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Unintended consequences of English school stock energy-efficient retrofit on cognitive performance of children under climate change

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A B S T R A C T

School building stock retrofit forms a key part of UK's commitment to net-zero carbon target by 2050. However, with a changing climate, the retrofit of school buildings may have unintended consequences on classroom thermal environments and cognitive performance of children in non-heating seasons. This paper aims to quantify the impact of school stock retrofit in accordance with increasingly tightening energy efficiency regulatory requirements on cognitive performance of English children, while also exploring the potential adaptation measures under climate change. The results indicate that English schools that undergo envelope insulation exhibit higher Cognitive Performance Loss (CPL) of children compared to their original conditions. Passive climate adaptation measures, especially increased daytime ventilation rate was found to be an effective strategy for mitigating the impact of climate change on cognitive performance. However, the benefits of passive measures will diminish as the climate warms, while air conditioning will be required to maintain cognitive performance loss at relatively low levels. In addition to the reduction of heating load, envelope insulation can provide benefits for English schools in cooler climatic regions from both cognitive performance and energy point of view. The study calls for the CPL to be added as one of the key performance indicators when considering the long-term impact of climate change on schools. This would enable policy makers and relevant stakeholders to make more holistic decisions regarding school stock retrofit while ensuring that classrooms are conducive to learning.

1. Introduction

In England, there are around 83 % of schools constructed before energy-saving policies were introduced in 1976 [1]. As a result, a large number of these older school buildings are likely to undergo energy efficiency retrofit. Compared to retrofitting of individual buildings, planning school building retrofit at the stock level is a more challenging task, because the English school building stock is characterised by diverse geometries, construction characteristics and climate contexts [2]. In addition, there are many other challenges facing school building stock retrofit, including the impact of climate change, the energy efficiency regulatory requirements, and the consideration of children's cognitive performance.

1.1. Climate change

Climate change has led to widespread warming across the UK. Given the projected increase in temperatures across all UK regions, hot summers are expected to become more common, with the possibility increasing further to around 50–60 % by mid-century [3]. This poses greater challenges on thermal conditions of English school buildings, especially considering that most of them are free running during non-heating seasons [4,5]. Indoor overheating may occur if classrooms experience prolonged high indoor temperature, which can have detrimental effects on the health, comfort, and well-being of children [6].

In recent years, the concept of 'climate resilience' has been introduced into building performance evaluation [7]. Though there is no consistent definition in the literature, climate resilience of buildings generally refers to buildings' capability to resist extreme weather and hazardous events in the short and long term [8]. For school buildings, climate resilience is closely linked to providing healthy and comfortable classrooms that foster effective learning. A common method for evaluating a building's climate resilience involves simulating its performance under present and future climatic conditions using building modelling and simulation [9].

For existing buildings, there are two types of approaches which might affect their climate resilience [10].

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Abbreviations

KPI	Key Performance Indicator
CPL:	Cognitive Performance Loss
PDSP	Property Data Survey Programme
DEC	Display Energy Certificate
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
HDD	Heating Degree-Days
CIBSE	Chartered Institution of Building Services Engineering
TRY	Test Reference Year
DSY	Design Summer Year
HVAC	Heating, Ventilation, and Air Conditioning

Nomenclature

RPt	Relative performance in relation to change in indoor air temperature
CPLt	Cognitive performance loss in relation to change in indoor air temperature
RP_{IAQ}	Relative performance in relation to change inindoor air temperature
CPL_{IAQ}:	Cognitive performance loss in relation to indoor air temperature and air quality at a given ventilation rate

a. *Climate mitigation:* refers to strategies and actions taken to reduce emissions by energy efficiency design and operation. Typical mitigation measures include envelope insulation, LED lighting, energy-efficient appliances, and high-performance HVAC systems.
b. C*limate adaptation:* focuses on effectively coping with the impacts of climate changes that are already occurring. Typical adaptation measures include natural ventilation, solar shading, and green roofs [11].

As adaptation gradually becomes as important as mitigation, it is necessary to consider the synergistic relationship between adaptation and mitigation measures in designing and retrofitting climate resilient school buildings.

1.2. Energy efficiency regulatory requirements

The UK has set ambitious targets to achieve net-zero greenhouse gas emissions by 2050 in response to climate change [12]. To support this goal, energy efficiency regulations such as Approved Document L2 (Part L) have been launched by the UK government to encourage the building sector to strive for lower emissions [13]. The latest version of Part L (2021 edition) has set higher performance targets, aiming for reducing CO_2 emissions by 27 % for dwellings and 31 % for non-dwelling buildings. This results in increasingly tightening energy efficiency regulatory requirements, including lower U-values for building envelopes and higher system efficiency.

School buildings are responsible for approximately 2 % of total energy consumption and contribute to 15 % of the UK's public sector carbon emissions [14]. In addition, the energy costs of UK schools contribute to a large proportion of government expenditure. The average energy bills are £31,000 for primary schools and £90,000 for secondary schools [15]. Thus, energy efficiency retrofit of the school buildings offers the opportunities to reduce a significant amount of energy use, associated GHG emissions and energy expenditure for schools and the whole country [16].

The introduction of the new version Part L has driven envelope upgrades of existing buildings, which involve highly insulated and airtight building envelopes. As they are cost-effective, envelope insulation is being widely adopted in school building retrofit across European countries [17]. In temperate climate countries such as the UK, due to long heating seasons, envelope insulation mainly aims to reduce heating energy demand, while it may lead to unintended consequences, either positive or negative effects on buildings. In some cases, envelope insulation has positive impacts on Indoor Environmental Quality (IEQ) of buildings throughout the year. Specifically, they can retain heat indoors by minimising heat loss during heating seasons and minimise heat gains to improve indoor thermal conditions during non-heating seasons [18,19]. In other cases, however, such measures may yield negative unintended consequences during non-heating seasons, such as overheating [20]. These phenomena have been observed in the case of dwellings, while the impact of envelope insulation on the classroom environment of English school buildings has not been fully understood. Some studies highlight that in the school settings, minimising negative impacts of the classroom environment on children should be treated equally with energy efficiency or even prioritised [21,22]. As the evaluation of building regulations and guidelines typical requires building performance assessment at the stock level [23–25], it is important to understand the unintended consequences of energy efficiency retrofit for the school stock, which will better inform ongoing updates to the regulations and guidelines.

1.3. Cognitive performance

As children in the UK spend approximately 70 % of their daily time in classrooms [26], the quality of the classroom environment has a profound impact on them. Poor IEQ can cause discomfort, illness and distraction, which lead to decreased learning performance [14,78]. Some previous studies rely on test scores in an attempt to understand the effects of classroom environments on children's learning performance [27–29], since test scores are traditionally used to evaluate the quality of school teaching and the academic progress of children [30]. However, educationists are now recognising that cognitive ability is a more accurate predictor of children's long-term success [31]. Consequently, cultivating cognitive ability has become a new educational priority. In light of this, understanding the relationship between cognitive performance and the indoor environment has become a prominent research interest in the field of built environment [32].

Many studies have found excessively high indoor temperature can detrimentally affect the cognitive performance of children [21,33,34]. With outdoor average temperature rising due to climate change, there is a growing concern that the prolonged exposure to poor thermal conditions may have adverse, long-term consequences for the cognitive performance of children [5]. Moreover, in cases where school buildings undergo retrofit measures aimed at enhancing the thermal performance of their envelopes, unintended consequences may emerge. By reducing heat transfer to the outside, there is a risk of intensifying overheating during the summer, especially in English schools that mostly rely on natural ventilation for cooling. Therefore, school building retrofit in England should ideally not only aim to meet the requirements of Part L, but also minimise the cognitive performance loss of children.

Several experimental studies have investigated the impact of thermal conditions on cognitive performance of children in well-controlled environments [33,35]. However, these studies are context specific and focus on the children's short-term exposure to indoor environment, while all children in England may experience cognitive performance loss in their classroom throughout the non-heating seasons in the future [36]. In this case, a modelling study might be an alternative approach to understanding the impact on long-term exposure to indoor environment on all English children. However, there are no regulatory documents that specify cognitive performance evaluation methods and metrics that benchmark and capture cognitive performance of occupants, developing and applying cognitive performance of children as a KPI is the core of cognitive performance evaluation in educational buildings. Therefore, integrating such KPI into building stock modelling is useful to understand the energy-efficient retrofit impacts on cognitive performance of children throughout non-heating seasons, under the context of climate change.

1.4. Aim and objectives

By employing cognitive performance loss as the KPI, this study aims to explore the unintended consequences of school building stock retrofit on the cognitive performance of children under climate change. Based on the aim, this study will address the research questions shown as follows:

1) Does envelope insulation driven by Part L improve or degrade the cognitive performance of children in English schools?
2) To what extent do passive climate adaptation strategies minimise cognitive performance loss in retrofitted schools under climate change?
3) To what extent does air conditioning minimise cognitive performance loss under changing climates, and what would be the implication on energy demand?
4) To what extent does envelope insulation impact energy demand and cognitive performance in air-conditioned schools?

