Cumulative exposure to urban heat can affect the learning capacity of students and penalize the vulnerable and low-income young population: A systematic review.

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Abstract

Background: Elevated temperatures negatively impact human well-being, heighten mental health risks, and impair cognitive function, with young populations being especially vulnerable. Prolonged exposure to rising ambient temperatures further exacerbates these effects, potentially hindering student's cognitive performance under extreme heat conditions.

Objectives: This paper systematically reviews the existing knowledge on the long-term and cumulative exposure of students to heat stress, with the aim to synthesize evidence on the magnitude and mechanisms of the associated cognitive loss and on the adaptation measures and technologies to mitigate these cognitive impacts, evaluating their efficiency and potential limitations. Additionally, the paper explores the evidence provided by the existing literature on the social and economic inequalities and heterogeneities caused by prolonged heat exposure among students within and across countries and presents existing forecasts about the cognitive risks associated with future overheating.

Methods: We searched PubMed, Scopus, PsycINFO, Web of Science, Science Direct, and Google Scholar for eligible studies. We included peer-reviewed articles with the following characteristics: 1. Examining the long-term impacts of indoor or outdoor temperature on students' learning capacity, the social and economic inequalities established, the adaptive measures used, the future climate's effect on cognition, 2. Published in the last 15 years and up to December 2024, 3. Written in English. We excluded clinical trials, theses, reviews and studies on the effects of short-term exposure to heat. We mapped the effects of overheating, the adaptation strategies analysed, and the level of impact based on socioeconomic status and synthesised the results narratively. Bias was avoided by including studies with large numbers of participants and a robust analysis.

Results: 7 studies from 6 articles were included in the review. Collectively, these studies analyzed a dataset comprising nearly 14.5 million students from 61 countries. The findings suggest that long-term heat exposure negatively impacts students' cumulative learning and that the effect appears to be greater for complex tasks, e.g., mathematics, compared to simpler tasks, such as reading. Acclimatisation to higher temperatures combined with the increased prevalence of air conditioning in

warmer regions, appears to shield students from the cognitive disruptions associated with heat exposure. Populations experiencing vulnerability, particularly those with lower socioeconomic status, face the greatest impact from heat exposure's effects. As global temperatures continue to rise, these groups are disproportionately impacted, highlighting the need for targeted measures to address inequities and protect those most at risk.

The study presents limitations related to the heterogeneity of the populations participating in each study and that of the methodologies used.

1. Introduction

Heat stress is one of the most significant environmental and occupational health challenges. Prolonged exposure to high temperatures, humidity, and other severe climatic factors can result in partial or complete inability of the human body to regulate its temperature. Evidence shows that exposure to elevated temperatures, both indoors and outdoors, is strongly associated with adverse health outcomes. These include cardiovascular, respiratory, infectious, and other physical ailments [1], increased heat-related mortality and morbidity [2], and heightened risks of mental health issues, such as schizophrenia, dementia, and mood disorders [3]. Moreover, rising temperatures are associated with increased incidences of violent behaviour, including assaults [4], and higher suicide rates [5].

Cognition encompasses the brain's ability to perform tasks such as attention, memory, learning, action, reasoning, decision-making, planning, and communication. These processes demand considerable conscious mental effort [6]. The impact of high temperatures and heat stress on human capital productivity and cognitive performance is a well-documented area of research [7]. Most studies indicate that exposure to excessive heat detrimentally affects working memory, information processing, and knowledge retention, thereby impairing overall cognitive performance [8] [9] [10]. However, there are studies that have reported statistically non-significant effects of heat on cognitive function [11] [12].

Two main theoretical models explain the relationship between thermal stress and human performance: (a) the Inverted U model and (b) the Extended U model [7]. The Inverted U model is derived from the arousal theory known as the Yerkes-Dodson law [13]. According to this model, there is an optimal level of arousal at which task performance is maximized. Performance declines when arousal levels fall below or rise above this optimal level. Environmental psychologists have applied the arousal theory to understand how thermal environments influence cognitive performance. They propose an inverted relationship between cognitive performance and the intensity of environmental stress, where there is an optimal temperature that enables peak cognitive performance [14].

According to the Extended U model, there is a broad central plateau of acceptable temperatures, or the comfort zone, where human performance remains stable and near-optimal performance is achieved. On either side of the comfort zone, there is the maximum adaptability zone, in which acceptable and improved cognitive performance can still be maintained through psychological adaptive actions [15]. Heat stress occurs outside the maximum adaptability zone and can result in a sharp decline in cognitive function, potentially leading to life-threatening conditions

1.1. Heat and students' academic performance

The impact of high temperatures on students' academic performance is profoundly significant, influencing their educational, intellectual, and professional achievements. Exposure to elevated temperatures, coupled with demanding cognitive tasks, can hinder students' performance through various physiological mechanisms. These include disruptions in body temperature regulation, temperature-sensitive brain chemistry, and alterations in the brain's electrical properties, ultimately impairing its ability to function effectively under heat stress [16].

Several studies have explored the association between exposure to high temperatures and students' academic performance. These studies can be broadly categorized into two groups: (a) those examining the impact of momentary exposure to high temperatures, and (b) those investigating the effects of longer-term exposure on students' cognitive performance.

Momentary impact studies typically rely on either experimental or statistical approaches. Experimental studies often involve short- to medium-term monitoring campaigns where students are exposed to both low and high indoor temperatures in classroom settings. Their learning performance is then assessed using specific cognitive tests [17]. Most of these experiments adhere to the Inverted U model, identifying an optimal temperature at which cognitive performance is maximized. However, these studies yield diverse and sometimes contradictory findings due to factors such as the short duration of exposure, variability in the participants' skill levels, the complexity of cognitive tasks, and the lack of consideration for confounding environmental stressors. These limitations make it difficult to generalize results systematically [18].

Statistical studies, on the other hand, analyze the cognitive performance of a large number of students taking national exams conducted across a wide range of ambient temperatures, often under similar indoor climate controls [19]. While these investigations provide valuable insights into the short-term effects of high temperatures on students' performance, they do not account for the cumulative impacts of prolonged exposure to heat on cognitive function, ability, and achievement.

Recent research highlights that long-term exposure to high temperatures has a cumulative effect on students' cognitive function and performance [19] [20] [21] [22] [23] [24]. Unlike momentary studies, which focus on the immediate effects of temperature on cognitive performance—potentially caused by instant heat stress or other environmental stressors—long-term studies examine the sustained impacts of heat exposure across one or more school years.

These long-run investigations provide standardized assessments that account for the cumulative effects of prolonged heat exposure, removing the confounding influence of test-taking conditions. Most studies conclude that exposure to high temperatures one to four years preceding exams significantly impairs students' cognitive capital accumulation and has a causal, statistically significant impact on their performance. Each additional day of heat exposure above a threshold temperature in the years leading up to exams exerts a measurable negative effect on cognitive performance. The underlying mechanisms of this disruption are attributed to physiological effects on the brain, including elevated brain temperatures that impede its capacity to perform working memory tasks efficiently under heat stress [25]. For instance, Kiyatkin (2007) reported that high temperatures could increase brain temperature by up to 2.5°C [26].

Cumulative exposure to heat can impact students' learning capacity in two significant ways: (a) by hindering future learning when the body is unable to adapt and self-regulate to high temperatures, and (b) by continuously and repeatedly affecting students' learning abilities and acquired knowledge due to prolonged exposure to heat in school environments [22].

Long-term cognitive studies have provided strong evidence that cumulative exposure to high temperatures has a significant socioeconomic dimension both within and across countries. Disparities in heat protection measures between schools in deprived/overheated neighbourhoods and those in wealthier areas affect the magnitude of cognitive loss among students and contribute to significant racial heterogeneities. Park et.al. (2020) compared the cognitive loss of Black and Hispanic students to that of White students when exposed to heat during the previous school year and found that the impact is almost three times more severe for non-White students [24].

Analysis of student performance in the PISA International Exam has shown important cognitive heterogeneities across countries [19]. Cognitive losses caused by cumulative heat exposure are significantly higher in poorer countries than in richer ones. It is estimated that due to higher heat exposure, Brazilian students may exhibit almost 6% lower cognitive performance compared to their South Korean counterparts. Additionally, the impact of similar temperature events is found to be three times lower for high-income students compared to low-income students [19].

1.2. Future climate and cognitive performance

Global and regional climate change is expected to further increase the length and frequency of extreme events, thereby raising human exposure to high temperatures [27]. Assessments indicate that a temperature increase of 2.7°C by the end of the century (2080-2100) could leave one-third (22–39%) of people outside the human climate niche, which is defined as the historically conserved distribution of relative human population density with respect to mean annual temperature [28].

The future intensification of global warming will likely increase the proportion of the vulnerable population worldwide and potentially magnify the differences in cognitive capacity between rich and poor populations. Under the SSP2 (Shared Socioeconomic Pathways 2) scenario, it is estimated that a temperature rise of 2°C or 3°C will increase the vulnerable population in Asia to 54% and 65%, respectively, and in Europe to 20% and 42% [29].

The increase in urban ambient temperature caused by the Urban Heat Island effect and the thermal balance of cities raises heat stress levels for urban populations, leading to serious energy, environmental, and health problems, including significant mental health complications [30]. In many cities of the developing world, the magnitude of urban overheating may exceed 7-8°C [31]. The important synergies between global and regional climate change further intensify heat stress for urban residents [32].

