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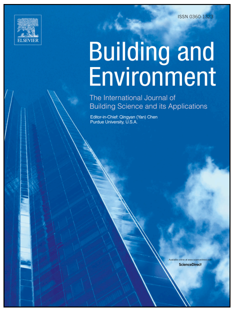

The relationship between classroom temperature and children's performance in school

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THE RELATIONSHIP BETWEEN CLASSROOM TEMPERATURE AND CHILDREN'S PERFORMANCE IN SCHOOL

ABSTRACT

The present paper reports a meta-analysis of published evidence on the effects of temperature in school classrooms on children's performance in school. The data from 18 studies were used to construct a relationship between thermal conditions in classrooms and children's performance in school. Psychological tests measuring cognitive abilities and skills, school tasks including mathematical and language-based tasks, rating schemes, and tests used to assess progress in learning including end-of-year grades and the examination results were considered as indicators of children's performance Due to the lack of complete measurements, thermal conditions were characterized by measured classroom temperatures. To create the relationship, the fractional change in performance of psychological tests and school tasks was regressed against the average temperature at which the change was recorded; all published data were used regardless of whether the change in learning outcome changed significantly with temperature. For other learning outcomes, no relationship was created because the data were insufficient. The relationship derived in the analysis shows that the performance of psychological tests and school tasks can be expected to increase on average by 20% if classroom temperatures are lowered from 30˚C to 20˚C and that the temperature for optimal performance is lower than 22°C. The relationship is valid only for temperate climates. It requires verification for other climates and extensions to temperatures lower than 20°C and higher than 30°C.

HIGHLIGHTS

- A relationship was developed between temperature and various indicators of learning outcomes.
- It is based on data collected mainly in temperate climates concerning the performance of psychological tests and school tasks.
- Reducing temperature by 10 K from 30°C to 20°C is expected to increase the performance of tasks relevant for learning by 20%.
- The effects of temperature on schoolwork seems to be greater in magnitude than has been found for office work.
- The optimal temperature for the performance of schoolwork seems to be lower than for office work.

KEYWORDS

Children; Learning; Cognitive performance; Elementary schools; Temperature; Thermal environment

1. INTRODUCTION

Research has documented that classroom environmental quality in elementary schools, where children spend a large part of their waking hours, is often inadequate [1] and that this may have far-reaching consequences for the learning process [2,3]. Thermal discomfort caused by elevated temperatures in classrooms has been shown to reduce the ability of pupils to perform typical school tasks [1,4–14] and to reduce the results they obtain in national tests examining progress in learning [15,16]. The heat stress caused by elevated outdoor temperatures has been shown to increase the number of pupils failing to pass exams [16,17]. Some studies have suggested that these negative thermal effects on performance are much greater for pupils who are less able [6,11,17].

One possible reason for the effects observed is that pupils cannot concentrate or are distracted when temperatures in classrooms are too high and that this has negative consequences for an effective learning process. Raised classroom temperatures may also have negative consequences for the work of teachers and even on parents, who may have to stay at home or leave work early when their children cannot attend school because of sickness or disability due to suboptimal classroom conditions. Such consequences would have considerable socio-economic implications [2].

Currently, it is difficult to estimate the actual size of the effect on learning due to suboptimal thermal conditions in classrooms because there is no agreed relationship quantifying the effects of the thermal environment on learning outcomes. Some relationships have been proposed [1,12,15], but they used only the results that had been obtained in their own measuring campaigns. This is probably because many different performance metrics have been used in studies to determine the effect on learning. They included psychological tests, typical schoolwork tasks, and national tests or exams. An additional complication for developing such a relationship could be that pupils participating in the studies varied regarding their age, learning abilities, skills, and socio-economic background.