2. Literature review

Prior studies have been conducted to examine the effectiveness of different retrofit measures and their impact on the performance of school buildings (Table 1). These studies propose retrofit scenarios or measures for individual buildings or building stocks and assess their impact from different aspects.

The existing literature on studying school building retrofit can be divided into three categories:

1) **Performance of zero/low carbon schools:** This category explores the energy performance and indoor of zero/low carbon buildings. Kolokotsa et al. [37], for instance, examined the building performance of a zero-carbon school in Greece. In this study, a zero-carbon school model was evaluated and compared with a benchmark model developed based on national building code in terms of energy consumption and indoor environment. Jenkins et al. [4] simulated overheating risks in two low-carbon schools in the UK under future climate scenarios. The study also explored the effects of shading and increased ventilation on reducing indoor temperature and discomfort hours in these schools.
2) **Energy-efficiency of retrofit measures:** The second category involves the impact of retrofit measures on the energy efficiency of school buildings. These measures are typically grouped into envelope upgrade (walls, roofs or opening), system upgrade and the application of renewables. Two primary approaches are employed to evaluate potential retrofit measures: The first, known as the simple method, assumes each retrofit measure is associated with a typical parameter. The proposed measures are usually examined individually while keeping the others unchanged, and their cumulative effects may also be assessed. For example, Alfaris et al. [41] examined the impact of energy-saving renovation plans on a girls' school in hot climates. The study recommends the measures to enhance the efficiency of air conditioning and lighting systems and assess their impacts on the school's energy use. Tahsildoost & Zomorodian [40] evaluated different retrofit measures for two schools in Iran, combining energy modelling with economic analysis to prioritize retrofit options. Bull et al. [39] presented a life cycle carbon and life cycle cost assessment of energy efficient retrofit measures. The measures applied to the building envelope and heating system were evaluated for four representative schools built in the UK. The second method, known as parametric method, proposes measures with a set

Table 1
Studies on evaluating the impacts of retrofit on school buildings.

	Locations	Scales	Research theme	Research method	KPIs for retrofit analysis
Jenkins et al. (2009) [4]	UK	A primary and a secondary school	Performance of zero/ low carbon schools	The effect of retrofit measures for reducing indoor temperature in different parts of the UK	Indoor temperature & discomfort hours
Dascalaki et al. (2011) [37]	Greece	A school	Energy-efficiency of retrofit measures	A holistic approach to in situ investigation of IEQ, energy audit and assessment of various measures were proposed	Primary energy consumption and CO2 emissions, related payback periods
Dimoudi (2012) [38]	Greece	School stock	Energy-efficiency of retrofit measures	Retrofit measures for reducing total energy consumption were evaluated	Heating & Cooling energy consumption
Bull et al. (2014) [39]	UK	School stock	Energy-efficiency of retrofit measures	A life cycle carbon and life cycle cost assessment of retrofit measures to the building envelope and heating system was presented	Net present value, net carbon saved and payback period
Tahsildoost & Zomorodian (2015) [40]	Tehran, Iran	School stock (represented by two typical schools)	Energy-efficiency of retrofit measures	The best retrofit options for buildings of different constructions are identified by considering energy, ecological and economic efficiency	Primary energy & Payback period
Alfaris et al (2016) [41]	Dubai, UAE	A girls' school	Energy-efficiency of retrofit measures	Several plans for improving the energy efficiency under hot climate conditions were proposed	EUI (Energy Use Intensity), CO2 emissions
Kolokotsa et al. (2019) [42]	Greece	A school	Performance of zero/ low carbon schools	The design and technologies of a zero energy schools were evaluated	Heating and cooling loads & thermal comfort
Moazzen et al. (2020) [43]	Turkey	Primary school	Trade-off between energy efficiency and resilience	A multi-parameter method to determine applicable retrofit scenarios was established	Primary energy, global cost, CO2 emission, Payback period & PMV/PPD
Akkose et al (2021) [44]	Turkey	A secondary school	Trade-off between energy efficiency and resilience	The effectiveness of passive retrofit scenarios targeting climate mitigation and adaptation was examined	Heating and cooling loads & PMV/PPD
Kükrer & Eskin, (2021) [45]	Istanbul, Turkey	A university building	Trade-off between energy efficiency and resilience	Upgrading measures for different spaces of a school building were analysed	Heating and cooling energy consumption, thermal comfort and productivity
Heracleous et al. (2021) [11]	Cyprus	A secondary school	Energy-efficiency of retrofit measures	Parametric analyses of upgrading measures on geometry, construction and operation were conducted	Heating and cooling degree hours
Grassie et al. (2022) [6]	England	School stock (represented by 116 school archetype)	Trade-off between energy efficiency and resilience	A novel approach to simultaneously modelling overheating, heating demand and IEQ at the stock level was proposed	Overheating risks, CO_2, $PM_{2.5}$, NO_2 concentration

of different building fabric and system efficiency parameters (such as insulation thickness, boiler efficiency). This allows parametric analysis to examine the effects of different combinations of design specifications. Heracleous et al. [11] evaluated the energy-efficiency of retrofit measures on schools in Cyprus by parametric method. This study expanded the range of retrofit possibilities and assessed how changes in specific parameters impact the overall building performance.

3) **Trade-off between energy efficiency and resilience:** The third category investigates the trade-off between energy efficiency and resilience to climates in school building retrofits. Researchers have evaluated different passive measures applied to the building envelope of schools based on their impact on energy consumption and indoor environments. Grassie et al. [6] developed an approach that evaluate different retrofit measures and simultaneously modelled overheating, heating demand and air quality for retrofitted school building stock in England and Wale under future climate conditions. Akkose et al. [44] evaluated the combined impacts of climate change and urban heat island effect on school building energy consumption and indoor thermal comfort, and suggested potential measures to mitigate such impacts. Kükrer & Eskin [45] not noly explored the impact of different retrofit measures, but also assessed operational strategies on energy consumption and student productivity in different functional spaces of a school.

Additionally, previous studies have adopted various KPIs for retrofit analysis based on the specific retrofit objectives. The most commonly used KPIs are energy-related, including heating and cooling loads, heating and cooling degree hours, and primary energy consumption, which were used to measure energy saving potentials after retrofit. Often, CO_2 emissions are also recognised as crucial aspects in building retrofit evaluation. Economic indicators, such as capital cost of investment [46], payback periods [40] and net present value (NPV) are also important metrics for private and government investors. For instance, cost-optimal analysis, introduced in EPBD-recast, was used in Ref. [43] to identify the cost-effectiveness of retrofit measures. A few other studies incorporate environmental KPIs in retrofit analysis. Thermal comfort metrics, such as Fanger's PMV/PPD index and overheating risks are often used to compare the effects of retrofit measures on schools or exclude the measures that negatively affect indoor environment. Other occupant-centric KPIs, such as productivity are also used to compare different retrofit scenarios for a multipurpose school building [45].

While a large number of studies have utilised building performance simulation to analyse school building retrofit by considering 1) energy efficiency, 2) climate change impact, 3) stock-level performance, most studies have focused on one or two aspects. Further, no studies have explored the energy-efficient retrofit impacts from the perspective of cognitive performance. This study aims to address this research gap by considering all three aspects in the context of English school stock and apply cognitive performance as the main KPI for school building retrofit assessment. Additionally, the study proposes adaptation measures and assesses their impact on cognitive performance of children and energy demand of schools under climate change.

3. Methodology

The workflow of this study involves proposing cognitive performance loss as KPI (Section 3.1), developing school archetype models and running dynamic simulations in EnergyPlus program (Section 3.2), and proposing climate adaptation measures (Section 3.3), as shown in Fig. 1.

3.1. Establish CPL as the KPI

The methodology for establishing CPL as the KPI was detailed in Ref. [36]. To summarise, we first conducted a literature review to search for previous studies that have developed linear functions linking cognitive performance and different IEQ parameters. Subsequently, using the functions, we calculated CPL with the IEQ parameters of the school archetype models as the independent variables, which can be simulated through dynamic simulationsoftware.

Based on the literature review, the existing relevant research can be broadly categorised into two types: case studies that are conducted in thermostatic chambers or classrooms, and meta-analysis studies that synthesise previous research to draw conclusions. However, case-based studies rely on specific conditions and may not be suitable for generalising their findings to assess school buildings at the stock level. Therefore, we opted for two recently published meta-analysis studies that encompass 9 to 18-year-old children, focused on cognitive performance in relation to temperature and air quality, respectively.