Future predictions of urban climate indicate a significant increase in both night and day temperatures, causing considerable health-related effects [2]. Several analyses have shown that future overheating will cumulatively affect the cognitive function of students [24]. It is estimated that by 2050, a potential temperature increase of 1.5°C in the USA could reduce the performance of elementary school students by 9.8%, assuming no adaptation measures are taken [23].

1.3. Adaptive measures to control heat exposure

Adaptive responses are necessary to mitigate the effects of cumulative heat exposure. Adaptation measures designed to reduce endogenous heat accumulation in the human body and environmental controls to improve classroom conditions have been developed and tested under both laboratory and real classroom settings. Most studies conclude that the use of air conditioning, advanced ventilation systems, higher airflow rates, and microclimate mitigation techniques can reduce cognitive impairment caused by overheating [17].

While the implementation of these adaptation measures can potentially eradicate cognitive disparities over time, several factors must be considered. These include the physiological acclimatization of people living in warm climates and their natural ability to cope with high temperatures, the adaptability of individuals accustomed to air-conditioned environments to heat shocks, increased energy consumption, the availability and affordability of air conditioning, especially for low-income populations, and the complex economic constraints related to the use of cooling technologies in hotter, poorer countries.

1.4. The research gap

Although there is a plethora of investigations on the momentary and short-term exposure of students to heat and its effects, there is a serious lack of knowledge and information on the impact of long-term exposure on the cognitive performance of young people. Given the rapid increase in temperature caused by global and regional climate change, understanding the consequences of cumulative exposure to high temperatures on the cognitive ability of students is an urgent priority.

1.5. Review objectives

The objective of this paper is to present the current state of knowledge on the mechanisms and consequences of cumulative heat exposure on young populations and students, highlighting associated deficiencies and training disparities. It also seeks to shed light on the social and economic inequalities caused within and across countries, the potential adaptive measures to counterbalance the impact of overheating, and to discuss forecasts about the cognitive risks associated with future overheating.

To our knowledge, this is the first systematic review article to present a holistic approach to the global spectrum of knowledge on the impact of cumulative heat exposure on the human capital of young students. We believe that the analysis and provided information can contribute to defining proper educational and protective policies to eradicate educational disparities in a warming world, improve understanding of the future costs of climate change, and support future generations in enhancing their educational accomplishments, avoiding compromised learning achievements, and ultimately improving their overall well-being.

2. Methodology

We conducted a comprehensive search of six major scientific databases, including PubMed, Scopus, PsycINFO, Web of Science, Science Direct, and Google Scholar. Additionally, we hand-searched field-specific journals and examined the references of relevant papers over the past 15 years, up to December 2024. The search was conducted from January to December 2024. Our search terms were relevant to: 1. the cumulative impact of heat exposure on the cognitive performance of students, 2. The adaptation and heat mitigation measures and technologies used, 3. The social and economic inequalities caused within and across countries, and 4. Future projections for the effects of long-term exposure to heat to students' cognitive abilities (Figure 1).

Figure 1. PRISMA diagram of study selection.

Two reviewers (KV and MS) searched the databases independently and screened articles based on title and abstract. After removing duplicates, the full texts were screened to identify the articles that met the inclusion criteria. We excluded any type of review articles, theses, articles on short-term exposure to heat and cognitive performance, clinical trials and general articles on cognitive performance.

We focussed on studies investigating the long-term impact of indoor or outdoor temperature on students' learning capacity. Our review considered all categories of students, including primary, secondary, and college students. We selected only studies that reported analysis and results from a very high number of students, typically several thousand per study to avoid bias. All types of cognitive functions and tasks were included in our review. No protocol was prepared for this review.

3. Results

Six articles reporting seven studies on the impacts of long-term exposure to heat on students' cognitive performance were selected and assessed by both reviewers, individually and collaboratively. The studies' characteristics are detailed in . All studies are based on the results of national examinations and cognition tests, with each study involving between 8,000 and 10 million students. Based on the reported figures, the studies include data from 61 countries, and the total number of participating students exceeded 14.5 million. The studies include results from cognition tests in various subjects: Mathematics (six studies), Reading (four studies), English Language (three studies), Science (one study), and History (one study). Seven studies reported results from high school students, while three included results from both high school and elementary school students. The effects on student cognition are reported in terms of academic achievement, i.e., test scores decrease as compared to the scores of cooler days/years/periods, per subject or as a mean of multiple subjects. There was no handling of the data of the included studies.

However, no articles describing adaptation measures, social and economic inequalities and future projections were based on long-term exposure of large student cohorts to heat. The respective paragraphs follow a narrative review and analysis of studies which are relevant but do not meet all the inclusion criteria for the systematic review process, followed for the first research question.

Table 1. The characteristics of the studies analysed in this review

No	Type of Data	Period of Data	Results		Reference
			Impact of Heat on Cognitive Performance	Heterogeneous Impact on Health	
1	Twenty-one million scores were generated from nearly 10 million high school students in the United States who took the PSAT exam in Math and Reading at least twice. The analysis examines the cumulative impact of high temperatures over the four years leading up to the exams.	2001-2014	A school year that is 1°F hotter reduces academic achievement by 0.002 standard deviations (SD) and decreases learning by 1% of a typical year's progress. An increase of one standard deviation in heat exposure—equivalent to more than three additional days above 90°F—lowers academic achievement by 0.002 SD. Both math and reading scores decline by similar magnitudes in response to additional heat exposure. A 1°F increase in the average temperature over the past four school years results in about a 0.006 SD decrease in test scores, which is equivalent to 2% of the typical annual gain in PSAT scores. Experiencing an additional day above 90°F in each of the four years reduces scores by 0.002 to 0.003 SD, or 1% of a typical school year's PSAT improvement. However, the presence of school air-conditioning offsets approximately 0.0025 SD of the	The impact of heat in prior years on students from lower-income ZIP codes is twice as significant as on students from higher-income ZIP codes. A 1°F increase in school-year temperatures over the past four years has a nearly 80% greater impact on Black and Hispanic students compared to White students. Similarly, experiencing one additional day above 90°F in each of the preceding four school years has a 40% larger impact (lower scores) on Black and Hispanic students than on White students.	Park et al, 2020 [24]

			learning damage caused by each 1°F temperature increase.		
2	Test results from over 4.5 million primary school students in India, focusing on Maths and Reading, were analyzed based on the Annual Status of Education Report (ASER). Additionally, data from the Young Lives Survey (YLS) was utilized, including 1,008 children born between January 1994 and June 1995, and 2,011 children born between January 2001 and June 2002.	2006-2014 for ASER and 2002 to 2011 for YLS	Test performance begins to decline when temperatures exceed 17°C. • **Impact of High Temperatures:** ○ Relative to a day with an average temperature between 15°C and 17°C, one additional day in the prior year with an average temperature above 29°C reduces math and reading performance by 0.003 and 0.002 standard deviations (SD), respectively. ○ Ten extra days with an average temperature above 29°C (85°F), compared to the 15°C–17°C range, decrease math and reading performance by 0.03 and 0.02 SD, respectively. • **Timing of Temperature Effects:** Only hot days in the previous calendar year affect current-year test scores; hot days during the current year have no measurable effect. • **Question-Level Insights:** Heat impacts harder questions on both math and reading tests. ○ Significant negative effects are observed on paragraph- and story-reading skills, but effects on word- or letter-reading skills are statistically insignificant. Similarly, division and subtraction skills are negatively affected, while single- and double-digit number recognition shows no significant effects. • **Day-of-Test Effects:** ○ A 1°C increase in the day-of-test temperature above 23°C reduces within-cohort math performance by 0.17 SD. However, no significant relationship is found between higher test-day temperatures and reading comprehension. • **Short-Term Heat Effects:**	Students from families receiving agricultural subsidies exhibited lower test scores.	Garg et al, 2020 [22]

			○ There is no evidence that heat exposure in the four days prior to a test affects performance. • **Long-Term Projections:** ○ By the end of the century, rising temperatures could reduce annual math and reading scores by 0.04 and 0.03 SD, respectively. Over the course of a student's education, this reduction is equivalent to the loss of approximately two years of schooling. • **Seasonal Variations:** ○ Hot days during the agricultural growing season have large negative effects on test scores, whereas those in the non-growing season have minimal impact.		
3	Test score data from 58 developed and developing countries participating in the Programme for International Student Assessment (PISA) includes assessments in Math, Reading, and Science. The dataset encompasses over 500,000 15-year-old students.	2000-2015	Heat on school days prior to PISA exams lowers test scores, while heat on non-school days (e.g., weekends and summer vacations) has little impact. Hotter temperatures in the years leading up to the PISA exam negatively affect student performance. Each additional day above 26.7°C (80°F) during the three years preceding an exam reduces scores by 0.18% of a standard deviation ($P = 0.007$; 95% confidence interval [CI] = −0.22 to −0.04). A one-standard-deviation increase in hot days, accounting for country and year fixed effects, is equivalent to 14 school days. The effect of high temperatures on learning is almost exclusively driven by hot school days. Each additional hot school day reduces scores by 0.22 standard deviations ($P = 0.002$; 95% CI = −0.36 to −0.08).	For lower-income students, the impact of the same temperature event is nearly three times greater. Increased heat exposure during the school year may result in Brazilian students learning 6% less per year (based on academic performance) compared to South Korean students. This difference could account for roughly one-third of the gap in their PISA performance.	Park et al, 2021 [19]
4	District-level annual test scores in English Language, Arts and Mathematics were collected from over 12,000 U.S.	2009-2015	Exposure to high temperatures during the school period prior to exams leads to reduced learning outcomes. For each additional day with temperatures of 26.7°C (80°F) or higher, student performance decreases by approximately 0.04% of a standard deviation. Additionally, for each school day with	High temperatures disproportionately affect the academic performance of disadvantaged students compared to their advantaged peers. Students in low-income neighbourhoods are	Park et al, 2021 [19]