Several relationships between temperature and performance have been derived for office work [18–22]. Seppänen et al. [18] used the results from 24 studies, of which eight were performed in offices [23–30], and used work performance or complex tasks as the performance outcome, one was performed in a factory [31] and one in an office [29], both of these using complex and simple tasks as performance outcome, eleven were performed in the laboratory [19,30,32–39] and used simple tasks related to office work performed by adult subject, and four were performed in the classrooms of elementary schools or colleges and the performance of schoolwork to measure performance [9,40–42]. Seppänen's relationship indicates that performance will decrease below 21-22°C and above 23- 24°C, and that optimal performance would be around 22°C [18]. The change in performance was about a 1% decrease for each 1°C increase in the temperature in the range 24-32°C. Another relationship between thermal conditions and performance was derived by Lan et al. [22]. They regressed thermal sensation against the performance of psychological tests and tasks simulating office work using data from three experiments performed in the laboratory with recruited adult subjects [22,43,44]. The relationship confirmed the relationship developed by Seppänen et al. [18] and predicted that optimum performance would occur when people feel slightly cool. Other relationships between thermal environment and performance were developed by Berglund et al. [19], Roelofsen [20] and Jensen et al. [21]. Berglund et al. [19] used the performance of wireless operators, Roelofsen [20] used a limited set of data to relate loss in performance to PMV, while Jensen et al. [21] used data from 12,000 office occupants and a Bayesian model to develop their relationship. They differed only slightly from the relationships derived by Seppänen et al. [18] and by Lan et al. [22], but it should be noted that none of the above analyses attempted to estimate specifically effects on children in school.

In view of the above, it is worth attempting to develop a relationship that specifically addresses thermal conditions in classrooms and their impact on the performance of schoolwork, which it is reasonable to assume can predict learning and thus learning outcomes such as school grades and examination results. Such a relationship would be particularly useful in cost-benefit analyses of practical ways to improve classroom conditions. It would be useful for the owners and administrators of school buildings, and for the decision makers setting codes, standards, and regulations. Finally, it would be useful for educators and professionals dealing with teaching when different methods and approaches for optimizing and improving the teaching process, in particular, ergonomic solutions, as the thermal environment in the classroom must be considered as an important ergonomic factor. The present work was undertaken to develop such a relationship.

2. METHODS

The archival literature was surveyed to find articles reporting studies examining the impact of thermal conditions in classrooms on the performance of schoolwork and on learning outcomes as defined above. The inclusion criteria were that the articles must have reported both measurements of thermal environment and measurements of the performance of schoolwork or of learning outcomes. Only studies performed with elementary school pupils (primary, middle or secondary school pupils) were accepted, i.e. with children younger than 19 years old. Data from college and university students, published by Pepler and Warner [41], Murakami et al. [45], Ito et al. [46] and Sarbu and Pacurar [47], among others, were thus not included.

Diverse measures of the above dependent variables were accepted, including the performance of psychological tests measuring cognitive skills and abilities to perform schoolwork, some typical tasks encountered in schoolwork, results of aptitude and national tests examining progress in learning, the results of midterm and final exams, and end-of-year grades. Studies reporting only subjectively rated performance were not included. Proxies for reduced performance, such as the prevalence and intensity of acute health symptoms, especially fatigue, difficulty in concentrating, sleepiness or headaches were not considered as valid predictors of learning outcomes. Neither were perceived disobedience, behavioural changes, reported discomfort in the classroom environment or sick leave statistics accepted as valid predictors of learning outcomes.

From each study, the details were obtained as illustrated in Table 1 and Tables A1 and A2 in the supplementary material. They included the location of the study, type of the study, population, temperature measures, type of performance metric used for estimating learning outcomes and the main results. The temperatures and performance outcomes (independently of their type and of whether the thermal conditions could be shown to have affected them significantly) were used to develop a relationship describing the effect of temperature on the performance of schoolwork.

The analytical approach used to develop the relationship was the same as used by Seppänen et al. [18,48]: the fractional change in performance was calculated per 1°C change in the range of temperature examined (λ) for each measure of performance as illustrated in Equation 1. This was done in the case when only two levels of temperatures were examined.

Equation 1: $$\lambda = (P(T_L) - P(T_H) / P(T_H)) (1/ (T_H - T_L))$$

where $P(T_L)$ is the performance at the lower temperature, and $P(T_H)$ is the performance at the higher temperature, T_L represents the lower temperature and T_H the higher temperature.

To estimate λ at the midrange (λ_{mid}) of temperatures in each study, Equation 2 was used, λ_{mid} giving the effect of temperature on performance at the midpoint of the range of temperature to which subjects had been exposed [18]

Equation 2: $\lambda_{mid} = \lambda / 1 + (0.5\ \lambda)\ (T_{H} - T_{L})$

λ and λ_{mid} were calculated separately for the speed at which the tests had been performed or the reaction time if reaction time was reported, and for the accuracy or percentage of errors committed.

When subjects had been exposed to more than two levels of temperature, a linear regression was fitted using the reported measurements, and the slope of the regression line was used to represent the change in performance. It was assumed that the underlying relationship was linear within the rather narrow range of conditions for which the change was calculated, as was assumed when calculating λ and λ_{mid}.

