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# Using empirical science education in schools to improve climate change literacy

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ABSTRACT

Providing children with a clear understanding of climate change drivers and their mitigation is crucial for their roles as future earth stewards. To achieve this, it will be necessary to reverse the declining interest in STEM (Science, Technology, Engineering and Mathematics) education in schools in the UK and other countries, as STEM skills will be critical when designing effective mitigation solutions for climate change. The 'Heat-Cool Initiative' was co-designed and successfully implemented in five primary/secondary UK schools, as a playful learning tool to unleash student interest in STEM subjects. 103 students from two cohorts (years 5–6 and 7–9) participated in five Heat-Cool activity sessions where they used infrared cameras to explore the issue of urban heat. Their learning was evaluated using a multi-functional quantitative assessment, including pre- and post-session quizzes. Climate change literacy increased by 9.4% in primary school children and by 4.5% in secondary school children. Analyses of >2000 infrared images taken by students, categorised into 13 common themes, revealed age-related differences in children's cognitive development. At primary school age, images of the 'self' dominated; secondary school children engaged more with their physical environment. This novel approach demonstrated the importance of developing tailored technology-enhanced STEM education programmes for different age cohorts, leading to a high capacity for improving learning outcomes regarding climate change. Such programmes, embedded in school curricula nationally and internationally, could become a much-needed positive contribution to reaching the United Nation's Sustainable Development Goals, especially Goals 4 (Quality Education) and 13 (Climate Action).

*Abbreviations:* **Activities**, This includes two quizzes (pre- and post-sessions) and thermal imaging sessions of the study; **AIC**, Akaike Information Criterion; **CDF**, Cumulative Distribution Function; **CFD**, Car Free Day; **$CO_2$**, Carbon dioxide; **Cohort/Student group**, Group of up to 20 students from each school. In the case of PS; it is composed of Years 5 and 6 students. For SS, it includes Year 7–9 students; **EYFS**, Early Years Foundation Stage; **FLIR**, Forward Looking InfraRed; **GLL**, Guildford Living Lab; **Heat-Cool**, How building heats and trees cool our cities? **IAS**; Institute of Advanced Studies, **iPAD-IR**; Interactive Personal Application Device- InfraRed, **MSX**; Multi-Spectral Dynamic Imaging, **NASA**; National Aeronautics and Space Administration, **NCE**; National Curriculum in England, **OECD**; Organisation for Economic Co-operation and Development, **OFSTED**; Office for Standards in Education, Children's Services and Skills; **PDF**, Probability Density Function; **POA**, Play Observe and Ask; **PS**, Primary School; **Sessions**, These are 4–5 thermal imaging sessions comprising hands-on experience with iPAD-IR and taking pictures of indoor and outdoor objects to understand the heating and cooling principles in the context of climate change; **SDG**, Sustainable Development Goal; **SI**, Supplementary Information; **SS**, Secondary School; **STEM**, Science Technology Engineering and Mathematics; **Sub-group**, Group of 3–5 students formed for any session from each student cohort of a school; **UK**, United Kingdom; **UNESCO**, United Nations Educational Scientific and Cultural Organisation; **UNFCCC**, United Nations Framework Convention on Climate Change; **UNICEF**, United Nations International Children's Emergency Fund.

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## 1. Introduction

### 1.1. The climate change urgency

The worldwide devastating impacts of climate change are intensifying air pollution and unpredictable weather conditions, causing an increase in the frequency and intensity of natural hazards such as storms, floods, droughts, heatwaves, and wildfires [1,2]. These were responsible for ~43.5% in loss of lives and ~74.5% in economic damages of global aggregate during 1998–2017 [3,4]. Mitigating and adapting to the impacts of climate change is one of humanity's biggest challenges in the coming decades. The Conference of the Parties (COP) is an important international forum that assesses progress in dealing with climate change. The goals of the 2021 United Nations Annual Climate Change Conference (COP26) are to achieve global net zero carbon emission by mid-century, build adaptation capacity of human societies and natural environments, mobilise the necessary financial capital to combat the impacts of climate change on humanity and foster collaboration among governments, businesses, and civil societies. Participating countries agreed to a new 10-year Work Programme on Action for Climate Empowerment to promote youth engagement, climate education and public participation [5]. Therefore, climate change needs to be addressed by collaborative and innovative problem-solving approaches that span across multiple disciplines of socio-economic, political, environmental, and very importantly, educational sectors [6].