The study of Wargocki et al. [47] derives a function linking temperature and cognitive performance, as shown in Equation (1):

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

where t represents indoor temperature, RP represents relative performance, it should be noted that in equation (1), performance at 20 °C is used as a reference, and performance at that temperature is set to 100 %. Any changes in performance at temperatures higher than 20 °C are calculated using the relationship expressed in equation (1). Due to a lack of empirical data, it is assumed by Wargocki et al. [47] that cognitive performance will not further decrease when the temperature exceeds 28 °C. The cognitive performance loss due to change in indoor air temperature is calculated from RP, as shown in Equation (2):

$$CPL_t = 100\% - RP_t \tag{2}$$

CPL_t represents cognitive performance loss due to change in indoor air temperature. Since no data is available over 28 °C, the CPL_t will reach its upper limit of 20.6 % at 28 °C. In the present study, we used CPL as

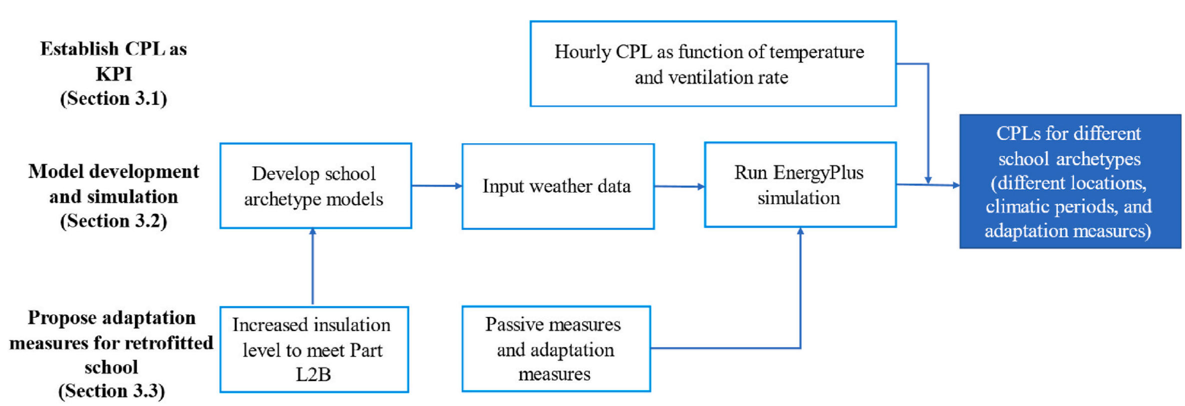

Fig. 1. The diagram of methodology design.

our KPI instead of the broader term "cognitive performance', which aims to specifically focus on understanding the potential adverse outcomes (or consequences), associated with building retrofit and climate change.

In study of Wargocki et al. [48], the authors developed a function that links indoor air quality (using ventilation rate as the proxy) and cognitive performance. To incorporate the impact of ventilation rate on cognitive performance by improving IAQ, we used 5 l/s-p as the baseline ventilation rate (minimum ventilation rate requirements for the UK classroom [49]). The relative performance at a certain ventilation rate was calculated in Equation (3):

$$RP_{IAQ} = 0.0086 * VR + 0.9368 \tag{3}$$

RP_{IAQ} *is* the relative performance modified by the change in indoor air quality due to ventilation rate and VR is ventilation rate. To calculate the combined effects of indoor temperature and IAQ (ventilation rate), we made an assumption that CPL_t could be adjusted by introducing a modifying coefficient, denoted as α. α is determined by comparing the RP_{IAQ} at a specific ventilation rate with the RP_{IAQ} at the baseline ventilation rate.

Subsequently, the cognitive performance loss was calculated using Equation (4), which takes into account these adjustments and factors in the changes in indoor temperature and IAQ:

$$CPL_{t+IAQ} = CPL_t/\alpha \tag{4}$$

where CPL_{t+IAQ} refers to the hourly cognitive performance loss by temperature and air quality at a given ventilation rate. Due to the lack of relevant quantitative studies, other two main IEQ parameters: lighting and acoustics were not included in the calculation of cognitive performance and their parameters were assumed to be constant.

3.2. Model development and simulation

3.2.1. Physical property of school building archetypes

This study used archetype-based approach - one of the bottom-up building stock modelling approaches to characterise the English school stock. The archetype-based approach entails the categorisation of building stocks into distinct category and subsequently development of building models to represent the typical features of each category [24]. The school archetype models used in this study were developed through the Data dRiven Engine for Archetype Models of Schools (DREAMS) framework [50]. The main procedures of model development are summarized as follows.

1) Datasets for school buildings geometry were derived from PDSP (The Property Data Survey Programme) [1] and DEC (Display Energy Certificate).
2) 'Seed models' were developed to represent schools built in five different construction ages: Pre-1919, Inter-war, Post -war, Post 1976. The U-values of seed models (shown in Table 2) were defined based on [51–53].
3) School buildings in England are distributed in 13 climate regions defined by CIBSE Heating Degree Days (HDDs) [54], and in each climate region schools were classified into different archetypes according to different ventilation types (natural or mechanical ventilation) and construction types (single- or multi-block school). The school archetype models were developed from the 'seed models' by using the parameters representing the typical characteristics of each archetype (Fig. 2).
4) In this study, the school archetype models developed for secondary schools in Thames Valley, West Pennines, and Borders are chosen to represent all secondary schools in Southern England (HDD18 °C < 2000), Central England (2000 <HDD18 °C < 2200) and Northern England (HDD18 °C > 2200). In these regions, the multi-block school archetypes with natural ventilation were selected as they account for the largest proportion (95 %) across all schools.

Table 2
The built-up characteristics of the seed models (In the UK, the built-up characteristics of the seed models are corelated to the construction eras).

Construction age	'Seed' model EnergyPlus file	U-value of Ground floor (W/m^2-K)	U-value of External Walls (W/m^2-K)	U-value of Roof (W/m^2-K)	U-value of Windows (W/m^2-K)
Pre-1919		1.5	1.9	3.0	5.7
Inter-war		1.5	1.9	3.0	5.7
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

3.2.2. Non-physical properties of school models

The assumption is made that all types of schools follow the same system parameters and schedule, as shown in the following information (Table 3).

1) Classrooms are occupied by children from 9 a.m. to 4 p.m., Monday to Friday, except lunch hour. School days adhere to the typical school calendar outlined by the Department of Communities and Local Government [55].
2) The internal load generated by people, lighting, and equipment is assumed based on the guidelines provided in Building Bulletin 101 (BB101), which is the Department for Education's guide for assessing ventilation, thermal comfort, and indoor air quality in schools [49].
3) In order to propose criteria for school building standards, this study assumes fixed ventilation rates of 5l/s-p for each school model between 9:00 and 16:00. This rate corresponds to a daily average of 1500 ppm CO_2, which meets the minimum requirements for naturally - ventilated schools specified in BB101.

3.2.3. Weather files and EnergyPlus simulation

EnergyPlus v8.9 [56] was selected as the dynamic simulation software in this study, as it allows rapid model development and batch simulation with the help of Python script. In EnergyPlus, weather file is the key input for simulating building energy use and IEQ. This study utilised weather files from UK Chartered Institute of Building Services Engineers (CIBSE). Two types of weather file: the Test Reference Year (TRY) and the Design Summer Year (DSY) have been generated for 14 locations in the UK for characterising current climatic conditions [57]. In addition, CIBSE was in collaboration with UK Climate Impacts Programme (UKCIP) to update its future weather files. The UKCIP09 scenarios make use of RCMs (Regional Climate Models) and generate weather files by using three 30-year time slices labelled according to the central decade of each. The updated CIBSE future weather files use three time periods: 2020s (2011–2040), 2050s (2041–2070) and 2080s (2071–2100) to represent the short-, medium- and long-term future climate projections respectively.

The future DSYs were chosen to simulate the impact of future climatic conditions on classroom environment and children. These DSYs were designed to model climate change effects on indoor environments (e.g., overheating risks). The future DSYs for each climate period can be further decomposed into three carbon emission scenarios (Low, Medium, High) and three probabilities (10th, 50th, 90th) [58], which relate probabilities of varying degrees of future climate change.

To ensure comparability of results across different climate periods, we conducted the analysis using DSYs with High emission scenario and 50th (central estimate). In addition, we selected the future DSY weather files for London, Manchester, and Newcastle to represent the future climates of Southern, Central, and Northern England, respectively.