The calculated fractional changes in learning outcomes at the midrange per 1°C change in temperature (λ mid) were regressed against the average temperature estimated based on the range of temperatures for which they were calculated (Figure 1). In this Figure, each point on the developed relationship shows what would be the change in performance if temperature would deviate by 1^{o}C. Fractional polynomials were used to determine the best fit [49]. The 95% confidence intervals were estimated using the equation for the variance of a fitted value as proposed by Royston and Sauerbrei [49].

Using Figure 1, the relationship presented in Figure 2 was created. The performance at temperature of 20^{o}C was used as a reference and then change in performance at any other temperature higher than 20^{o}C was calculated using the relationship showing the fractional change in performance per 1^{o}C (Figure 1). For example, starting with the relative performance at 20°C assumed to be 1, the relative performance at 21°C was estimated to be 0.96 as the fractional change in performance at this temperature for 1°C change in temperature according to Figure 1 is -0.04, then for 22°C the fractional change in performance per 1°C is -0.04 so the relative performance at this temperature was estimated to be 0.92, and so on. It was arbitrarily assumed that 20°C was the temperature at which the highest performance would occur, as suggested by the work of Wargocki and Wyon [2]; the performance at temperatures lower than 20°C could not be estimated. Consequently, the performance at that temperature was set to 100%, and the performance at higher temperatures was found to be lower.

To estimate the 95% confidence interval bands for the derived relationship, a bootstrapping method was used [50]. Following recommendations by Field [51], 1,000 random samples were created, and the curves that best fitted this samples were estimated using the functional form of the regression line describing the relationship between the fractional change in performance and the temperature. Using these curves, performance was estimated for all temperatures between 20°C and 30°C with a step-size of 0.5°C, producing 1,000 performance estimates for each temperature level. These data were used to calculate the 2.5th and the 97.5th percentile, which were used to fit the curves that were then assumed to represent the 95% confidence intervals.

3. RESULTS

Eighteen studies satisfied the inclusion criteria for the present literature review (Table 1). They were published as early as in 1967, and as late as in 2018, i.e., they cover nearly half a century of research on the topic of thermal environment and learning outcomes. Only ten studies were used to develop the relationship. The reason for not including some studies is provided in Table 1. Generally, it was either because it was not possible to calculate the fractional change in learning outcome due to lack of data or the authors did not measure classroom temperatures or because they used outdoor temperatures as the independent variable and simply assumed that classroom temperatures would be affected.

The studies that were included were performed in areas with generally moderate rather than exceptionally high or extreme outdoor temperatures and relative levels of humidity. They reported the effects of thermal conditions in classrooms on the performance of psychological tests and school tasks. Some studies had taken place in the classrooms normally used by the children participating in the experiments [1,4–6], and some in climate chambers [9,14,52]. One study [13] transported the children in buses to other classrooms where their performance was measured.

The thermal environment in the classrooms was characterized by temperature measurements; daily or weekly average temperatures were used to derive the relationship. Most of the studies were performed in classrooms with temperatures between 20°C and 27°C. The thermal sensation or thermal discomfort experienced by pupils was seldom reported in thesed studies, and consequently, no analyses could be made using these metrics. The age of the pupils participating in the studies ranged between 9 and 18 years old.

The detailed information concerning all of the studies considered for inclusion in the present analysis is presented in Tables A.1 and A.2, while a short description of them is included in Appendix A in the supplementary material.

Figure 1 shows the estimated fractional change in speed or reaction time per 1°C change in temperature (λ) of the fifty-two cases that could be used in the present analysis. They are plotted against the average temperature, based on the range of temperatures for which the fractional changes (λ) were calculated, as described above. The figure shows that there was a non-linear relationship between fractional change and temperature, indicating that the effects on performance were higher the lower the temperature. The shaded area in Figure 1 represents the 95% confidence interval of the curve and indicates that at temperatures higher than 28°C no further reduction in performance is to be expected.

Based on the estimated regression line in Figure 1, the relationship presented in Figure 2 was created. Following the rationale provided in the Methods section, the curve was extrapolated below the lowest average temperature of 21.8°C, to 20°C. Figure 2 suggests that changing the classroom temperature from 30°C to 20°C would increase performance by about 20% and that the largest effect would occur between 26°C and 20°C.

No relationship was derived for the fractional change in accuracy, because data were available only from the studies of Johansson [9] and Wargocki and Wyon [1].