	school districts. These results, representing third to eighth graders, are based on data from the Stanford Education Data Archive (SEDA) and include over 270 million test scores		temperatures of 26.7°C or higher, scores decline by 0.07% of a standard deviation. The impact of hot days on mathematics performance is nearly three times greater than on English Language Arts (ELA) achievement. Each additional school day above 26.7°C reduces math scores by 0.11% of a standard deviation, while ELA scores decrease by less than 0.04% of a standard deviation.	significantly more impacted by heat than those in high-income areas. For each additional school day with temperatures above 26.7°C, test scores in low-income schools decrease by 0.12% of a standard deviation, while the impact on higher-income schools is statistically insignificant. Similarly, each additional school day above 26.7°C reduces the scores of Black and Hispanic students by 0.10–0.12% of a standard deviation, whereas the effect on non-Hispanic White students is negligible. One week of temperatures above 26.7°C decreases the learning capacity of the average Black or Hispanic student by an amount equivalent to a 5–6% reduction in teacher value-added effectiveness.	
5	Data from 8,003 children aged 14–22 in the United States were analyzed from the National Longitudinal Survey of Youth (NLSY). The analysis focuses exclusively on mathematical test performance	1987-2006	There is an insignificant relationship between climate and human capital. A 1-degree day increase in temperature across all days between two tests—a substantial change—results in a decrease in math performance of only 0.630 percentile points. This suggests that parents are offsetting more than a 6-percentile-point accumulated decline in human capital caused by exposure to warmer temperatures. It is concluded that individuals engage in significant adaptation efforts to mitigate the impact of high-temperature days on the human capital accumulation of children	Analysis is not provided	Zivin et al, 2018 [21]
6	The dataset from the Stanford Educational Data Archive (SEDA), USA,	2008-09 to 2014-15	In geographic regions with an average maximum temperature of 55°F, a 1°F increase results in a reduction in average achievement by 0.00213, equivalent to a 4.71% decrease in the mean. In	The estimated effects for each racial group align with previous research on achievement gaps. Asian students	Roach & Whitney , 2022 [23]

	includes assessment outcomes for students in third through eighth grade, covering both English Language Arts and Math tests		warmer areas, with an average temperature of 75°F, the decrease is smaller at 0.00117, or 2.6% of the mean. It is statistically significant that additional days with temperatures exceeding 100°F negatively impact student learning, while more days with temperatures below 60°F enhance learning outcomes. Specifically, for each additional day above 100°F, average student achievement decreases by 2.3% of the mean, whereas additional days below 60°F are associated with increased scores	demonstrated the highest performance, followed by White, Hispanic, and Black students. Additionally, the marginal effect of an increase in median income decreases when race controls are included in the analysis.	
7	The dataset includes information from 1,729 high schools across 164 cities in Korea, encompassing 1.6 million students. The assessments cover Reading, Mathematics, and English Language	2009-2013	High summer temperatures significantly impact math and English test scores. An additional summer day with a maximum temperature of 34°C or higher, compared to a day with a maximum temperature in the 28–30°C range, reduces math and English test scores by 0.0042 and 0.0064 standard deviations, respectively. Over ten such days, these reductions amount to 0.042 and 0.064 standard deviations, respectively. There is no significant impact on reading test scores. However, higher temperatures in the previous year negatively affect overall test performance Previous summer had negative effects on the test scores.	High summer temperatures have a greater impact on the test scores of students residing in relatively cool cities, while they do not have a statistically significant effect on students living in warmer cities. In cities with an average maximum daily temperature below 28.5°C, one additional day with a maximum temperature of 34°C or higher, compared to a day in the 28–30°C range, decreases reading, math, and English test scores by 0.0073, 0.0124, and 0.0105 standard deviations, respectively	Hyunkuk Cho, 2017 [20]

Park et al. (2020) analyzed test scores of approximately 10 million American high school students who participated at least twice in the Preliminary Scholastic Aptitude Test (PSAT), a national standardized exam, between 2001 and 2014. They associated the test scores with local daily average maximum ambient temperatures and the number of days exceeding a given multiple of 10°F (~5.55°C) in the 365 days before the test. Racial, economic, and demographic data were also collected and associated with the temperature data [24].

The study found that exposure to high ambient temperatures during school days, up to four years prior to the test, has a significant impact on students' cognitive capacity. An increase of 1°F (0.55°C) above 26.7 C, during school days in the year prior to the test decreases the mean learning gain of students by almost 1% over a complete year. Each additional school day with an average maximum temperature of 90°F (32.2°C) or 100°F (37.77°C), relative to a day with a temperature close to 60°F (15.55°C), lowers cognitive gains by 0.17% and 0.26% of the annual worth of learning, respectively [24].

Exposure to high temperatures during school days up to four years prior to the test causes a considerably higher cognitive loss than exposure during the year prior to the test. Sustained exposure to daily maximum ambient temperatures up to 2°C higher compared to the current temperatures, reduces cognitive gains by 7% compared to the average worth of learning. Exposure to high temperatures outside the school period was not found to impact students' cognitive capacity.

Garg et al. (2020) analyzed two sets of cognitive test results in India. The analysis included Mathematics and Reading test scores for over 4.5 million primary school students, based on the Annual Status of Education Report (ASER). It also incorporated data from the Young Lives Survey (YLS), which included 1,008 children born between January 1994 and June 1995, and 2,011 children born between January 2001 and June 2002. The test results were associated with local temperature and other climatic data from the year before the tests. Temperature data were classified into 10 different bins, with the coldest bin including average daily temperatures below 13°C and the warmest bin including temperatures above 29°C. The YLS test results were also linked to local socioeconomic information [22]. A flexible econometric model was used to associate the scores with temperature, humidity, and rainfall, drawing on previous research by Deschenes and Greenstone (2011) [33] and Hsiang (2016) [34].

It was found that one additional day in the previous year with an average daily temperature higher than 29°C, compared to a day with a temperature between 15°C and 17°C, decreases Reading and Mathematics performance by 0.002 and 0.003 standard deviations, respectively, in the present year. Ten extra days with an average daily temperature above 29°C in the previous year were found to reduce Reading scores by 0.02 and Mathematics scores by 0.03. Additionally, story reading ability and division-solving ability were reduced by 1 percentage point, while the impact on word or letter reading skills was insignificant. These results were statistically significant, with the impact of hot days being significant only for the harder questions in both reading and mathematics tests. The study did not identify any impact of short-term temperatures on test scores, and heat stress over the four days prior to the test did not have a significant impact on student performance [22].

Park et al. (2021) analyzed global test score data from more than 500,000 students in 58 developing and developed countries that participated in the PISA International Student Assessment between 2000 and 2015, administered by the Organisation for Economic Co-operation and Development. The assessment involves representative samples of 15-year-old students taking harmonized exams in mathematics, reading, and science. The test scores were associated with country-specific temperature and income data to identify the impact of heat stress on students' cognitive performance. Data on the daily maximum temperature of each station were used, clustered into temperature bins of 5.5°C, ranging from -17.7°C to 60°C. The number of days in each bin over the previous 5 years was counted for each station. The study investigated the impact of all days with a daily maximum temperature above 26.7°C on student performance. The analysis concluded that school days with high temperatures during the last 3 years prior to the PISA exam impacted students' performance. Each additional school day above 26.7°C during the 3 years prior to the exam decreased exam scores by 0.18% of a standard deviation, while an increase by a standard deviation of the days above 26.7°C, conditional on year and station, resulted in 14 school days. Robustness tests showed that the findings were robust and not driven by false associations between long-term cognitive achievement trends and local warming patterns. School days before the exam were found to exclusively impact exam scores and human capital accumulation, while the impact of high-temperature during non-school days was insignificant, indicating that exposure to heat interferes with learning time [19].

Park et al. (2021) analyzed the test scores in mathematics and English Language Arts (ELA) from schools in over 12,000 US districts. The tests were administered to third and eighth graders. The data were sourced from the Stanford Education Data Archive (SEDA). In total, over 270 million test scores covering the period from 2009 to 2015 were analyzed. The test data for each district were associated with the corresponding climatic data, particularly the daily maximum temperature for school days from June 1 to February 28 in the year before the test, collected from 3,400 climatic stations [19].

The analysis showed that exposure to high temperatures during the school period significantly affects student performance. For each additional school day with temperatures above 27.6°C, student performance was reduced by almost 0.04% of a standard deviation. Specifically, mathematics scores were reduced by 0.11% and ELA scores by 0.04% of a standard deviation, with the average score reduction being close to 0.07% of a standard deviation [19].

Zivin et al. (2018) analyzed data from 8,003 children and young people aged 14-22, participating in the National Longitudinal Survey of Youth (NLSY) in the USA. The study examined the short- and long-term exposure to high temperatures on mathematical test scores. To assess the impact of long-term exposure to high temperatures, three climatic indicators were used: a) the average of the degree days base 21°C over the relevant period, b) the percentage of days in each 2°C bin, and c) the average temperatures during January to February and July to August. All days, including school and non-school days, were considered. Two models were defined and used. The first model investigated the impact of the sum of temperature between successive tests, while the second model examined the impact of accumulated temperature from birth until the date of the test. It was found that the impact of high temperatures on mathematical scores was not significant for both models. A 1-degree day increase in temperature across all days between two tests, a rather substantial change, decreased mathematics performance by only 0.630 percentile points. The lack of impact is attributed to potential adaptation measures undertaken to minimize the impact of high temperatures on students' cognitive performance [21].