3.3. Climate adaptation measures for energy-efficient retrofitted schools

To evaluate the potential impact of retrofitting building envelope on

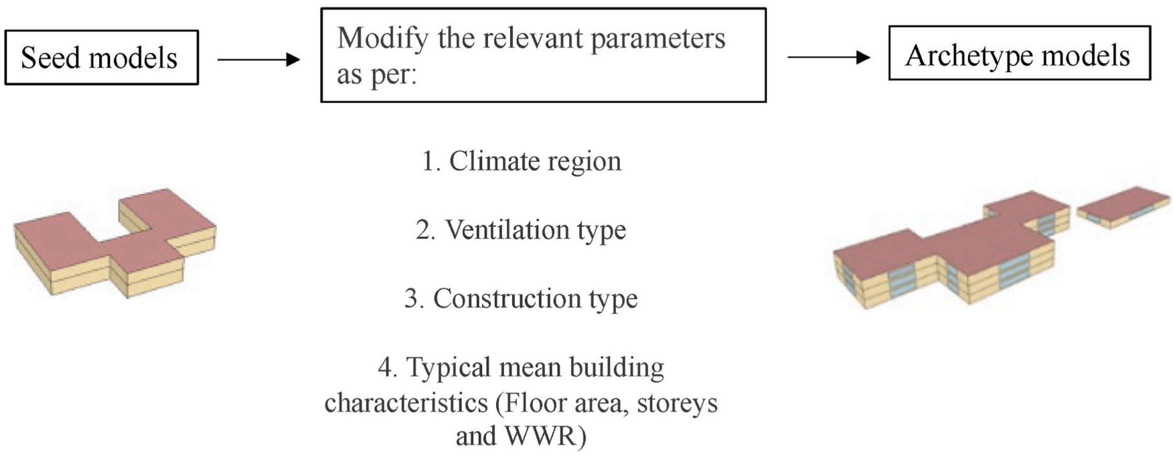

Fig. 2. The school archetype models developed from the 'seed' models. (For the muti-block school, there is an original building representing the largest building in a school, and an additional building representing the aggregation of the floor area of the rest of the buildings in the school.) [50].

Table 3
Modelling parameters assumed in EnergyPlus.

Internal load	Value	Schedule	
Lighting	7.2W/m^2	09:00–16:00	No internal gain during 12 – 1pm
Occupancy	0.58 ppl/m^2	09:00–16:00	
Equipment	10W/m^2	09:00–16:00	
Thermostat			
Heating set-point temperature	19 °C	09:00–16:00	
Ventilation rates	5 l/s-p	09:00–16:00	

the indoor environment, this study assumes that schools' envelopes will be upgraded to meet the requirements of Part L2B [13]. To achieve this, a set of retrofitted school models were created by assuming that the envelope of all school archetypes will be insulated to achieve a target minimum U-values, as detailed in Table 4. The insulation were applied to all school archetypes regardless of their construction characteristics and locations. For construction elements without insulation layer, additional insulation were added to the EnergyPlus pre-retrofit school models. For construction elements with insulation layer, their thicknesses were varied to ensure the U-value meet the standards.

Subsequently, several passive adaptation measures were proposed in the study, along with typical technical parameters found in design guidelines and other papers [79–81], including increased albedo, shading, and increased day-time ventilation and introduction of night-time ventilation. We simulated and compared the individual impacts of these passive measures on cognitive performance of children. In addition, we investigated the cumulative effects of these passive measures on cognitive performance of children.

In terms of active retrofit measures, all school archetypes models incorporate air conditioning with two different set-point temperatures: 21 °C and 25 °C. These set-point temperatures align with the recommendations in GIBSE Guide A, corresponding to the lower and upper limit of summer operative temperatures for teaching spaces. To ensure adequate IAQ for the classrooms, the ventilation rate of 5 l/s-p is maintained in all schools during occupied hours. Table 5 provides an overview of the proposed passive and active measures, illustrating the strategies considered in this study.

Table 4
Part L2B standards for U-value of building elements.

Element types	Roof (flat roof)	Roof (pitched roof)	Walls	Floors	Windows
U-value (W/m2·K)	0.18	0.16	0.26	0.18	1.6

4. Results

4.1. The impact of envelope insulation on school buildings

Tables 6–8 present the CPL of children in English schools before and after envelope insulation during the non-heating school days under 2020s, 2050s and 2080s climate scenarios. The tables utilise median and interquartile ranges to describe the distribution of CPL values and compare the percentage changes in the median between the two scenarios. The overall findings from these tables suggest that envelope insulation of schools does not show positive effects on the cognitive performance of children in their classrooms. In fact, the results indicate that insulating the envelope of school buildings may have negative effects on the cognitive performance of children in schools located in Central and Northern England, regions known for their relatively cooler climates. In 2020s, Central England schools experience a median CPL increase ranging from 11.6 % to 20.4 %, while Northern England schools see a median increase ranging from 23.3 % to 25.4 %. However, as the climate becomes warmer in the future, these negative differences gradually become smaller. Interestingly, in schools located in Southern England, there seems to be minimal change in cognitive performance after insulation in all climatic periods (0 %–0.5 % decrease). This result is not indicative of the envelope insulation having no impact. Instead, it is primarily because median CPL in schools before envelope insulation in this region is already quite close to the upper limit (20.6 %). Consequently, envelope insulation shows a limited negative impact on the cognitive performance of children in these school buildings.

Table 5
Proposed climate adaptation measures applied in school archetypes.

Climate adaptation measures	Details:
Passive measures	
Increased Albedo (reflectivity)	Solar reflective exterior walls and roof, reflectivity = 0.8
Shading	External shades during school hours when the solar radiation >200m^2
Increased ventilation rates (daytime)	Increased ventilation rates from 5 l/s-p (baseline) to 8 l/s -p
Night-time ventilation	8 l/s - p (21:00–6:00)
Active measures	
Air conditioning	21 °C and 25 °C

Table 6
Cognitive performance loss of children in English schools before and after retrofit in 2020s.

		Non-retrofit	Retrofit	
		Median (Interquartile)	Median (Interquartile)	Change in Median
Southern England	Pre-1919	20.5 (17.9–20.6)	20.6 (18.7–20.6)	0.5 %
	Inter-war	20.5 (18.0–20.6)	20.5 (18.8–20.6)	0.5 %
	1945–1966	20.4 (18.1–20.6)	20.6 (19.1–20.6)	1.0 %
	1967–1976	20.5 (17.9–20.6)	20.6 (18.8–20.6)	0.5 %
	Post 1976	20.5 (18.0–20.6)	20.6 (18.9–20.6)	0.5 %
Central England	Pre-1919	15.4 (11.0–18.7)	16.2 (12.5–19.1)	17.5 %
	Inter-war	14.9 (10.4–18.3)	15.5 (11.9–18.5)	16.8 %
	1945–1966	15.2 (11.0–18.6)	16.6 (13.0–19.3)	20.4 %
	1967–1976	15.5 (11.3–18.8)	16.7 (13.2–19.4)	18.7 %
	Post 1976	16.1 (11.9–19.1)	17 (13.4–19.6)	16.1 %
Northern England	Pre-1919	13.4 (7.3–17.2)	14.7 (9.1–18.0)	25.4 %
	Inter-war	13.3 (7.3–17.1)	14.3 (8.9–17.5)	23.3 %
	1945–1966	13.8 (8.4–17.4)	15.5 (10.4–18.4)	25.4 %
	1967–1976	13.8 (8.0–17.4)	15.4 (10.2–18.3)	24.6 %
	Post 1976	13.2 (7.6–16.8)	14.2 (9.0–17.4)	23.5 %

Table 7
Cognitive performance loss of children in English schools before and after retrofit in 2050s.

		Non-retrofit	Retrofit	
		Median (Interquartile)	Median (Interquartile)	Change in Median
Southern England	Pre-1919	20.6 (19.5–20.6)	20.6 (20.0–20.6)	0.0 %
	Inter-war	20.6 (19.4–20.6)	20.6 (20.0–20.6)	0.0 %
	1945–1966	20.6 (19.5–20.6)	20.6 (20.2–20.6)	0.0 %
	1967–1976	20.6 (19.4–20.6)	20.6 (20.1–20.6)	0.0 %
	Post 1976	20.6 (19.5–20.6)	20.6 (20.1–20.6)	0.0 %
Central England	Pre-1919	17.3 (13.4–19.9)	18.1 (14.8–20.2)	4.6 %
	Inter-war	16.9 (12.9–19.6)	17.4 (14.3–19.8)	3.0 %
	1945–1966	17.2 (13.6–19.9)	18.3 (15.3–20.3)	6.4 %
	1967–1976	17.4 (13.6–20.0)	18.4 (15.4–20.4)	5.7 %
	Post 1976	17.8 (14.1–20.2)	18.7 (15.6–20.5)	5.1 %
Northern England	Pre-1919	15.7 (10.1–18.8)	16.8 (11.7–19.4)	7.0 %
	Inter-war	15.5 (10.1–18.6)	16.4 (11.4–19.0)	5.8 %
	1945–1966	15.9 (10.9–19.0)	17.3 (12.6–19.7)	8.8 %
	1967–1976	15.9 (10.6–18.8)	17.2 (12.6–19.6)	8.2 %
	Post 1976	15.5 (9.9–18.5)	16.3 (11.3–18.9)	5.2 %

Table 8
Cognitive performance loss of children in English schools before and after retrofit in 2080s.