4. DISCUSSION

The relationship shown in Figure 2 was developed using data from studies examining the effect of the thermal environment on performance outcomes. In the present analysis, temperature was used as a proxy for thermal environment. Many other parameters can affect the quality of thermal environment and the thermal responses of building occupants. These parameters were however not consistently reported in the identified literature. Temperature was the only parameter that was always reported and this is why it was used. Use of temperature can be considered a limitation of present work but is a consequence of the limitations of the available data that set the constraints for subsequent analyses. Future studies on the effects of thermal environment on humans, either in classrooms or in offices, should therefore ensure that the thermal environment is characterized much better than in the studies included in the present work and that they as a minimum include all six parameters that influence thermal response, and if possible thermal sensation of building occupants.

The derived relationship provides crude estimate of the possible effects of classroom temperature on performance of schoolwork. The relationship should be used taking into account all assumptions and limitations associated with it. The relationship is valid in the range of average temperatures between 21.8°C and 29.5°C. It is likely that it follows an inverted U-shape as found by other authors [12,18,22], although this shape could not be determined in the present analyses. Whether the curve would inflect at 21.8°C or at a lower temperature is not clear from the available data. In the present analysis, it has been arbitrarily assumed that it would deflect at 20°C, based on the results obtained by Wargocki and Wyon [2]. This assumption is further supported by the following simple analysis. If the results of Lan et al. [22] are valid for children, it would be expected that maximum performance would have been observed at the temperature at which pupils felt slightly cool; recent results of Porras-Salazar et al. [6] for children support this assumption. If the PMV-model is applied for a typical summertime school garment of 0.5 clo, air speed = 0.1 m/s, RH = 50%, and activity level of ca. 1.4 met, the temperature at which pupils would feel slightly cool would be estimated to be around 19.5°C [53].1.4 met was used rather than 1.2 met for sedentary activity because studies show that pupils in elementary schools have a metabolic rate that is about 15-20% higher than adults, probably because of a higher activity level [54,55]. The basic metabolic rate of children (BMR) is about 15-20% higher than adults [56,57]. The 0.5 clo was considered the insulation value of a summertime school garment by de Dear et al. and Porras-Salazar et al. [6,58]. Consequently, as indicated by this analysis, it can be inferred that the temperature for optimal performance of children in schools might be lower than it is for adults,. This, as a matter of fact, agrees with findings that suggest that there is a difference between the thermal perception of children and adults: children have been found to prefer classroom temperatures up to 2-3°C lower than those preferred by adults in offices [59–62]. For temperatures higher than 29.5°C, the performance may further decrease with increasing temperature, or it may asymptotically approach a minimum value; in the present case, the curve shown in Figure 1 suggests that at temperatures higher than 28°C no further decrease in performance would be expected. A plausible explanation is that only a few studies reported any data on learning outcomes around 30°C. Another plausible explanation is that temperatures of 30°C and above cause such a high level of dissatisfaction that any further increase in temperature would have an only a minor impact on performance this is already low. Future studies are needed to confirm examine these two possibilities.

The performance of psychological and school tasks at different temperature was used to develop the present relationship, as there were insufficient data for other learning outcomes. Each of them measures different aspects of cognitive performance that are important for efficient learning. No information was found which would allow weighting of how important they are for learning outcomes and how well they reflect the educational level that has been attained. It was therefore decided not to weight them against each other. This differed from the approach of Seppänen et al. [18], who applied arbitrary weighting coefficients to different performance tests. For overall work performance, a coefficient of 1 was used, for single tasks simulating work the coefficient was 0.5 and for psychological tests the coefficient was 0.25. There was, however, no justification in the scientific literature for the selected coefficients and they were based only on the expert judgment of the authors. These coefficients turned out not to have a significant impact on the relationship developed by Seppänen et al. [18].

Present analysis focused only on the relationship between classroom temperature and performance of schoolwork. The latter can be affected by many factors including fatigue, difficulty to concentrate and think clearly, headaches and sleepiness that were shown to be affected by temperature and are related to performance [22]. A relationship between changes in objectively measured performance and mentioned symptoms would be useful but it was not the objective of the present work. Many studies provided the results on performance of schoolwork only at two levels of temperatures. This is why the linear relationship was assumed to determine the fractional change in performance per 1°C change. The same assumption was made in the analysis made by Seppänen et al. [18,48]; their method was followed in the present analyses. With the information retrieved from the studies it is not possible for the authors to corroborate if the linearity assumption is true.

