and Northern England. The key findings of the study are as follows:

- Future climates are projected to result in increased cognitive performance loss of children in English school stocks. The impacts of outdoor climates on the school stocks vary primarily based on regional climate characteristics, as observed from the perspective of cognitive performance.
- Ventilative cooling and air conditioning can positively influence the cognitive performance of children in their schools. Increasing ventilation rates prove to be effective in reducing cognitive performance loss in the near future, although their effectiveness diminishes in the far future. Introducing air conditioning becomes more beneficial in the far future, despite the associated increase in cooling energy demand.
- Increased ventilation rates in air-conditioned classrooms have greater positive impacts on cognitive performance of children. This strategy also helps reduce cooling loads in Central and Northern England schools, while leading to increased cooling loads in Southern England schools.

The study aims to provide quantitative insights for informing climate adaptation strategies to enhance the climate resilience of the school building stock in England. Given that adapting schools to future climates requires the involvement of governments and experts from education sector, the use of cognitive performance loss as a key performance indicator (KPI) allows for better communication and understanding of climate change risks faced by schools among building and non-building experts. However, it is important to note that the consensus regarding the relationship between cognitive performance and indoor environmental parameters is yet to be reached among psychological studies. Therefore, the research outcomes presented in this study demonstrate a theoretical trend of future climate impacts and require further validation through empirical data. The proposed evaluation approach can be continuously updated and enhanced as new psychological research emerges, leading to more realistic and robust results.

CRediT authorship contribution statement

Jie Dong: Writing – original draft, Visualization, Methodology, Conceptualization. **Yair Schwartz:** Writing – review & editing, Supervision. **Ivan Korolija:** Writing – review & editing, Supervision. **Dejan Mumovic:** Writing – review & editing, Supervision.

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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Appendix

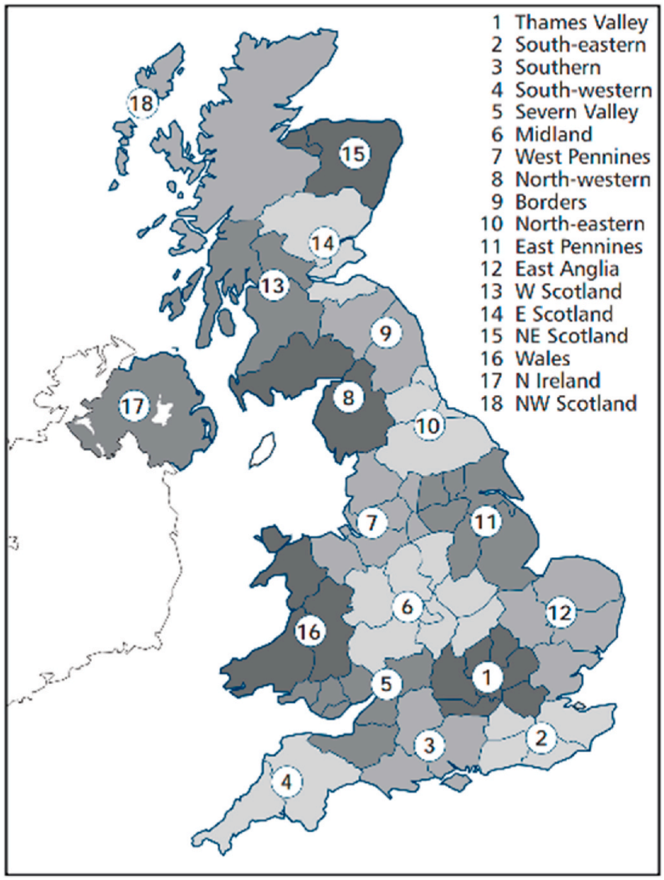

Fig. A1. UK climate regions based on Heating Degree-Day (HDD).

Table A1
The mean outdoor temperature during school hours in non-heating school days

	May	June	July	Sep	Non-heating school days
Southern England (London)	18.8 °C	19.7 °C	23.2 °C	19.0 °C	20.0 °C
Central England (Manchester)	14.2 °C	14.5 °C	18.9 °C	14.8 °C	15.4 °C
Northern England (Newcastle)	9.0 °C	15.0 °C	17.1 °C	13.9 °C	13.5 °C

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