		Non-retrofit	Retrofit	
		Median (Interquartile)	Median (Interquartile)	Change in Median
Southern England	Pre-1919	20.6 (20.4–20.6)	20.6 (20.6–20.6)	0.0 %
	Inter-war	20.6 (20.4–20.6)	20.6 (20.6–20.6)	0.0 %
	1945–1966	20.6 (20.4–20.6)	20.6 (20.6–20.6)	0.0 %
	1967–1976	20.6 (20.4–20.6)	20.6 (20.6–20.6)	0.0 %
	Post 1976	20.6 (20.5–20.6)	20.6 (20.6–20.6)	0.0 %
Central England	Pre-1919	19.0 (16.0–20.5)	19.6 (17.0–20.6)	3.2 %
	Inter-war	18.7 (15.5–20.5)	19.2 (16.5–20.5)	2.7 %
	1945–1966	19 (16.0–20.5)	19.7 (17.3–20.6)	3.7 %
	1967–1976	19.2 (16.2–20.6)	19.8 (17.4–20.6)	3.1 %
	Post 1976	19.4 (16.7–20.6)	20 (17.7–20.6)	3.1 %
Northern England	Pre-1919	18.0 (13.1–20.2)	18.7 (14.4–20.4)	3.9 %
	Inter-war	17.8 (12.9–19.9)	18.3 (14.1–20.2)	2.8 %
	1945–1966	18.1 (13.7–20.1)	19 (15.1–20.6)	5.0 %
	1967–1976	18.1 (13.3–20.2)	19 (15.0–20.6)	5.0 %
	Post 1976	17.8 (12.8–19.9)	18.2 (13.8–20.2)	2.2 %

Fig. 3 illustrates the distribution of CPLs per hour for children in each school archetypes after envelope insulation under future DSYs. The overall trend shows that from “2020s” to “2080s,” the three boxplots for each archetype successively flatten and the middle line becomes higher, indicating that each school’s CPL will increase along the 21st century. In Southern England schools, CPL values were near the upper limit for most hours under the 2080s, suggesting that under the 2080s climate scenario, children would have a CPL of 20.6 % for most of the non-heating school days. Schools in Central England and Northern England performed relatively well in the 2020s, while future climatic conditions are expected to cause their cognitive performance to decline more sharply.

4.2. *The impact of adaptation measures on schools with envelop insulation*

4.2.1. *Passive adaptation measures*

Figs. 4–6 depict the effects of passive climate adaptation measures on the cognitive performance of children in all school archetypes over different climate periods. The effects of these measures are evaluated both individually and collectively on schools that have undergone envelope insulation. The bars in the figures represent the median values of hourly CPLs that children spend at schools during the non-heating season (528 h in total). Overall, the median CPL will be reduced by using passive adaptation measures in all three regions. However, as the climate warms and the average ambient temperature increases, the cognitive performance loss will increase accordingly, suggesting that the effects of all passive adaptation measures will diminish. In addition, adaptation measures have different relative impacts in different regions. In Southern England, the passive measures were found to be less effective, with most individual measures showing limited improvement. Only increased daytime ventilation will result in relatively significant declines in CPL. Even when all climate adaptation measures were implemented in Southern England schools, the median CPL remained as high as 16.6 % in the 2020s and 18.8 % in the 2080s.

In contrast, passive adaptation measures showed more positive outcomes in schools located in Central and Northern England, particularly increased day-time ventilation rate, which will reduce the median CPL to 9.9 % in Central England and 7.5 % in Northern England in 2020s. Night-time ventilation (from 21:00 to 6:00) and external shading were also effective, while improving albedo will have the smallest impact. By implementing these measures collectively, the median CPL can be further reduced to 9.4 % in the Central England and 6.5 % in the Northern region in 2020s. In 2050s, the median CPL in the Central England will be lowered to 11.9 %, and in the Northern region, it will be reduced to 9.5 %.

4.2.2. *Active adaptation measures*

This section shows the potential of air conditioning as an active adaptation measure in reducing cognitive performance loss among children. Fig. 7 present the frequency distributions of cognitive performance loss of children in their schools at different cooling set-point temperatures (21 °C and 25 °C) during non-heating seasons, as compared to school without air conditioning. As there are currently no specific building regulations or guidelines that categorise the extent of cognitive performance loss, for ease of observing the distribution of cognitive performance levels, in these graphs, the hourly CPLs were categorized into four levels: no loss (CPL = 0 %), non-significant loss (0 < CPL<5 %), moderate loss (5 %< CPL<20.6 %) and severe loss (CPL = 20.6 %). At the set-point temperature of 25 °C, most hours fall into the category of ‘moderate loss’, while at 21 °C, almost all hours are associated with ‘non-significant loss’. Notably, adjusting the set-point temperature does not significantly impact the percentage of hours at the ‘no loss’ level. This suggests that the primary function of air conditioning in reducing cognitive performance loss among children lies in its ability to stabilise indoor air temperatures and create a more comfortable learning environment.

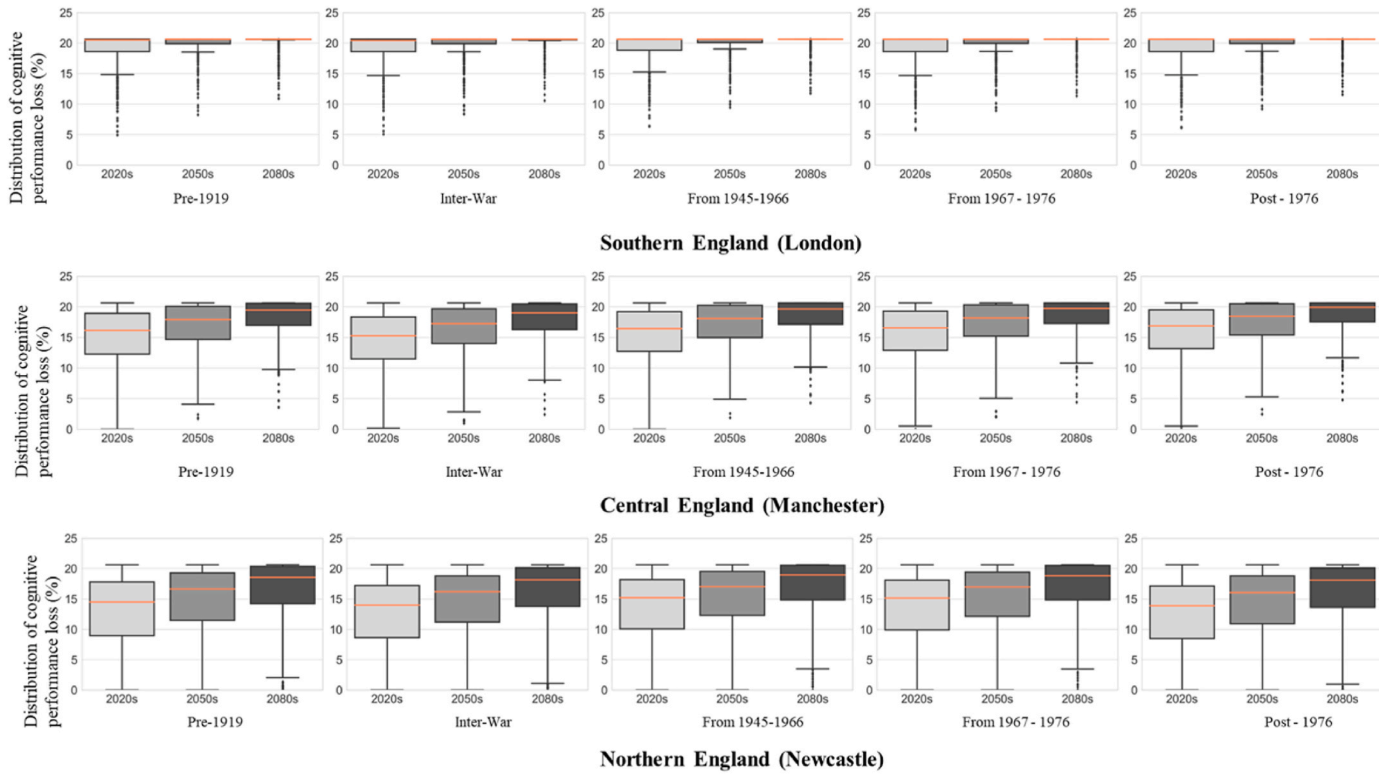

Fig. 3. The climate change on cognitive performance loss of children in school archetypes.