Changes in performance were calculated for all data reported by the studies, independently of whether the change in performance was statistically significant or not. No evaluation of the quality of reported results was made. This can be considered as a significant limitation of the present approach. However, it was adopted to ensure that data from all studies were treated equally and to avoid overrepresentation of the results of performance tests that are more sensitive to changes in classroom conditions. No normalization or weighting of the effects was made based on the number of pupils taking the test. Taking the above into account, it is fair to say that the relationship that was derived provides a conservative and crude estimate of the effects of classroom temperature on performance.

The present relationship reflects mainly acute effects of temperature on performance, as they are based on intervention studies observing and changing the temperature in classrooms while monitoring pupil performance; the change was mainly a decrease in temperature from what was normal, although in a few studies classroom temperatures were also increased. It would be useful to examine whether these acute effects influence other learning outcomes such as the end-of-year grades, national test results or examination results. Such an analysis was made by Park [17]. He showed that both acute and chronic exposure to heat indoors due to elevated outdoor temperatures (assumed to affect conditions indoors) negatively affects learning outcomes. Future experiments should pursue this avenue of validation more quantitatively.

Three cross-sectional studies reported other learning outcomes than the ones used to develop the relationship presented in Figure 1, namely standard test scores and examination results; an important difference from intervention studies is that they did not perform measurements of classroom conditions concurrently with measurements of learning outcomes. Even though they could not be used when developing the present relationship, for the reasons given earlier, it is still worth noting the observed effects and comparing them with estimates made using the present relationship. Haverinen-Shaughnessy and Shaughnessy [15] reported a 0.6% decrease in the score of a standard test assessing proficiency in mathematics per 1°C change in classroom temperature, over the range of temperatures between 20°C and 25°C, which yields ca. 3% per 5°C. This is lower than is predicted by the present relationship.

Park [17] and Goodman et al. [16] estimated the effects of elevated temperature on learning outcomes; they did not use the measurements of classroom temperatures but used measurements (observations) of outdoor temperature. Park [17] estimated that there had been a 4.5% reduction in the performance of year-end school examinations when outdoor temperature had increased from 22°C to 32°C. This corresponded to a 10.9% lower chance of passing an exam. Goodman et al. [16] showed that high school students scored lower after hotter days relative to their scores in cooler days. A school year with a 0.55°C (1°F) higher temperature (on average) was estimated to reduce academic achievements by 0.002 standard deviations, implying about 1% lower performance.

In the present analysis, the data were analysed using the method that Seppänen et al. [18] had applied to develop the a relationship between temperature and office work performance. Cohen's effect size is usually calculated in a meta-analysis and provides a standardized difference that allows comparison of effects obtained in different studies with diverse populations, having different size and even when the measuring scales were different. It could not be calculated in the present analysis as only a few studies included in Table 1 provided data on standard deviations necessary to derive Cohen's d. For the available data [1] the effect size was calculated and is shown in Table A.1 in the supplementary material. Median Cohen's d for speed was 0.19 meaning that in a group of 100 pupils eight would perform less well. For accuracy, the median of Cohen's d was very low (0.04).

Using data from tropically acclimatized children, Porras-Salazar et al. [6] found that pupils performed school tasks better at 25°C than at 30°C. This temperature is higher than predicted by the present relationship. Consequently, another metric to describe the thermal environment in classrooms would be pertinent. This metric should take into account all other parameters that influence thermal response of children. Pupil's thermal sensation would be a useful metric, as in the study reported by Lan et al. [22]. Present analysis does not make any distinction between any potential seasonal differences in the performance of schoolwork. It should be treated as an estimate of an average performance of schoolwork throughout the school year that is independent of the season.