Roach and Whitney (2022) analyzed data provided by the Stanford Educational Data Archive (SEDA), USA, including assessment outcomes from 2008-09 to 2014-15 for students in third through eighth grade for both English/language arts and mathematics tests. The test scores of each district were correlated with the corresponding median daily maximum ambient temperature. The study included data only for the school period, excluding non-school days. Daily temperature data were clustered into bins of 5.5°C (10°F), centred at 37.77°C (100°F), 32.22°C (90°F), 26.66°C (80°F), and so on. It was found that in areas with an average maximum temperature of 55°F (12.77°C), an increase in temperature by 1°F (0.55°C) decreased the average score by 4.71%, while in areas with a warmer average maximum temperature of 75°F (23.88°C), the corresponding average decrease was 2.6%. Additionally, for each additional day above 100°F (37.77°C), the mean student achievement was found to decrease by 2.3% [23].

Cho (2017) analyzed test data from the Korean college entrance exam in reading, mathematics, and English language from 1,729 high schools located in 164 cities in Korea. The sample included almost 1.3 million observations of tests performed in November over the period 2009-2013. The test scores were associated with the corresponding daily maximum ambient temperature data. It was observed that high ambient temperatures during the previous summer had negative effects on the scores of the current year. An additional summer day with a maximum daily ambient temperature above 34°C, compared to a summer day with temperatures between 28-30°C, resulted in a decrease in mathematics and English language scores by 0.0042 and 0.0064 standard deviations, respectively. Ten additional warm days decreased the test scores by 0.042 and 0.064, respectively. In contrast, the impact on reading scores was insignificant [20].

4. Climate adaptation techniques and their impact on student cognitive performance

Various techniques aiming to lower indoor temperatures, improve thermal comfort and increase wellbeing have been implemented and studied.

4.1. Adaptation techniques to reduce endogenous heat accumulation

Exposure to heat causing hyperthermia can affect cognitive functions in humans, resulting in reduced performance and effectiveness. Hyperthermia may lead to elevated brain, skin, and core temperatures, which are inexorably associated with significant cognitive impairments in attention, memory, recognition, and processing speed [35] [36]. Medical research has provided some limited evidence that skin and brain cooling may modulate potential increments in cognitive function, improve thermal comfort, and reduce thermal strain, thereby supporting human physiological and psychological wellbeing [37] [38] [39].

Several cooling techniques aimed at reducing endogenous heat accumulation, and thus limiting core and/or skin temperature, have been explored to investigate how temperature reduction affects cognitive performance and reduces heat stress [40] [41]. Cooling techniques that decrease core temperature can reduce thermoregulatory responses caused by information received via endogenous thermoreceptors, chemoreceptors, and baroreceptors, while skin cooling aims to reduce blood flow in the skin and alleviate cardiac and brain strain [41]. Both cooling techniques aim to improve cognitive functions by increasing the attentional availability of resources. Techniques investigated include head cooling using cold packs, cooling collars, cold air exposure of the torso, ice slushies, slurries, cooling the blood in the common carotid artery, cooling vests, ice towels, cool showers, menthol mouth rinses, and water cooling of the face [42] [43].

Although there isn't full agreement on the beneficial impact of localized head cooling on cognitive performance, and the corresponding literature remains equivocal, many medical researchers agree that the potential positive effect is task-specific [44]. This is attributed to the different homeostatic temperatures of various brain areas, with a dorso-ventral temperature gradient being demonstrated in human bodies [45]. Application of head cooling to a specific brain area seems to reduce its load, thereby recovering its potential to execute the respective cognitive tasks [8]. Experiments have shown that head cooling improves the capacity of working memory but not visual recognition, mainly due to the different impacts of localized head cooling on the frontal and temporal parts of the brain responsible for specific cognitive functions [46] [47]. In general, there is agreement that cooling the frontal part of the brain presents the highest benefits compared to the occipital and temporal portions of the head [48].

4.2. Adaptation measures to improve operational conditions in work and learning environments

Engineering environmental controls designed to improve operational conditions in work environments have been proven to significantly impact cognitive components. The use of air conditioning, optimized airflow rates, personalized ventilation systems, clothing control techniques, and urban heat mitigation measures are among the most studied engineering adaptation strategies. Two relevant studies conducted in the USA have shown a significant increase in student performance following the installation of air conditioning systems [24]. The installation of a cooling system in previously non-air-conditioned schools in New Haven, Connecticut, was found to increase reading scores by 15% of a standard deviation [49]. Similarly, the use of air conditioning in the Los Angeles Unified School District increased reading and mathematics scores by 5-10% [50].

4.3. Use of air conditioning as an adaptation measure

The impact of indoor temperature levels and the potential use of air conditioning in classrooms on students' cognitive performance is typically investigated through direct or indirect experimental studies. These studies often involve short- or medium-duration exposure of students to a range of classroom temperatures, usually varying between 20°C and 30°C.

Direct experiments assess the cognitive performance of two separate groups of students with similar characteristics, placed in air-conditioned and non-air-conditioned rooms, respectively. Indirect experiments evaluate the performance of a predefined group of students placed in the same room and exposed to a range of indoor temperatures over a short or medium period. Finally, non-experimental assessment studies analyze a large number of test results from students participating in major national exams, conducted in various locations with different ambient temperatures. These studies consider the relative impact of local temperature levels on students' performance.

Numerous indirect experimental studies aim to assess the impact of indoor temperature on students' cognitive performance. These studies vary in the size of the testing panel, the duration of the experiment, the nature of the tests performed, the range of temperatures considered, the type of cognitive component assessed, local climatic conditions, and the methodology used to analyze the results.

An analysis of 18 indirect experimental studies concluded that in temperate climates, student performance increased by an average of 20% when the classroom temperature was lowered from 30°C to 20°C. Optimal performance is achieved at temperatures below 22°C [17]. In tropical climates, studies found that the optimal temperature for acclimatized students is a few degrees higher compared to temperate climates [51] [52].

Relationships between relative cognitive performance and classroom temperature have been proposed by Auliciems (1972) and Wargocki and Wyon (2013) [53], [54]. A third relationship proposed by Seppanen et al. (2006), was based on results collected from various environments, not just classrooms [55]. These relationships follow the Inverted U model, which postulates an inverted U relationship between relative cognitive performance and indoor temperature, suggesting a single optimum performance temperature varying between 16.1°C and 22°C [14].

However, numerous other environmental, task-related, and performer-related confounding factors that are not considered by these proposed relationships can affect students' cognitive performance [55], [56]. Additionally, the suggested correlations pool together performance data from a plethora of cognitive tasks of diverse nature and complexity related to various human performance domains processed by different parts of the human brain. The impact of thermal stress on cognitive performance depends on the specific part of the brain engaged, and the influence of temperature varies for different tasks depending on their nature and complexity [57] [7].

There are five direct experimental studies assessing the impact of air conditioning on students' cognitive performance [58], [60], [60], [61], [62], [63].

Schoer and Shaffran (1973) exposed a group of 10-12-year-old pupils to an air-conditioned classroom maintained at 22.5°C, while a second similar group was assigned to a non-air-conditioned classroom kept at 26°C. The experiment lasted between six to eight weeks, during which the students performed nineteen different simple and complex tests. The performance of the students in the air-conditioned classroom was about 5.7% higher compared to the group in the warmer classroom. However, concerns were raised that the difference in performance might have been influenced by the gradual anger and discouragement of the two groups of students over the course of the experiment [58].

Wargocki and Wyon (2006 and 2007) conducted a crossover experiment in pairs of classrooms in a Danish school during the summer period. Different air temperatures were imposed in each classroom using split-type air conditioners for a week, and the temperatures were switched between the classrooms in the following week. The average temperatures in the air-conditioned and non-conditioned classrooms were 21.6±1.6°C and 24.9±1.7°C, respectively. During the experiments, the students completed several types of cognitive tasks. Students in the air-conditioned classrooms showed increased speed in subtraction and addition tasks and a decrease in errors in subtraction but not in addition. There was no significant effect of lower temperature on tasks related to logical thinking, acoustic proof reading, and reading comprehension [60], [60].

Mishra and Ramgopal (2015) compared the performance of 50 university students in India who attended courses in air-conditioned (AC) and naturally ventilated (NV) classrooms over a two-year period. The average indoor temperatures in the AC and NV classrooms during the experiments were between 24°C – 24.5°C and 28°C – 30°C, respectively. Almost similar levels of average student satisfaction were observed in both classrooms, with the satisfaction percentage differing by no more than 5%. No statistically significant difference in average task performance was observed between the students in the NV and AC classrooms. However, significant differences were noted on specific days. The lack of differences in the long-term perspective is explained by the ability of students acclimatized to higher temperatures to adapt to their environment by adjusting critical parameters according to the magnitude of thermal stress [61]. This finding aligns with the extended U model of cognitive performance proposed by Hancock et al. (2007) [64].