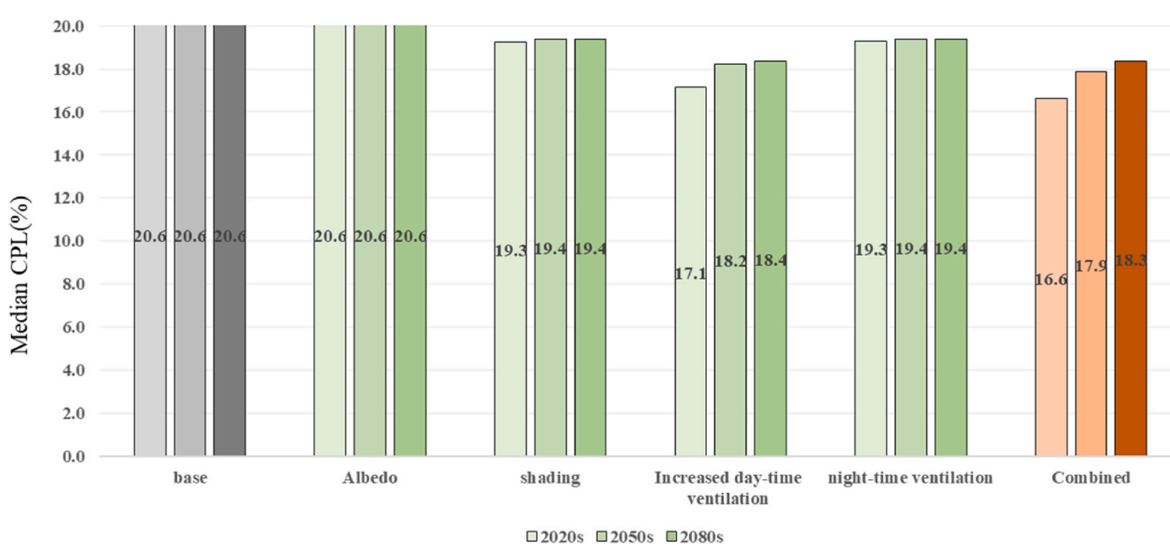

Fig. 4. The impacts of individual and combined climate adaptation measures on cognitive performance loss of children in Southern England schools in 2020s, 2050s and 2080s climatic periods.

The median CPL and the corresponding cooling loads at set point temperatures of 21 °C and 25 °C in schools across all three regions of England are depicted and compared in Fig. 8. The results demonstrate that despite the introduction of air conditioning, cognitive performance loss is expected to increase under future climates when the set point temperature is set at 25 °C (e.g., from 11.6 % to 15.4 % in Southern England). In contrast, at 21 °C cooling set-point, the median CPL in all schools are significantly reduced and remain stable at 4.4 %. However, the cooling loads will reach 75, 54 and 39 kWh/m^2 in the three regions, respectively. Thus, adjusting the set point temperature can impact the climate resilience of school buildings from both cognitive performance and energy view.

4.3. The impact of envelope insulation on energy demand and cognitive performance in air-conditioned schools

With the evident advantages of air conditioning on cognitive performance, it's likely that some schools will choose to install air conditioning systems in their future plans to ensure good learning environment for children. In the context of complying Part L, the trade-off between energy efficiency and cognitive performance in the decision-making process on retrofit strategy might need to be considered. Table 9 presents a comparative analysis of energy demand and cognitive performance of children across three regions before and after envelope insulation, considering one heating set point temperature (19 °C) and

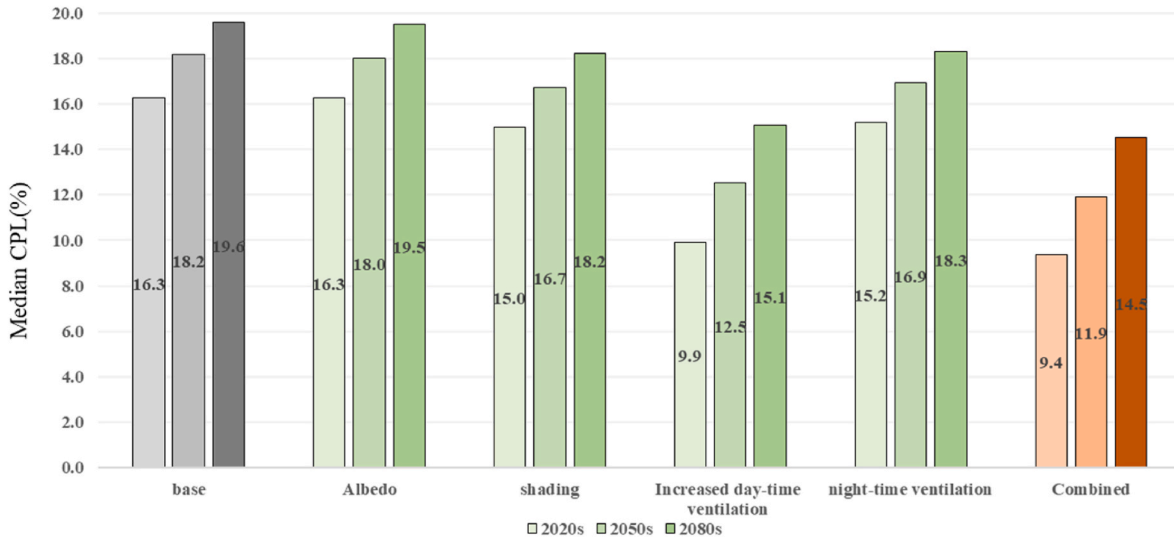

Fig. 5. The impacts of individual and combined climate adaptation measures on cognitive performance loss of children in Central England schools in 2020s, 2050s and 2080s climatic periods.

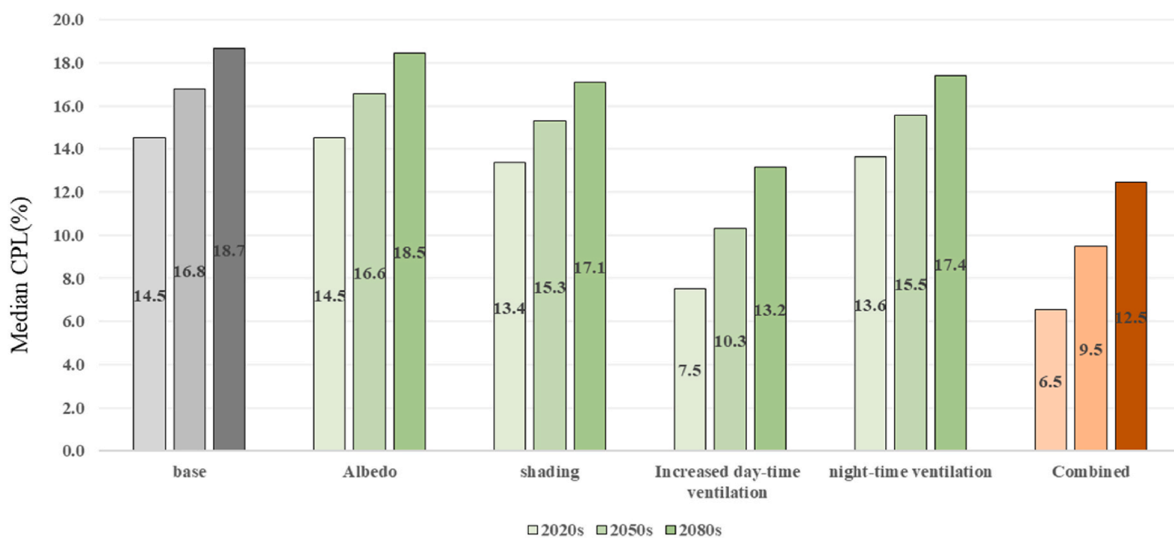

Fig. 6. The impacts of individual and combined climate adaptation measures on cognitive performance loss of children in Northern England schools in 2020s, 2050s and 2080s climatic periods.

two cooling set point temperatures (21 °C and 25 °C) in air-conditioned schools. In the table, positive values in energy demand indicate an increase after envelope insulation, while negative values indicate a decrease. At the 25 °C cooling set-point, the total energy demand of schools in all three regions is projected to decrease after insulation. However, in 2050s, the positive impact of envelope insulation will diminish, and there may even be negative impacts (e.g., Southern England school with 1 kWh/m^2 increase in total energy demand). By the 2080s, only schools in Northern England are expected to continue benefiting from envelope insulation, with 5 kWh/m^2 decrease in total energy demand. In terms of cognitive performance, envelope insulation proves to be advantageous for improving cognitive performance in air-conditioned schools in all three regions, and there is a clear trend of decreasing CPLs under future climates. By the 2080s, the CPL reduction in all three regions due to envelope insulation reaches 7.4 %, 7.2 %, and 5.7 %, respectively.

At the 21 °C cooling set-point, only Northern England is expected to experience a decrease (with 6 kWh/m^2) in total energy demand in 2020s, while energy demand is expected to increase in all three regions after envelope insulation in 2050s and 2080s. The cognitive performance, however, will remain unchanged before and after envelope insulation in all future climatic scenarios.