The relationship derived in the present study was compared with some relationships between temperature and performance developed previously. The comparison is shown in Figure 3. The figure shows the relationships developed by Auliciems [12], Wargocki and Wyon [2], which both used data on performance of schoolchildren, while Seppänen et al. [18] mainly used the performance of office work, and Lan et al. [22] used data from adults performing tasks relevant for office work. The last two reports integrated results from many studies while the three first used only their own data. Auliciems [12] derived two relationships between classroom temperature and the performance of schoolwork. The performance of children on continuous addition and cancellation tests were used to derive the relationships. As shown on Figure 3, children achieved maximum performance on the continuous addition test at a temperature of about 16.1°C and on the cancellation test at 17.2°C, the latter curve being based only on data from boys. The polynomial curves suggest that performance changed by 0.38 and 0.32 per degree Celsius, which is lower than in the relationship derived in the present study. This change is similar to the curve of Seppänen et al. [18] and Lan et al. [22]. Wargocki and Wyon [2] found that the relationship between temperature and performance of schoolwork exhibits a linear shape that extends down to 20°C, at which temperature performance was observed to be highest. However, it is worth mentioning that they did not extend their studies to temperatures lower than 20°C and thus it is difficult to predict where the optimum would have occurred. Nevertheless, their results together with results of Auliciems [12] justify that optimum temperatures for learning are lower than optimum temperatures for office work and support rightfulness of selecting temperature lower than 21.8°C as temperature that is optimal for performance of schoolwork. Seppänen et al. [18] proposed a relationship between temperature and office task performance with an inverted u-shape in which optimal performance would be achieved around 22°C. A similar curve and optimal performance temperature were derived by Lan et al. [22]. The difference between the relationship developed in the present work compared with those developed previously by Seppänen et al. [18] and Lan et al. [22] is that the effects of temperature on school work seem to be stronger in magnitude than for office work and that optimal performance would be expected at lower temperatures. Whether these lower temperatures correspond to thermal sensation slightly lower than neutral is difficult to predict as no data have been reported on this aspect, not even when the PMV model of Fanger was developed [63]. More studies are needed to permit prediction of the thermal sensation of children of school age as a function of the thermal conditions in classrooms [64].

The present results show that the impact of temperature on cognitive performance is not negligible and that the effect on learning outcomes (on the schoolwork of pupils) is much higher than for office work. The reason for the differences should be examined further in future studies, but it is likely that fewer opportunities to adapt and the increased vulnerability of children to increased temperature, due to a lower ability to sweat [65], are plausible explanations.

The socio-economic consequences of the observed effects are expected to be high, but there is very little evidence on this matter in the published literature. A hypothetical analysis of socio-economic benefits resulting from improving classroom air quality in Danish schools showed that increasing ventilation rates could increase Denmark's Gross Domestic Product (GDP) by €173 million per annum and increase the public finances by €37 million per annum [66]. The relationship developed in the present work could form the basis of similar cost-benefit analyses in the future.

The present results provide a powerful argument for decision-makers and regulators to revise the requirements in codes and standards so that providing an optimal learning environment will remain in focus, independently of whether the aim is to design, renovate or operate school buildings.

5. CONCLUSIONS

- A relationship between classroom temperature and learning outcomes was developed. It predicts the effects of changing the classroom temperature on the speed at which schoolwork and psychological tests are performed. The relationship predicts that reducing temperature by 10 K, from 30°C to 20°C, would increase the performance of schoolwork by 20%. This benefit is larger in magnitude than for office work performed by adults.
- The relationship shows that the temperature for the optimal performance of schoolwork is lower than for optimal performance of office work.
- Future studies are needed to identify the optimal temperature for schoolwork in different climatic zones. Such studies should develop a relationship between the thermal sensation of children and their performance of schoolwork. This will require more information on the relationship between classroom temperatures and the thermal sensation of children, which currently is almost non-existent. [67]

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Table 1. Summary of the data from studies examining the effect of temperature on learning outcomes

Study	Year	Location	Type	Population (schools)	Population (pupils)	Age of pupils	Temperature range examined/reported temperature levels (°C)	Learning outcomes	Studies used to develop the relationship presented in Figure 1
Holmberg and Wyon [4]	1967	Sweden	Field intervention: Classroom was heated	3 classrooms in an elementary school	50	9	20, 27, 30	School tasks	Included
Holmberg and Wyon [4]	1967	Sweden	Field Intervention; Classroom was heated	4 classrooms in an elementary school	80	11	20, 30	School tasks	Included
Wyon [5]	1969	England	A controlled laboratory study in a climate chamber	N/A	48	11	20, 23.5, 27	School tasks	Not included [2]
Ryd and Wyon [9]	1970	Sweden	A controlled study in a language	2 classrooms in an elementary school	34	13	20, 27	School tasks	Not included [3]
Ryd and Wyon [9]	1970	Sweden	Field study	4 classrooms in an elementary school	89	13	23, 25, 27	School tasks	Not included [4]
Auliciems [10]	1972	England	Longitudinal 2-year field study	23 classrooms in 19 elementary schools	600	11-16	12 - 25	School tasks	Not included [5]
Schoer & Shaffran [11]	1973	USA (Iowa)	Field intervention: Air conditioners	2 classrooms in an elementary school	44	9	22.4, 24.9	Psychological tests and School tasks	Included
Schoer & Shaffran [11]	1973	USA (Iowa)	Field intervention: Air conditioners	2 classrooms in an elementary school	22	10	22.6, 26.1	School tasks	Included
Schoer & Shaffran [11]	1973	USA (Iowa)	Field intervention: Air conditioners	2 classrooms in an elementary school	40	11-12	22.3, 25.4	Psychological tests and School tasks	Included
Johansson [7]	1975	Sweden	A controlled laboratory study in a climate chamber	N/A	36	10	23, 30, 36	School tasks and Psychological tests	Included
Wyon. Andersen and Lundqvist [12]	1979	Denmark	A controlled laboratory study in a climate chamber	N/A	72	17	20 - 29	School tasks	Included