Porras-Salazar et al. (2018) conducted a comparative experiment with thirty-seven 11-year-old children in two classrooms in an elementary school in Costa Rica over a period of two weeks. During the first week, one classroom was air-conditioned using a split system, while no cooling was provided in the second classroom. In the second week, the second classroom was air-conditioned, while the first one was not, following a crossover experiment design. The indoor temperature varied between 24.5°C and 26°C in the air-conditioned classroom and around 30°C in the non-cooled classroom. Students were invited to complete specific sensation and cognition-related questionnaires and tests. About 25% of the students in the air-conditioned classroom were dissatisfied with the indoor temperature due to overcooling. Students in the air-conditioned classroom showed higher, but not statistically significant, performance on tasks related to the speed and accuracy of multiplication, and better performance in the speed of reading and comprehension, but not in accuracy. On average, students in the lower temperature classroom showed almost 7.5% better performance in speed and 0.6% in accuracy for each 1 C decrease in classroom temperature. The decrease in indoor temperature was found to improve the performance of less able students more than that of the most able ones [62].

Cedeno Laurent et al. (2018) evaluated the impact of air conditioning on the cognitive performance of 44 college students during heat waves in a heat-dominated climate in the USA using an observational cohort study. The experiment lasted for 12 days, and students were split into two groups. The first group lived in air-conditioned conditions, while the second group lived in a naturally ventilated, non-air-conditioned environment. Average indoor temperatures were approximately 21.4°C in the cooled environment and 26.3°C in the non-cooled environment. Comparative tests were performed to assess the cognitive speed and working memory of both groups of students. It was found that students living in air-conditioned spaces presented significantly higher cognitive performance, with improvements ranging from 4.1% to 13.4% in reaction time and reduction throughput compared to those living in the non-cooled space [63].

Park et al. (2020) analyzed the impact of air conditioning on the cumulative exposure of students to excess heat. The study examined the scores of 10 million students participating in the PSAT standardized exam. Using an econometric model, it was estimated that the potential use of air conditioning in classrooms can almost fully offset the effects of cumulative exposure to heat. On average, the potential use of air conditioning in classrooms can offset 73% of the cognitive impact on students during hot school days. An increase in the school year temperature by 1°F in schools without air conditioning reduces students' performance by 0.0032 standard deviations, while in fully air-conditioned schools, the impact is 0.0025 standard deviations lower [24].

Studies aiming to assess the association between short-term exposure to temperature and the performance of students participating in national exams, despite not directly referencing air conditioning, provide a valuable source of information due to the high number of participants and the extensive range of temperatures under which the data are collected. National exams are conducted during the same period for all students, likely under similar indoor climatic control conditions.

We analyzed three studies from the USA and China involving data from about 20 million exam records, covering a wide range of ambient temperatures. All studies associated the score of each specific record with the corresponding local ambient temperature and assessed the impact of short-term exposure to temperature on the global cognitive performance of the students [65], [21], [66].

Park (2022) analyzed 4,509,102 exam records from 999,582 students participating in the Regents Exams in New York, USA, covering 91 different exam sessions over a 13-year period from 1998-1999 to 2010-2011. He associated the score of each record with the corresponding ambient temperature, ranging between 21.1°C and 32.2°C, collected from the closest meteorological station. Nearly 18% of the students participated in at least one exam with temperatures exceeding 32.2°C [66].

The study found that high temperatures significantly affect students' achievement during exams and their chances of graduating. Students' performance decreased by 0.009 standard deviations for each degree Fahrenheit increase in exam time temperature. Taking an exam at 32.2°C decreased the chance of passing a particular subject by almost 10%. An increase in exam time ambient temperature by 3.4°C was found to reduce students' chances of graduating by about three percentage points [65].

Zivin et al. (2015) focused on analyzing the results of the National Longitudinal Survey of Youth (NLSY79) in the USA, investigating the short- and long-term impact of hot weather on students' cognitive performance. The NLSY survey involves over 12,000 young people aged 14-22 in the USA, and after 1986, the participants were surveyed in their homes. The study associated local ambient temperatures with the examination scores of each child in mathematics, reading recognition, and reading comprehension. High ambient temperatures were found to have a significant impact on children's performance. Performance in mathematics decreased almost linearly above 21°C, with a statistically significant decline above 26°C. However, the relationship between temperature and reading assessment was not statistically significant. The study did not identify any long-term impact of ambient temperature on children's cognitive performance [21].

Zivin et al. (2020) investigated the impact of ambient temperature on the high-stakes cognitive performance of students participating in the National College Entrance Examination in China. They used data from 14 million records collected between 2005 and 2011 from 2,227 counties in China. The performance data were correlated with the corresponding daily temperature records from 752 weather stations. The study found that high ambient temperatures affect students' cognitive performance, with most of the impact concentrated on high-performing students. An increase in ambient temperature by 2°C was found to decrease the total test scores by 0.68%, a percentage almost twice as large as the impact estimated in the USA [66].

4.4. Increased ventilation rates as an adaptation measure

It is widely agreed upon that increased air movement in buildings, whether through natural or mechanical means, can achieve thermal comfort conditions even at higher indoor temperatures [67]. While the impact of increased air movement on indoor thermal comfort is well documented, its effects on the cognitive performance of humans, particularly students, is only partially investigated.

Research has examined the impact of various ventilation systems and techniques on cognitive performance under higher indoor temperatures [60], [68], [69], [70], [71], [72], [73], [74]. Most studies have confirmed that higher airflow rates and lower indoor CO_2 concentrations positively affect students' cognitive performance in simple tasks such as language and mathematics, contributing to higher examination scores [75].

The potential contributions of personalized ventilation systems [76], [77] and ceiling fans [78] have also been experimentally tested to assess their cognitive impact in non-educational environments. Both systems were found to significantly improve participants' cognitive performance under increased indoor temperature conditions.

These studies confirm that poor air quality affects both typical schoolwork, i.e., performance in simple learning tasks like mathematics and language exercises, as well as pupils' examination grades and end-of-the-year results.

Wargocki and Wyon (2006) investigated the impact of increasing outdoor air supply from 3 to 8.5 l/sec during a one-week crossover experiment in two fully mechanically ventilated classrooms in Denmark [60]. Seven different cognitive tests, including numerical and language ones, were performed by the students under the two airflow conditions. Increased airflow rates resulted in a reduction of indoor CO_2 concentration from 1300 ppm to 900 ppm, significantly improving indoor air quality. Under the high airflow rate, almost 70% of the tests were better accomplished compared to the low ventilation conditions. Students significantly improved the speed at which they completed two language and two numerical cognitive tasks, while the impact on the number of errors was insignificant [60].

Murakami et al. (2006) studied the impact of low and high classroom ventilation rates on the cognitive performance of about 70 college students in Japan. An air handling unit was installed in each classroom to vary the ventilation rate. Numerous cognitive tests were performed to evaluate the students' understanding of the given lectures. The temperature during the experiments was kept at 25°C. The high and low ventilation rates were 1,190 m^3/h and 136 m^3/h, respectively, while the CO_2 concentration under the low and high ventilation rates was 1,000 ppm and 5,000 ppm, respectively. Higher ventilation rates were associated with a significant improvement in students' learning performance, varying between 5.4% to 8.7% depending on the cognitive task, compared to performance under the low ventilation rate [68].

Bakó-Biró et al. (2012) analyzed the impact of increased ventilation rates in 16 classrooms across 8 primary schools in the UK. A mechanical ventilation system was installed, increasing the air ventilation rate from 1 l/sec to 8 l/sec. The experiment lasted for at least 3 weeks, involving about 200 pupils. The indoor temperature during the experiments varied between 18°C and 26°C. Several computerized performance tests were conducted to assess the impact of increased ventilation on students' cognitive performance. Before the intervention, indoor air quality levels were quite poor. Increased ventilation rates significantly reduced indoor CO_2 levels below the accepted threshold. Higher ventilation rates significantly improved pupils' cognitive performance in attention and vigilance tasks. Compared to low ventilation rates, higher airflow contributed to increased scores in word recognition by 15%, picture memory by 8%, colour word vigilance by 2.7%, and choice reaction by 2.2% [72].

Haverinen-Shaughnessy et al. (2010) analyzed the association between ventilation rates and students' performance in one hundred elementary schools in the southwest United States. During the monitoring period, ventilation rates in the classrooms varied between 0.9 l/sec and 7.1 l/sec, while indoor CO_2 concentrations ranged from 661 to 6000 ppm. A linear association between classroom airflow rate and students' academic achievement was observed. An increase in the ventilation rate by 1 l/sec corresponded to an increase in mathematics and reading performance by 2.9% and 2.7%, respectively [70].

Two other studies with similar characteristics were performed by Haverinen-Shaughnessy and Shaughnessy (2015) and Mendell et al. (2016) [71], [74]. The first study, conducted in Southwestern USA, involved 3,109 students from 70 elementary school districts. It was observed that for each increase in the ventilation rate by 1 l/sec in the range between 0.9 – 7.1 l/sec/p, the average mathematics scores of the students increased by 0.5% [71]. The second study, conducted in California, used data from 150 classrooms in 28 schools. In most cases, a positive association between ventilation rates and test scores was observed. A statistically significant increase of 0.6 points was observed in English tests for each 10% increase in prior ventilation rates, while the impact of increased ventilation rates on mathematics tests was not statistically significant [74].

Coley et al. (2016) investigated the impact of higher ventilation rates on the cognitive performance of eighteen pupils aged ten to eleven in the UK. The range of airflow in the classroom was controlled by opening and closing windows. Temperature was maintained between 22.5°C and 24.5°C using a split air conditioner. CO_2 levels varied between 500 ppm and 4,000 ppm, depending on the ventilation rate. Students performed several computerized cognitive tests from the Cognitive Drug Research assessment, split into four test sessions under low CO_2 levels (below 1,000 ppm) with a ventilation rate close to 13 l/sec per pupil, and another four sessions under high CO_2 concentrations (2,000 ppm to 4,000 ppm) corresponding to 1.5 l/sec per pupil. Higher ventilation rates were found to significantly decrease the reaction time of the pupils, while the impact on accuracy scores, digit vigilance, memory, and continuity of attention was insignificant [69].