### 1.2. Education is essential to combat climate change

Education is key in people increasing their climate literacy and understanding, and hence responding to the impact of global warming and climate change [7]. Climate literacy serves as the foundation for well-informed adaptation and mitigation measures. Innovative education initiatives can lead the way to tackling the problem through advancement in cleaner air, leading to creation of good jobs, restoring nature and unleashing economic growth. Regardless of political affiliation, religious beliefs, or worldviews, scientific education and interventions can affect how people view climate change [8]. The United Nations Framework Convention on Climate Change [9] stated: "Education is an essential element for mounting an adequate global response to climate change". The increasing importance of effective education on climate change issues is reflected by the rapidly increasing number of scientific publications over the past two decades in this field. When searching the scientific literature using the terms 'climate change' and 'education' [10], reported that the number of published articles increased manifold from only 12 in 1990–1999, to 433 in 2000–2009, and to 1489 in 2010–2015. Our recent search using the same terms confirms a further sharp increase, reaching 6266 articles published in the time between 2015 and 2022.

Quality science education aims to produce scientifically literate students with a long-term goal of creating responsible citizens equipped with relevant science knowledge and skills. More broadly, the OECD has developed the notion of global competence as a response to our increasingly interconnected world, driven by globalisation and digitisation [11]. To enhance global competence, the OECD encourages learning opportunities that promote whole, relevant, deep, social, transformational, and 'in the world' dimensions. 'Whole learning' recognises the interdisciplinary nature of complex knowledge. 'Relevant learning' engages students intrinsically, while 'deep learning' involves opportunities to apply knowledge in novel situations. 'Social learning' allows for learning with interactions between students and others, while 'transformational learning' refers to long-lasting changes in insight and mindset. Finally, "in the world learning" recognises the importance for students to engage in learning that embraces the ambiguity, complexity, and unpredictability of the world outside of the classroom [11]. The OECD proposes that these dimensions can guide the development of learning experiences that can result in citizens with the skills to work collaboratively to solve complex problems such as climate change.

### 1.3. Contemporary educational theory in science teaching

The global competence approach to learning aligns with calls for the traditional curriculum to be infused with a scientific, experimental, and data-driven approach so that students are able to visualise, comprehend and investigate the complex scientific phenomenon underlying the concept of global climate change [12]. To support the development of such competencies, the Science Capital Teaching Approach [13] outlines an approach to science teaching that aims to be inclusive of all students, promoting learning that produces a science-literate population who are prepared to be active citizens in society. For students to become interested and confident learners in science they need to see science as being as relevant to their lives and have opportunities to engage with and talk about science, while valuing the lived experiences that they bring to the learning context [13].

There are numerous examples of educational programmes designed to enhance science learning in schools. For example, the Science, Technology, Engineering and Mathematics (STEM) education integrated into various arts programmes allows students to engage in critical discussions about the role of science and art in society [14]. To promote climate change literacy among the students [14], used an education programme that consisted of seven sessions. In each session, students used different techniques to actively explain the concepts of weather and climate. A questionnaire was used to gauge the impact of the programme on students' climate literacy; the results of this study showed that the programme had a positive impact. Likewise, a nature education project with 60 middle school students significantly improved knowledge about the importance of renewable energy [15]. The teaching strategies employed are equally as important as the curriculum when educating students about climate change. Designing empirically based, innovative curricular resources that focus on the earth's climate system and global climate change is important for students to develop climate literacy [16]. In general, effective interventions to address climate change through education have the following features: (1) Deliberative discussion to help learners better understand their own and others' viewpoints and knowledge about climate change; (2) Interaction with scientists to experience the scientific process for themselves; (3) Addressing misconceptions about climate change; and (4) Designing and implementing school or community projects [17]. These common features align with the intent of the Science Capital Teaching Approach [13] and link students with scientific experts and real-world projects to develop global competencies.

Systematic work carried out by several organisations (e.g., NASA Climate Kids, UNESCO, World Wildlife Fund, and Oxfam Education) has demonstrated that perspective and behavioural changes in young people can be triggered through climate change education as a subject that they can relate to Refs. [18–20]. Hence, education can advance the knowledge and skills of children regarding climate change-related impacts and support them to make informed decisions to reduce and adapt to them [21]. Yet, despite the clear call from the international community and response from academia about the importance of education in responding to climate change, this resource is rarely mentioned in discussions considering contemporary and readily available major climate solutions and adaptation plans [22]. Therefore, it is essential that education becomes a top priority for scientists and policymakers to develop effective educational initiatives that aim to increase public understanding of the drivers and impacts of climate change and how to address them through behavioural and technological changes. Since children are the future of mankind, teaching them about climate change risks and solutions through STEM education is a crucial responsibility of society.