Wargocki and Wyon [1]	2007	Denmark	Field intervention: Air conditioners	2 classrooms in an elementary school	44	10-12	20, 23.6	School tasks	Included
Wargocki and Wyon [1]	2007	Denmark	Field intervention: Air conditioners	2 classrooms in an elementary school	44	10-12	21.6, 24.9	School tasks	Included
Bakó-Biró et al. [13]	2012	England	Field intervention: slightly cool outdoor air was introduced into the classrooms through a mobile ventilation equipment	2 classrooms in an elementary school	36	9-10	23.1, 25.3	Psychological tests	Included
Haverinen-Shaughnessy and Shaughnessy [15]	2015	U.S.A (Southwest)	Cross-sectional study	140 classrooms in 70 elementary schools	3019	10	20-25	National tests examining progress in learning	Not included [6]
Park [17]	2016	U.S.A. (New York)	Cross-sectional study	947 high schools	1 million	17-18	15.5-35 [1]	National tests examining progress in learning	Not included [6]
Goodman et al. [16]	2018	U.S.A.	Cross-sectional study	N.A.	10 million	14-17	N.A. [1]	National tests examining progress in learning	Not included [6]
Porras-Salazar et al. [14]	2018	Costa Rica	Field intervention: Air conditioners	2 classrooms in an elementary school	37	10-12	25.0, 30.0	School tasks	Not included [7g]

[1] Used outdoor air temperatures from nearby weather stations instead of classroom temperatures
[2] No change in performance was seen, therefore data were not reported by authors
[3] No numerical results were provided
[4] No significant effects were observed, therefore data were not reported by authors
[5] Proposed his own relationships
[6] Learning outcomes were retrieved from national tests
[7] Schoolwork was performed by tropically acclimatized subjects

All temperatures are air temperatures except for Wyon. Andersen and Lundqvist [12] that reported the arithmetic mean of the air and radiation temperature and Porras-Salazar et al. [14] that reported operative temperature.

FIGURE 1. The fractional change in performance per 1°C change in temperature at the midrange (λ_{mid}) plotted against average temperature for the range for which the fractional change was calculated. The data is for speed at which the tests were performed. Negative values indicate reduced performance with increased temperature. The lines show the regression (solid line) with 95% confidence bands (dashed lines). Dots show the estimated λ_{mid} for individual tests or tasks (see Table A.1 in Supplementary Material). The function describing relationship between % change in performance and temperature is as follows: $y = 0.4596\ t - 14.086$; where t is the air temperature. $R^2 = 0.19$; $P< 0.001$.