5. Discussion

5.1. Main findings

To strike a balance between energy efficiency and indoor environments for buildings is important and complicated, especially for schools where children are often regarded as a vulnerable group. By using cognitive performance loss as the KPI, this study quantifies the cognitive performance loss of children in schools during non-heating school days, supposing the schools' envelope have been upgraded to meet Part L building standards. The findings reveal that simply increasing insulation levels to comply with Building Regulations Part L2B standards, without implementing climate adaptation strategies, may have counterproductive effects in the future, because the CPL of children will be higher, especially in Central and Southern England schools. This implies that

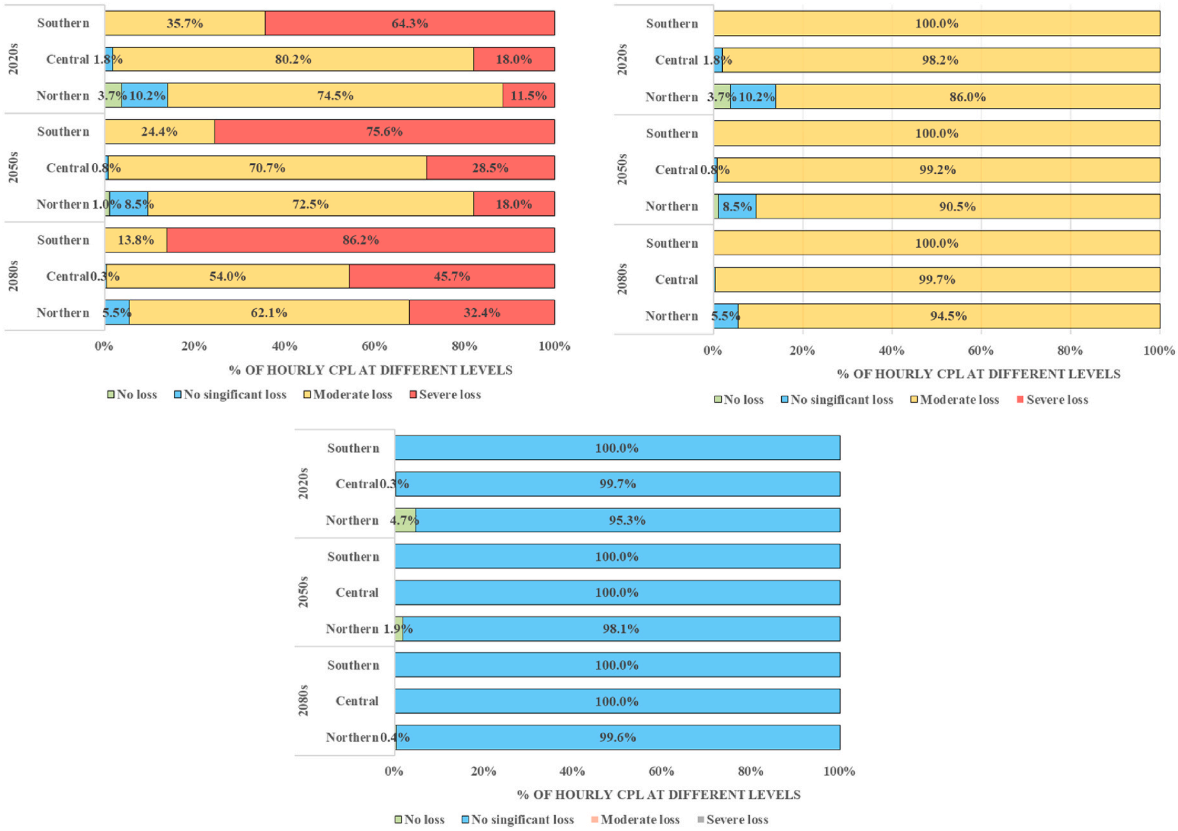

Fig. 7. Distributions of hourly CPLs at different levels. a) no air conditioning; b) 25 °C; c)21 °C.

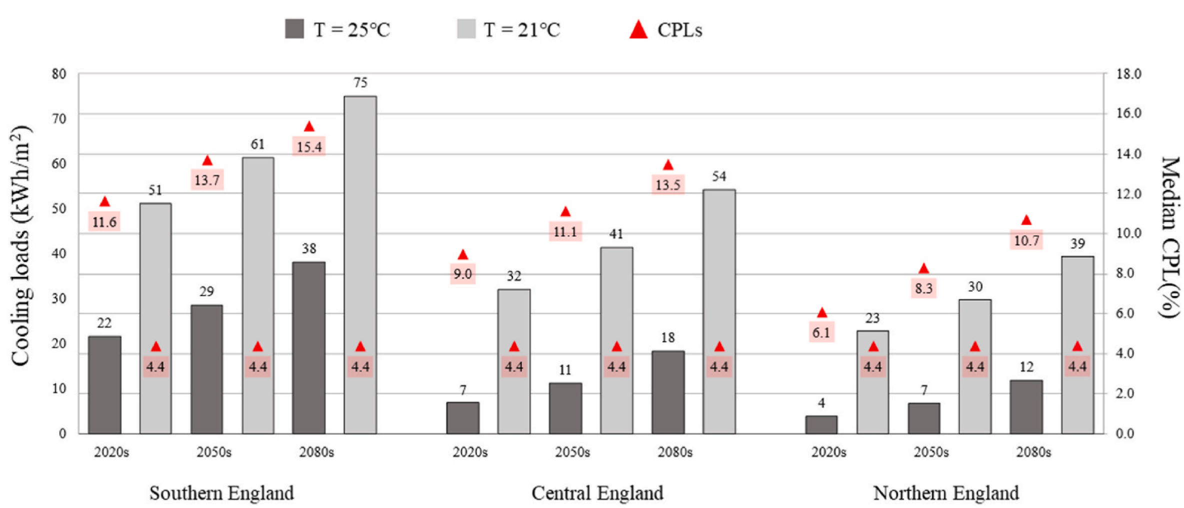

Fig. 8. The comparison of cognitive performance loss and corresponding cooling laod (kWh/m^2) at the set-point temperature of 21 °C and 25 °C.

energy-efficient retrofitted schools may become less resistant to the effects of climate change from the perspective of cognitive performance. Furthermore, the climate change will further increase CPL of children across all schools with upgrade envelope. Most of the non-heating school days in Southern England schools will reach its upper limit CPL (20.6 %) in 2080s. Therefore, it is therefore important to carefully consider these findings when making decisions regarding the energy-efficient retrofit of school buildings.

The study also examines the effects of typical passive climate adaptation measures, such as albedo, external shading, day-time ventilation, and night-time ventilation, in reducing cognitive performance loss. Results indicate that the impacts of these measures vary across different regions in England, with passive measures being more effective, in schools located in Southern England. Among these measures, increased day-time ventilation proves to be the most effective strategy for reducing CPL of children in 2020s, particularly in schools in Central England (6.7 % reduction in median) and Northern England (7 % reduction in median). Night-time ventilation and shading are ranked second in effectiveness. However, the effects of these passive measures on cognitive performance in schools across England will diminish as the climate warms. These findings align with other studies comparing the impacts of adaptation measures in different types of non-air-conditioned buildings,

Table 9
The compassion of cooling and heating demand (kWh/m^2) and cognitive performance in schools in all three regions before and after envelope retrofit.

			19 °C/25 °C			19 °C/21 °C		
			Southern	Central	Northern	Southern	Central	Northern
2020s		Change in cooling	3	2	1	12	11	8
	Energy demand	Change in heating	−4	−6	−14	−4	−6	−14
		Change in total	−1	−4	−13	8	5	−6
	CPL	Change in Median	−3.8 %	−2.7 %	−1.0 %	0 %	0 %	0 %
2050s		Change in cooling	3	2	2	15	15	11
	Energy demand	Change in heating	−2	−4	−11	−2	−4	−11
		Change in total	1	−2	−9	13	11	0
	CPL	Change in Median	−6.1 %	−5.1 %	−2.9 %	0 %	0 %	0 %
2080s	Energy demand	Change in cooling	5	5	3	21	21	14
		Change in heating	−1	−2	−8	−1	−2	−8
		Change in total	4	3	−5	20	19	6
	CPL	Change in Median	−7.4 %	−7.2 %	−5.7 %	0 %	0 %	0 %

such as [59–61]. Changing albedo was found to be the least effective measure (in case of CPL), as well-insulated buildings is less sensitive to increased short-wave reflectivity [62].

In 2050s and 2080s, air-conditioning may be a more effective solution for reducing CPL in retrofitted schools, while it will increase energy demand for cooling. The findings of this study indicate lower cooling set-point temperature to 21 °C can significantly reduce cognitive performance loss while leading to increased cooling loads. It is important to note that the results of this study only reflect the cooling energy demand per unit area, and considering the use of air conditioning for cooling is becoming a trend across countries [63], the total cooling energy demand of the whole English school stock could potentially experience significant growth in the future. However, the use of air conditioning systems can exacerbate urban heat island effect by releasing wasted heat, and necessitate significant transitions in the national energy mix by shifting from gas to electricity [64]. Therefore, the combination of passive and active adaptation measures to reduce cooling energy demand while maintaining good indoor environments has been suggested in previous research [60].

The research findings also demonstrate that the envelope insulation will lead to changes in both cooling and heating energy demand which collectively influence the changes in total demand in schools with air conditioning. It is suggested that if the demand for air conditioning in schools increases in the future, it is still worth increasing insulation levels of building envelope in cooler climates, provided that the cooling set-point temperature is maintained at 25 °C, because it can still moderately reduce the overall energy demand and cognitive performance loss. However, it might increase total energy demand of schools in the future climatic periods, especially those in warmer climatic regions (Southern England). At 21 °C set-point temperature, However, both energy use and cognitive performance in all schools may not benefit from envelope upgrade.