Petersen et al. (2016) investigated the impact of increased airflow rates on the cognitive performance of 10-12-year-old students in a crossover experiment conducted in four classrooms across two different schools in Denmark. Four different cognitive performance tests, focusing on logical thinking and short-term concentration, were performed. The indoor CO_2 levels in the low and high concentration classrooms were approximately 900 ppm and 1,500 ppm, respectively, over a period of 3.5 hours. Indoor temperatures were kept almost constant during the experiment, ranging between 19°C and 21°C. For all types of tests performed, students exposed to higher ventilation rates (6.6 l/sec) and lower CO_2 levels showed better performance compared to those exposed to higher CO_2 concentrations and lower ventilation rates (1.7 l/sec). Specifically, performance improved by 7.4% in reading and comprehension, 6.3% in the addition test, 4.8% in number comparison, and 3.2% in grammatical reasoning [73].

4.5. Other adaptation and heat mitigation measures and technologies

Several efficient adaptation measures and heat mitigation technologies capable of counterbalancing the impacts of overheating have recently been developed and implemented in large-scale projects [79]. Available technologies and techniques include the use of advanced materials for building and city fabric, increasing greenery coverage, solar control devices, evaporation systems, and cooling systems based on the use of low-temperature natural heat sinks [80]. Advanced reflective, photonic, and fluorescent materials for building envelopes and urban fabrics exhibit very high reflectance to solar radiation and high thermal emittance in the atmospheric window [81]. When combined with well-irrigated greenery and solar control systems, these materials can decrease peak ambient temperatures by up to 4.5°C and improve the local microclimate [83], [84]. Further studies are necessary to investigate the impact of these natural and artificial mitigation and adaptation techniques on students' cognitive performance.

5. Social heterogeneities in cognitive performance caused by overheating

Existing studies have identified significant racial and geographic heterogeneities in the cognitive performance of students caused by cumulative exposure to heat. Differences in access to air conditioning and higher ambient temperatures in deprived geographic areas are considered the main reasons for these disparities

Past research has shown that fewer schools in disadvantaged areas in the USA have air conditioning compared to those in wealthier areas [84], [85]. According to Park et al. (2020), lower-income students in the USA are 6.2% more likely to attend schools with inadequate air conditioning compared to higher-income students [24]. Additionally, previous research has shown that disadvantaged households in the USA, Australia, and Europe live in warmer neighbourhoods where the urban heat island effect can be up to 6°C higher than in areas where wealthier people live. These disadvantaged areas also have a lower density of green spaces, public goods, and environmental amenities [86], [87], [82], [88], [90].

Racial inequalities in educational outcomes are well-documented and are primarily attributed to social discrimination, racial bias, and cultural differences [89], [90]. Additionally, cumulative exposure to heat can have varied impacts based on income, race, and geographic location. Studies by Park et al. (2020), Garg et al. (2020), Park et al. (2021), Roach and Whitney (2022), and Cho (2017) have shown that cumulative heat exposure significantly affects the cognitive performance of minorities and disadvantaged low-income students more than their advantaged counterparts [20], [24], [22], [19], [23], [20]. The reasons for these disparities include: a) Substantially lower access to school and home air conditioning for minorities and low-income students. b) Higher ambient temperatures in neighbourhoods where minorities and low-income students live. c) The lack of capacity for disadvantaged families to compensate for cognitive loss due to overheating, such as through private tutoring. d) Advantaged students may attend schools where teachers can compensate for lost learning [24].

Several studies have documented that cumulative exposure to excess heat significantly contributes to racial disparities in educational outcomes. According to Park et al. (2020), the cognitive performance of Black and Hispanic students in the USA is almost three times more inhibited by potential heat exposure during the previous school year compared to white students. The impact of heat exposure from the previous year was nearly twice as high for students living in low-income zones compared to those in high-income zones [24].

Exposure to a 1°F , (0.55 C), warmer school year over the past four years has been found to cause an almost 80% larger impact on Black and Hispanic students than on white students. Additionally, one extra day above 90°F (32.2°C) in each of the four previous school years has a nearly 40% higher impact on Black and Hispanic students compared to white students. These performance differences are due to discrepancies in heat exposure during the school period, caused by the partial lack of air conditioning in schools in the poorest geographic zones, as well as significant differences in ambient temperatures between the zones where various racial groups live. Cognitive losses due to cumulative heat exposure seem to explain between 3% and 7% of the gap in PSAT scores between white, Black, and

Hispanic students. The authors estimate that heat exposure accounts for up to 13% of the racial achievement gap in the USA.

Garg et al. (2020), in their analysis of the cumulative impact of heat on the cognitive performance of students in India, found that students from the poorest families receiving state subsidies had lower test scores compared to students from wealthier families [22].

Park et al. (2021) analyzed the performance of students in PISA exams and concluded that the impact of heat exposure on cognitive performance is higher in poorer countries compared to richer ones. The effect of the same temperature event was almost three times greater for low-income students than for high-income students. Based on their analysis, it was concluded that Brazilian students may learn 6% less than their South Korean counterparts due to much higher heat exposure, which accounts for almost 33% of the differences in exam performance [19].

Park et al. (2021) analyzed the impact of cumulative heat exposure on students in grades three to eight in the USA and concluded that low-income and disadvantaged students living in deprived neighbourhoods are more affected than their advantaged counterparts. Each additional school day above 26.7°C results in a 0.12% decrease in test scores for low-income schools, while no significant impact is observed in higher-income schools. For each week above 26.7°C, the average cognitive performance of Black and Hispanic minorities is reduced by an amount equivalent to reducing teacher value-added by 5-6% of a standard deviation. This disparity is explained by significant differences in the availability of air conditioning in schools and homes between the White population and other minorities [19].

Roach and Whitney (2022), in their study on the impact of cumulative heat exposure on elementary and middle school students in the USA, found that their data aligns with previous research on the impact of heat on different racial groups. Asian students were found to perform better than White, Hispanic, and Black students [23].

The impact of heat and the corresponding differences in performance seem to be more significant in cooler geographic regions than in warmer ones. Goodman et al. (2020) found that cognitive losses in the USA are more significant in heating-dominated zones compared to cooling-dominated zones. Similarly, Cho (2017) found that exposure to high summer temperatures in Korea mainly affects students living in cooler parts of the country, while the impact on students living in relatively warm cities was not statistically significant. In cities with an average maximum daily temperature below 28.5°C, one additional day at or above

34°C, compared to a day with a maximum daily temperature between 28°C and 30°C, decreased students' scores in reading, mathematics, and English by 0.0073, 0.0124, and 0.0105 standard deviations, respectively [20].

6. Expected Impact of Climate Change on the Future Cognitive Performance of Students

Considering the significant impact of cumulative exposure to excess heat on the cognitive performance of students, three studies have assessed the potential future cognitive losses due to global warming [22], [23], [24].

Garg et al. (2020), using a longitudinal study from Southern India and future climatic projections for the years 2075-2099 obtained from the Community Climate System Model (CCSM v4, Gent et al., 2011), reported that the expected temperature increase would decrease reading and mathematics scores by 0.03 and 0.04 standard deviations (SD) each year, respectively [91]. Over the course of a student's education, this corresponds to a schooling loss equivalent of nearly two years. Using the assumptions and methodology proposed by Evans and Yuan (2019) [92], and assuming that an increase in literacy skills by one standard deviation corresponds to a 51% increase in wages, it was estimated that a potential rise in hot days by 10 could result in a 3% decrease in wages [22].

Park et al. (2020) estimated the magnitude of heat-related learning disruptions caused by global warming for an average high school student by 2050, relative to a student attending school in 2010. Considering climatic model predictions that foresee an average increase in ambient temperature in the USA by 5°F (~2.8°C) and a 10-year cumulative impact of heat on students' lives before the PSAT exams, it is estimated that future overheating would reduce the 2050 cognitive achievement of students by 0.1 standard deviations, assuming no additional penetration of A/C systems in schools and homes and neglecting potential non-linearities in the association between temperature and cognitive losses for temperatures outside the range of historical values. If A/C use in schools increases according to the existing trend, the loss in cognitive performance could be less than 0.05 standard deviations. If all schools are air-conditioned by 2050, the damage would be less than 0.025 standard deviations. The impact of overheating on cognitive performance is found to be higher in the Northeast and other cooler geographic zones of the country, where the cognitive impact per degree of temperature increase is greater [24].

Additionally, the damage will be considerably higher for poorer populations in the USA and globally due to reduced penetration of air conditioning, especially among low-income groups. As reported by Pavanello et al. (2021), air conditioning penetration in developing countries is unevenly distributed across various income groups, with very low penetration figures for the poorest people [93]. Despite a significant increase in air conditioning penetration by 2050 [94], it is estimated that between 64 to 100 million families with electricity access in countries like India, Mexico, Indonesia, and Brazil will not be able to adequately satisfy their cooling needs.