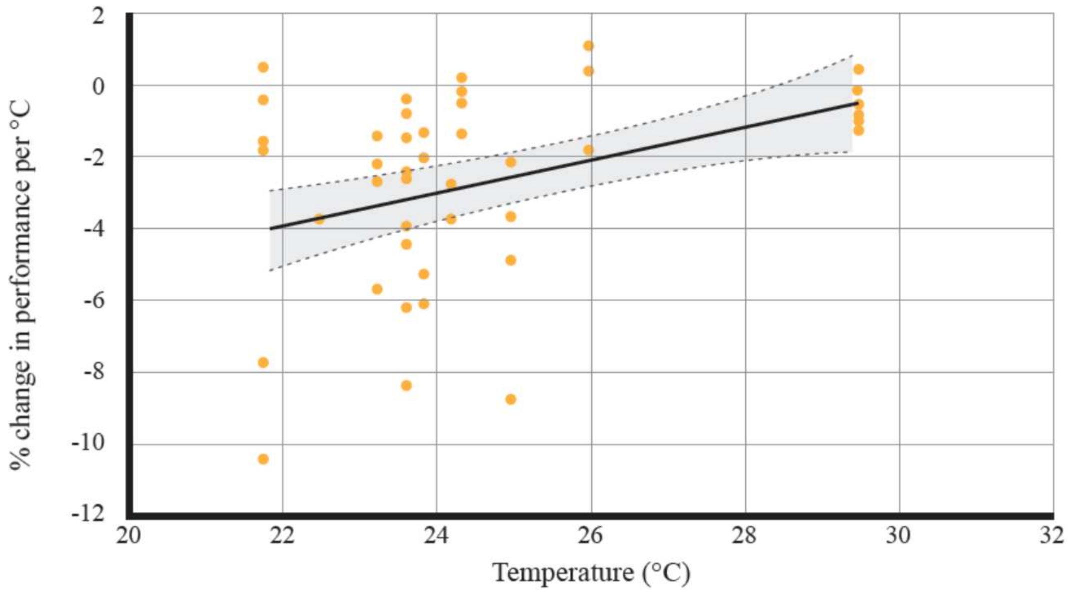

FIGURE 2. Performance of schoolwork as a function of classroom temperature. Performance is the speed at which tasks or tests were performed. The lines show the relationship derived from the curve in Figure 1 (solid line), with the 5th (top) and the 95th (bottom) percentiles (dashed line) considered to represent the 95 confidence interval. 100% has been set arbitrarily at 20°C (see text) and is considered optimal performance. The function describing relationship between relative performance and temperature is as follows $y = 0.2269 t^2 - 13.441 t + 277.84$; where t is the air temperature.

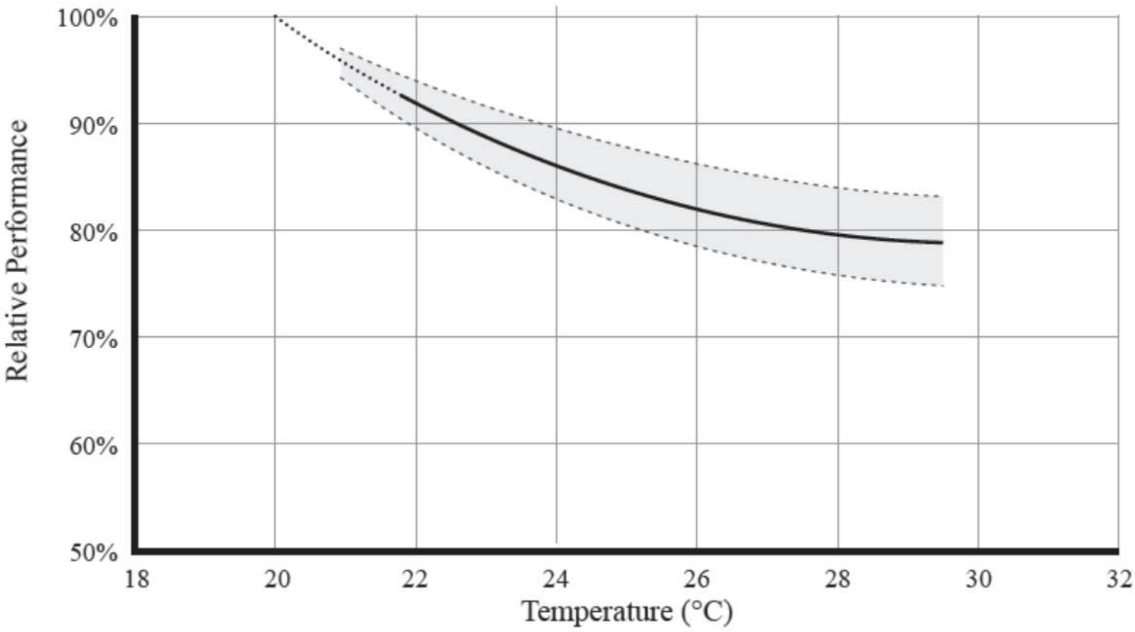

FIGURE 3. Comparison of the relationship developed in this study with the relationships proposed by Auliciems [12], Wargocki and Wyon [2], Seppänen et al.[18], and Lan et al.[22]. Dashed lines show relationships for schoolwork while continuous lines for adults doing mostly office work. Optimal conditions for performance are considered to occur when performance is 100%. The details of these relationships can be found in the supplementary material Table A3.