5.2. Study implications

This study emphasizes the importance of considering both climate mitigation and adaptation in school building retrofit. In other words, energy efficiency retrofit for school buildings should be carefully planned, taking into account not only the energy-saving potentials, but also their resilience to climates. This aligns with the suggestions from previous studies on other building types in temperate climates [65,66]. Poulsen et al. [67] point out that while architects and building engineers are aware of the risks posed by climate change and the need for adaptation measures, current climate-responsive design practices remain conceptual. This study is to provide quantitative insights into climate resilience of buildings, with the intention of offering robust evidence for English school stock to effectively respond to climate change. Furthermore, apart from addressing climate change, previous studies on school building retrofit highlight other key factors need to be taken into account in future school design and retrofit practices. One such key factor is the increased internal heat gain resulting from the growing use of IT equipment [4], which has the potential to exacerbate the risk of indoor overheating and impair cognitive performance of children. In addition, while this study demonstrates the increased ventilation rates and shading can have positive effects on cognitive performance, the selection of ventilation and shading system for each school should been customised based on the conditions of the school buildings, such as function, orientation and construction [45]. The estimated retrofit cost also is a crucial factor [43], because large-scale school building retrofit requires continuous investment from the government and the schools. Lower initial investment costs and shorter payback periods can serve as the incentives for the successful implementation of retrofit measures.

It should be also noted that the retrofitting school building should not only include physical adaptations but also behavioural adaptations, because the effectiveness of climate adaptation measures also depends on how occupants respond to variations in internal and external conditions [68]. For instance, increased ventilation rates through opening windows only prove effective when the outdoor temperature is lower than indoors. Therefore, educating users about the design intent and providing effective training to children and teachers in schools forms an integral part of achieving the full potential of climate adaptation strategy in school buildings [17,68]. Additionally, this study demonstrates that school buildings in different English regions will face distinct climate risks. Therefore, it is recommended to incorporate regional climate characteristics into school building standards and design guidelines.

In the context of a paradigm shift from a purely building physical perspective to a human-centric perspective, employing occupant-centric KPI encourages buildings experts to consider building design and retrofitting from occupants' need [69]. Unlike psychological studies that aim to understand the impact of classroom environments on individual children, the development of CPL as the KPI for evaluating school performance serves a different purpose. The primary objective is to provide an effective way to assess building performance and guide retrofit practices from the lens of cognitive performance. Building retrofit practices typically encompass multiple objectives, such as energy efficiency, indoor environment quality, children's comfort and performance, requiring collaboration among various stakeholders. The key stakeholders, such as educationists and school administrators are often more familiar with cognitive performance than with traditional building performance KPIs. Using CPL as the KPI can serve as an important means of bridging the communication gap between building experts and various stakeholders in the educational sector in school building retrofits. The complex decision-making process for retrofit can be also enhanced by the application of system dynamics methods, as they can provide a better understanding of the complex relationship between building, energy efficiency and occupant's wellbeing and performance [18,70], so as to make more holistic decisions regarding school stock retrofit while ensuring that classrooms are conducive to learning. Additionally, It's important to note that children's cognitive performance may be impaired not only when the classrooms are overheating but even when they feel thermally comfortable [71]. Therefore, CPL serves as a valuable complement to the evaluation framework of indoor environment, especially in educational settings where thermal comfort-related KPIs have been predominantly used [72].

Despite this study being focused on school buildings, the methodological framework adopted can be generalised to other types of buildings and other locations. Firstly, the archetype-based approach has been widely employed for modelling building stock in many countries, and there have been archetype models developed for different building types (residential buildings and non-residential buildings) and different scales (urban, regional and national scale) for building performance assessment at the stock level [24,25,73]. Secondly, the cognitive performance functions of other groups (e.g., office workers [74]) can also be embedded in the framework to model the occupant's performance in different types of buildings (e.g., office). In addition, many countries have created weather data for building simulation and developed localised weather files [75]. These weather files include the 'epw.' format files which are compatible with EnergyPlus for simulating the impact of local climates. Lastly, this paper only proposes a few options of climate adaptation measures for school buildings. The impact of other measures, including passive and active techniques, occupant behavior, and HVAC management, can also be analysed through this methodological framework.

5.3. Limitations and future work

- **CPL as a KPI:** In order for cognitive performance to become a KPI that can truly guide building design and retrofit, further research is needed to address several issues. The first issue to address is the establishment of well-recognized and standardized methods and metrics for cognitive performance in building regulations. Existing research on cognitive performance primarily consists of case studies and the findings are inconsistent because of different participants and measurement conditions. As a result, a consensus on the associations between classroom temperature and cognitive performance has not yet been reached, hindering the extrapolation of findings to population levels in real world [76]. The meta-analysis for previous findings is a strategy to address this issue to some extent, but its results still have some inherent limitations, as summarized in Refs. [36,47]. In addition, this study analyses long-term cognitive performance changes to reflect school building environmental quality, assuming that cognitive performance undergoes transient changes with temperature. However, due to the thermal adaptation of the human body, students' cognitive performance may not necessarily vary in response to temperature changes. The long-term cognitive performance KPIs should be validated by the longitude studies which can reflect the variations of student's performance over a long period of time. Further, in addition to temperature and ventilation rate, there are other environmental factors, such as lighting and acoustics, as well as human factors, such as age and gender which may have an impact on cognitive performance [32]. Future studies can benefit from incorporating different mediate factors into cognitive performance functions.
- **Archetype modelling**: The archetype modelling approach adopted in this study simply use uniform geometry to represent the school buildings within a specific construction era. This approach may not be able to capture the diverse geometrical features of all the buildings in the category represented by the archetypes. Consequently, the prediction results may lack generalisability to other school buildings within the same category represented by the archetype models, because variations in volume/surface ratio can be the key determinants affecting indoor thermal condition and air quality. Ongoing research aims to provide a greater disaggregation of school buildings or even create one-by-one school buildings for the entire stock [77], which would allow for a more accurate description of the unique characteristics of each school. As a result, validating simulated cognitive performance outcomes derived from these individual school models against actual measurements from respective buildings could ensure the accuracy and reliability of the results.
- **Climatic scenarios:** Only the weather files with High emissions scenarios, 50th percentile is used in this study. It should be noted that the climate change projections have some degrees of uncertainty due to the selection of the selection of global climate models, emissions scenarios, and downscaling methods. Future research could consider the evaluation of school building performance under different future climate projections to incorporate the uncertainty in the prediction results.

6. Conclusion

This study presents a methodological framework to quantify the unintended consequence of envelope upgrade for English school stock on children's cognitive performance in their classrooms under climate change and explore the adaptation measures to mitigate these consequences. Key findings are shown below.

- Schools in England that undergo envelope insulation exhibit higher cognitive performance loss compared to their pre-upgrade conditions, especially those in Central England (11.6 %–20.4 % increase in median) and Northern England (23.3 %–25.4 % increase in median) in 2020s.
- Climate change will further increase cognitive performance loss across all schools with envelope insulation. Most of the non-heating school days in Southern England schools will reach its upper limit CPL (20.6 %) in 2080s.
- Passive adaptation measures showed more positive outcomes in schools located in Central and Northern England, particularly increased day-time ventilation rate, which will reduce CPL to 9.9 % in Central England and 7.5 % in Northern England in 2020s.
- The effects of passive measures will diminish as the climate warms, while air conditioning can maintain cognitive performance loss at relatively low levels, with 4.4 % CPL at 21 °C cooling set-point in the future, while the increased cooling energy demand should be accounted for.
- At 25 °C cooling-set point temperature, envelope insulation provides benefits for air-conditioned schools in 2020s from both cognitive performance and energy point of view, while it might increase the total energy demand in 2050s and 2080s, especially in Southern England schools.

The study emphasises the importance of considering both climate mitigation and adaptation in school building retrofit to avoid negative unintended consequences on children. School energy-efficient retrofit should be carefully planned, not only taking into account energy-saving potential for schools but also their resilience to climates. The use of CPL could provide a new 'language' familiar to educators in characterising the classroom environment, which bridging the gap between building experts and stakeholders from the educational sectors in the decision-making process of school retrofit. CPL also acts as a valuable complement to the evaluation framework of indoor environments, especially in educational settings where thermal comfort-related KPIs have been predominantly used. Despite this study being focused on school buildings, the methodological framework adopted can be generalised to other types of buildings and other locations. Due to the inherent limitations of archetype models, the study suggests adopting building-by-building modelling and simulation for the school stock for the future work, in order to prioritise retrofit measures for each school building. Validation at the individual school level is also recommended to ensure the robustness and reliability of simulated results.

CRediT authorship contribution statement

J. Dong: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Y. Schwartz:** Writing – review & editing, Supervision, Methodology. **I. Korolija:** Writing – review & editing, Supervision. **D. Mumovic:** Writing – review & editing, Supervision, Funding acquisition.

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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