Roach and Whitney (2022) have also assessed the potential cognitive loss caused by global warming in the USA by 2050. Using the IPCC forecast for a temperature increase of 1.5°C, they estimated that the average performance of elementary school students may decrease by about 9.8%, assuming no adaptation measures are taken. Similar to Park et al. (2020), they found that in geographic zones with average temperatures below 65°F (18.3°C), cognitive loss will be significantly higher than in warmer zones. An increase in temperature by one degree in cooler parts (<18.3°C) may significantly reduce students' cognitive performance, while the impact in warmer areas (>84°F or 28.9°C) is not expected to be statistically significant [23].

7. Discussion and conclusions

We reviewed seven existing studies that investigated the effects of prolonged heat exposure on students' cumulative cognitive performance. Collectively, these studies analyzed an extensive dataset comprising nearly 14.5 million students from 61 countries, linking individual learning outcomes to heat exposure. The findings suggest that long-term heat exposure negatively impacts students' cumulative learning. Six of the seven studies identified a statistically significant negative relationship between extended heat exposure and cognitive performance, while one study found the impact to be minimal [21].

The studies examined the influence of heat exposure over periods ranging from one to five years prior to the tests. However, the estimated timeframes during which heat exposure affected cognitive performance varied across the studies. Two studies focusing on the PISA exam concluded that high temperatures influenced cognitive performance up to three and four years before the tests, respectively [19], [24]. Meanwhile, two studies observed the impact as limited to the previous school year [22], [20], and another two studies restricted the effects to the current school year [19], [23].

Significant differences in the modelling approaches adopted by these studies may explain the observed discrepancies. The choice of temperature data used as a proxy appears to have a substantial impact on the results of the analyses. Two studies linked cognitive performance to the average daily temperature, while the remaining studies used the daily maximum temperature as a proxy [22], [21]. The use of daily maximum temperature seems to be a more appropriate choice, as schooling typically takes place during the hours when maximum temperatures occur. In contrast, the average daily temperature includes nighttime data, which is unlikely to influence cognitive performance significantly.

The effect of the selected temperature proxy becomes particularly evident in analyses of the same dataset of Brazilian students. Melo and Suzuki (2021), who based their analysis on temperature during the exam, found a pronounced impact of heat on students' performance [95]. Conversely, Li and Patel (2021), who used the average daily temperature, arrived at opposite conclusions [96]. A further analysis of the dataset by Melo and Suzuki (2021), employing both temperature proxies, demonstrated that using the average daily temperature significantly reduces the effect estimates [95].

There remains an open question as to whether cognitive loss occurs primarily during the school period or if exposure to high temperatures during non-school days in previous periods affects students' cognitive performance. Four studies have excluded weekends and non-school days from their analysis of the relationship between temperature exposure and learning performance [24], [66], [23], while the others have included them. Park et al. (2020, 2021) investigated the impact of weekends and holidays on student performance using econometric models and found no evidence of diminished achievements among students [24], [19]. None of the studies concluded that the impact of non-school days is significant. Although further research is required, it appears that time spent in school plays a decisive role in human capital loss and accumulation.

The characteristics of cognitive tasks performed and assessed determine the magnitude of the loss associated with heat exposure. Cognitive tasks of varying types and complexities activate different regions of the brain. Heat stress affects the temperature of different brain regions in distinct ways, and potential cognitive loss depends on the specific thermal load experienced by the brain areas involved [57], [97]. According to Ayres and Paas (2012), the Cognitive Load Theory of instructional design posits that the cognitive system consists of Working Memory (WM) and Long-Term Memory (LTM) [98].Working Memory has limited capacity and duration and is utilized to hold and process information needed for immediate tasks, such as problem-solving, decision-making, and learning [99]. In contrast, Long-Term Memory is theoretically limitless in capacity and serves as a repository for informative knowledge stored indefinitely. Under conditions of heat stress, the limited resources of Working Memory may struggle to handle demanding cognitive tasks, such as complex mathematical operations. In contrast, cognitive tasks like reading comprehension and proofreading, which rely on the participants' skills and are primarily based in Long-Term Memory [100], require less attention since the information is already assimilated. As a result, these tasks may be less sensitive to temperature compared to more complex tasks [36].

The conclusions from long-term exposure studies appear to align with the previous findings. Four studies have separately analyzed the impact of cumulative heat stress on mathematics and reading. Three of these studies found that the effect of prolonged heat exposure was significantly greater for mathematical tasks compared to reading tasks [19], [20], [22]. In contrast, one study reported that the cognitive loss for both tasks was nearly identical [24]. Park et al. (2021) observed that the long-term exposure to heat had approximately three times the impact on mathematics as it did on reading and verbal tasks [19]. Meanwhile, Cho (2017) found that during days with maximum temperatures between 28°C and 30°C, mathematics and reading scores decreased by 0.0105 and 0.0073 standard deviations, respectively [20].

Besides temperature, a wide range of factors—environmental, task-related, and performer-related—may influence students' cognitive performance [7]. Environmental confounding factors include climatic variables such as humidity, precipitation, wind speed, and solar radiation, which can affect the body's thermoregulation system. Additionally, perceived indoor environmental elements—such as lighting quality, acoustics, indoor pollution, spatial layout, decoration, furniture, and cleanliness—impact students' mental well-being and satisfaction [3].

Numerous studies have investigated the impact of humidity on thermal comfort [101]; however, little is known about its effect on human cognitive performance [102]. Laboratory research on short-term reductions in cognition under humid conditions revealed that humidity negatively impacts mean skin temperature, as well as the accuracy and response time of participants during cognitive tests [102]. Additionally, three studies on long-term heat exposure examined the influence of humidity, wind speed, and pressure on students' cognitive performance [24], [22], [20]. All these studies concluded that humidity and other climatic parameters have minimal effects on point estimates.

The impact of non-temperature-related Perceived Indoor Environmental Characteristics (PIEC) on cognition has been extensively studied among office workers [9]. Research highlights that factors such as improved visual quality, spatial layout, furniture, and privacy positively influence occupants' mental well-being and satisfaction. However, limited research exists on the effects of PIEC on students' cognitive performance, despite evidence showing that children are more susceptible to environmental conditions than adults. Comparative studies suggest that indoor environmental conditions in classrooms have a greater impact on students' performance than on office workers' productivity [103], [104]. This is because children sweat rate is less than in adults while absorb more heat because of their smaller body and the higher ratio of surface area to body mass [105].

Most short-term classroom studies examining the effects of PIEC on students' cognitive function have focused on indoor temperature and thermal comfort [106]. Only a few, however, have explored the role of lighting [107], [108]. Notably, classroom lighting conditions significantly affect cognitive performance, particularly attention span, working speed, and accuracy. Strategies such as utilizing LED lighting, balancing artificial and natural light, and implementing high Correlated Colour Temperature (Cool White light) systems appear to enhance students' cognitive and psychological processes [108].

The confounding impact of perceived indoor environmental characteristics (PIEC) on students' cumulative cognitive performance remains unaddressed in existing long-term heat exposure studies. These studies rely on macro-level statistical data provided by national authorities, which lack detailed, classroom-specific information. However, findings from short-term studies suggest that PIEC may significantly influence students' cognitive performance over time. Therefore, it is crucial to design and implement long-term heat exposure studies that combine experimental data on perceived indoor environmental conditions and other mediating factors with statistical insights into students' cognitive outcomes. Such studies would help uncover the relative impact of key confounding variables.

Performer related factors influencing the cognitive performance of young people primarily include thermal acclimatization, gender, hydration levels, emotional state, and skill level [7]. Individuals living in warmer climates are better acclimatized to heat compared to those in colder regions, making them more adept at managing heat exposure [109]. This adaptation arises from behavioural, cultural, and environmental responses to heat stimuli, such as enhanced sweating efficiency, improved blood circulation, and other cardiovascular adjustments [110], [111]. The degree of heat acclimatization depends on the intensity of heat exposure and individual characteristics.

Limited research exists regarding the effects of heat acclimatisation on cognitive performance. A study examining the impact of acclimatisation on soldiers' performance under heat-stress conditions found that non-acclimatised participants demonstrated reduced response accuracy on complex tasks. However, no significant effects were observed on attention-related tasks [112].

Three studies on the long-term effects of heat exposure on students' cognitive performance found that students living in cooler regions experience greater cognitive disruption per unit of temperature increase compared to those in warmer areas [20], [23], [24]. Park et al. (2020) reported that an additional day with temperatures exceeding 32.2°C impairs cognitive performance in students from cooler regions three times more than in those from warmer regions in the U.S. Furthermore, the cumulative impact of a 1°F, (0.55C), rise in temperature throughout the school year is nearly twice as significant in cooler areas. Similarly, the cumulative effect of each extra day above 32.2°C per year is five times greater in cooler regions [24]. Roach & Whitney, (2022), found that increase of the ambient temperature by 1F, decreases the performance of students in the cooler and warmer areas of the country by 4.71 % and 2.6 % respectively [23]. Additionally, Cho (2017) found that an extra school day with a maximum daily temperature of 34°C or higher impairs reading scores by 0.0073 standard deviations in cooler regions and 0.000 standard deviations in warmer regions. For maths, the corresponding decreases were 0.0124 and 0.0011 standard deviations, respectively [20]. The pronounced differences in cognitive loss between students living in cooler and warmer geographic areas, attributed to cumulative heat exposure, may result from a combination of long-term heat acclimatisation among students and the more extensive use of air conditioning in households located in warmer regions.

Long-term exposure to heat appears to have a greater impact on the cognitive performance of younger students compared to older ones. Park et al. (2021) found that each additional hot day at school reduces the performance of third to fifth graders by 0.08-0.13% of a standard deviation, while the effect on students in grades six to eight was negligible [19]. This aligns with earlier findings indicating that children have a reduced capacity to adapt to heat due to their less developed and less efficient biological systems for regulating body temperature, as well as their limited ability to sweat effectively [113].

Limited knowledge exists regarding the impact of heat exposure on the performance distribution of students. Zivin et al. (2020) found that short-term heat exposure during exams disproportionately affects the success rates of high-performing students, while low-performing students remain largely unaffected by environmental conditions. Given the already low expected success rates of low-performing students, the relative decrease due to heat exposure may be statistically negligible. In contrast, for high-performing students, the absolute reduction in success rates can be significantly higher in absolute terms [66]. Adverse conclusions are drawn from short term studies assessing the impact of heat exposure during normal courses period. Porras Salazar et. al. (2018), found that higher exposure to heat disproportionally affected the less able 11-year old pupils while decrease of the classroom temperature had more beneficial impact for them compared to the high-performance pupils [62].

Considering the reduced adaptability of children to heat, as well as findings from several short-term school experiments on students' temperature preferences, it has been suggested that indoor classroom temperatures should be 2–3°C lower than those recommended for adults [17]. However, while implementing such lower indoor temperature conditions poses significant energy challenges, further research is required to thoroughly assess the physiological and cognitive benefits of these measures across varying climatic conditions.

Research on the physiological responses and heat adaptability of individuals working under natural ventilation (NV) and air conditioning (AC) conditions has demonstrated that those in NV environments exhibit superior physiological acclimatisation and a greater ability to cope with heat compared to their AC counterparts [114]. This raises questions about whether reliance on AC is the most effective adaptation strategy for climate change. Consequently, the potential risks and negative impacts of prolonged AC usage in classrooms—particularly when not accompanied by substantial improvements in students' cognitive performance—should be thoroughly evaluated and documented.

The penetration of air conditioning in poorer developing countries is low and unevenly distributed among various income groups [93]. In low-income groups, the availability of air conditioning is severely limited due to reduced economic affordability

[115]. Systemic cooling poverty, driven by economic and social deficiencies alongside a lack of supporting infrastructure, restricts the ability of lower-income households and neighbourhoods to maintain comfortable living temperatures.

In developed countries, the adoption of air conditioning among low-income and ethnic minority households is significantly lower compared to middle- and high-income households. In regions of the USA with above-average temperatures, the percentage of households without air conditioning is 12% for the low-income group (less than $25,000 per year), 7% for the middle-income group (less than $80,000 per year), and 3% for the high-income group [119].

Additionally, ethnic minority households —namely Black, Hispanic, and Asian-led households — are less likely to have air conditioning compared to white households. In these warm regions, 14% of Asian-led, 13% of Black-led, 9% of Hispanic-led, and 4% of white-led households do not have air conditioning [119]. Furthermore, financial challenges prevent 12% of Black-led and 10% of Hispanic-led households from using air conditioning, compared to 5% of white-led households. In these areas, approximately 22% of low-income households experience unhealthy indoor temperatures, and 42% report reducing or foregoing necessities due to high energy bills. By comparison, these issues affect only 3% and 7% of upper-income households, respectively [119].

The additional energy consumption and costs associated with air conditioning usage reveal significant disparities between countries and income groups. The electricity consumption penalty for air conditioning is notably higher in developing nations compared to developed ones [116]. For example, De Cian et al. (2025) reported that, on average, households in Indonesia and the U.S. allocate approximately 1.6% and 3.5% of their expenditures to electricity, respectively. However, air conditioning usage increases electricity consumption by 66% in Indonesian households and by 29% in U.S. households, placing a significantly greater economic burden on Indonesian households [116].

Predictions regarding the penetration of air conditioning in developing countries indicate that cooling devices will remain largely inaccessible to low-income groups [93]. Given the anticipated significant rise in temperatures in almost all parts of the world, along with the increasing frequency and duration of extreme heat events, serious concerns emerge about the potential cognitive losses among younger generations due to overheating. The development and implementation of zero- or low-energy heat mitigation and adaptation technologies for educational premises appear to be essential strategies to prevent a decline in learning capacity and to avert substantial societal and developmental consequences for low-income population in developing and developed countries.

8. Limitations

There are several limitations of this study that need to be mentioned and considered. Firstly, direct comparison of the results of the seven reported long-term heat exposure studies is not possible. This is due to the use of populations with varying characteristics, such as age, heat acclimatization, knowledge, and cultural backgrounds. Additionally, the methodologies employed in these studies differ significantly, including variations in the proxy temperatures considered and the statistical approaches used.

Moreover, the absence of data on indoor classroom climatic conditions limits the analysis of how indoor environmental quality may affect cognitive performance.

Finally, none of the studies address the magnitude or characteristics of other environmental stressors beyond temperature, such as indoor pollution, lighting quality, and their impact on cognitive decline in students. As a result, these factors cannot be adequately assessed.

Further research is essential to fully understand the magnitude and impact of key environmental stressors on the long-term cognitive performance of students.

9. Conclusions

Impairments related to cognitive and human capital loss of the young generation may affect the future progress of nations because of the associated dramatic economic, social and cultural implications caused by persistent disruptions to the learning process. The social cost of global overheating on human capital associated to the potential reduced capacity of young people to undertake intensive cognitive activities, will unfortunately affect equity and quality of life of vulnerable and low-income population unable to be protected from the climatic phenomena. It will accelerate societal discrepancies and will impede economic progress in less developed countries suffering from excessive heat exposure. There is an urgent need to adopt a new perspective on the cognitive implications of climate change by advancing technologies and implementing robust, targeted policies to safeguard both current and future human capital.

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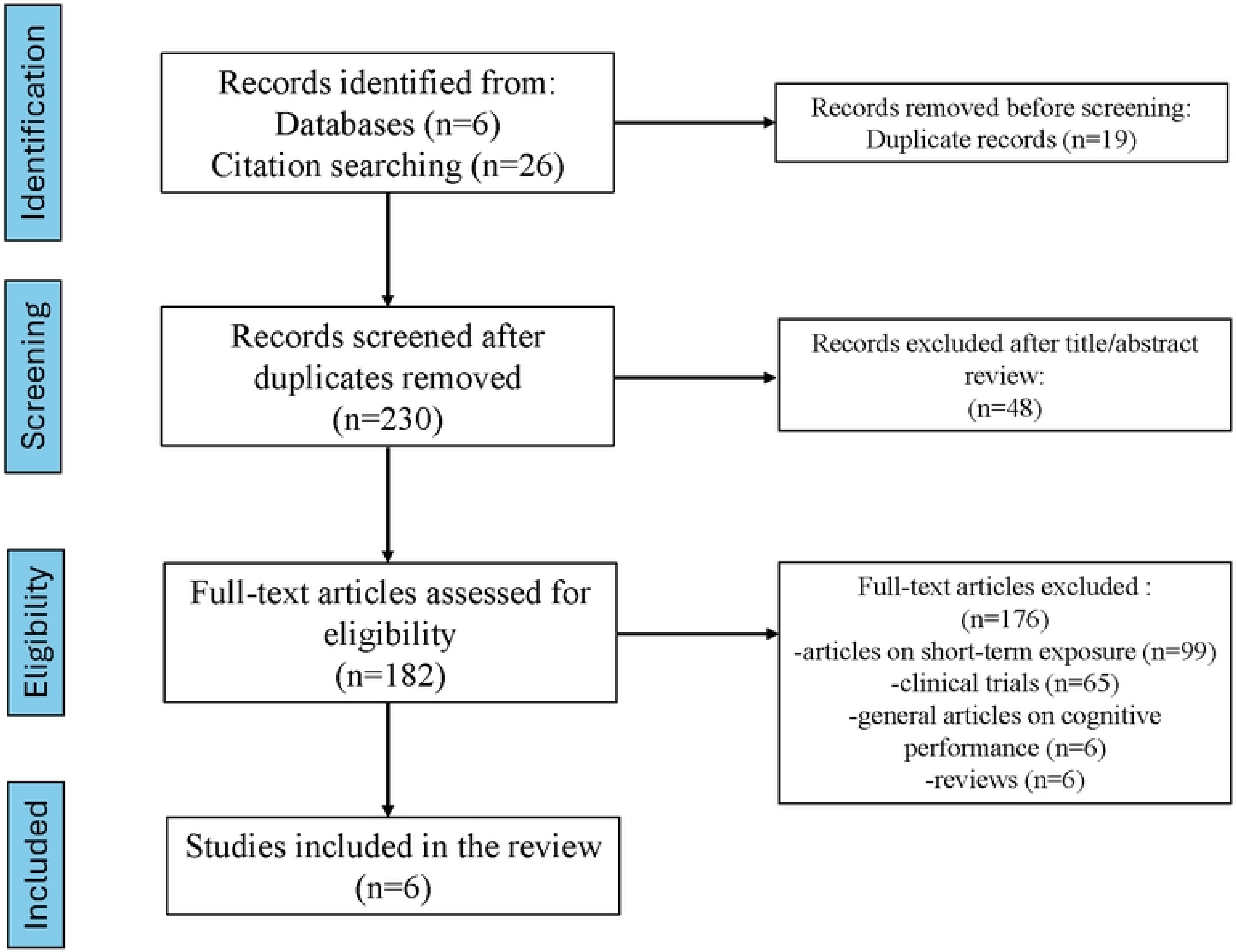
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(n=182)
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(n=176)
-articles on short-term exposure (n=99)
-clinical trials (n=65)
-general articles on cognitive
performance (n=6)
-reviews (n=6)
Included
Studies included in the review
(n=6)

Figure