### 1.4. Declining interest in STEM education

Evidence suggests that interest of children aged 5–12 years towards STEM subjects are declining in the UK [23,24]. This is a matter of concern considering the growing need for STEM educated workers to ensure technological innovation and economic growth. If this declining trend in students' STEM learning interest is not reversed, future generations are less likely to have the skill-set necessary to devise social and technical solutions to mitigate and adapt to climate change impacts, whilst maintaining social and economic prosperity and environmental stability. In fact, the continued declining trend in the STEM interest in primary and secondary school students around the world is alarming [e.g., 25–30,24]. For instance, interest in STEM subjects in both primary and secondary schools has dropped by 36% since 2015 [31].

This declining interest in STEM has been linked to the nature of the traditional science curriculum and its apparent limited capacity to make science relevant and interesting to students [32–34]. Most of the science-related concepts in schools are explained through laboratory-based experiments using traditional methods for measuring and representing the quantities related to core concepts. However, this approach does not address the need for schools to understand the changing nature of student attitudes towards STEM and the importance of teaching STEM through topics and approaches that are of most interest and relevance to students. Previous studies have developed and field-tested various methodologies that improve the dissemination and communication of climate change education (Table 1). These studies generally focused on understanding the attitudes of the students about climate change using diverse approaches. None of them has explicitly focused on participatory or citizen-science approaches to co-design and co-create climate initiatives at primary and secondary school levels using engaging learning activities. To develop a comprehensive understanding of climate change issues, concepts and terminology relating to climate change, such as the greenhouse effect, carbon footprint, and global warming, programmes need to be designed in an accessible and age-relevant way. Teaching these concepts through the traditional science curriculum has been described as inadequate [35]. Thus, there is a lack of information regarding a holistic and integrated set of approaches that can teach climate education and thereby increase the students' interest in STEM in an engaging, interesting, and enjoyable manner. To overcome this, an important approach is to develop curricular activities

**Table 1**
Summary of selected studies around climate change-related educational initiatives in schools.

| Country (location) | Key findings | Reference |
|---|---|---|
| England | 626 primary and secondary school teachers were surveyed about their perspective on climate change education. They supported action-focussed climate change syllabus to be integrated across subjects, beginning with preservation projects in early primary school. The majority (54%) also trusted that this should extend to engagement in civil disobedience in secondary schools. | [36] |
| United Kingdom | This study developed a programme to engage and encourage students to reflect on their personal impact on the environment, while also appreciating their place within society to bring about positive societal change. The designed multidisciplinary approaches allowed the students to explore themes around climate change in a novel and engaging way. | [37] |
| United States | The study presented an overview of recent studies on public views on climate change, student views and misconceptions, and resources for making connections in the classroom and laboratory between the concepts of chemistry and climate change. Such connections can help produce engaging chemistry courses and more climate educated citizens. | [38] |
| United States | The study investigated the suitability and effectiveness of applying a self-generated utility value intervention with students in fifth- and sixth-grade science classes. Results produced preliminary evidence that the intervention was used properly, and it was effective for increasing students' utility value and interest in science. | [25] |
| Malaysia | The effect of a 5E (Engage, Explore, Explain, Elaborate and Evaluate) learning cycle-based climate change curriculum was tested by designing a hypothesis on Malaysian primary students' knowledge about climate change and attitudes towards the environment and the relationship that exists between knowledge and attitude. The data for the analysis involved about 115 Year 5 students (11 years of age) from two primary schools (A and B) in a metropolitan area of Malaysia. The students from School A and School B were randomly assigned to treatment and comparison conditions. The treatment group consisted of 55 students from School A and the encompassing theme of energy was taught using 5E learning cycle-based climate change activities. Whereas the comparison group consisted of 60 students from School B and the theme of energy was taught in a conventional, teacher-centred manner. The result showed that the treatment group appeared to have helped the students understand climate change-related problems. | [39] |
| Global | This study drew on information from a "European Network (Changing with the Climate)" and its activities with schools across countries to generate an exercise for future science teachers about the location of Climate Change Education in the Syllabus. Using the data from the research on the nature of climate change education in the UK and Florida, the differences can be accounted for by the stakeholder's perspective about teaching in general, and about climate science as a science. | [40] |
| Singapore | This study investigated six Singaporean geography teachers' understandings of climate change education. The findings indicate that the participants held very different beliefs about the primary purposes of climate change education, in spite of the highly centralised national curriculum and the unambiguous state support for the science of climate change. | [41] |
| Global | This work examined whether education considerably increases coping capacity with regard to specific climatic changes, and whether it improves the resilience of societies to climate-related risks in general. The result showed that investment in worldwide primary and secondary schooling was the most effective approach for preparing students to address the risks associated with future climate change. | [42] |
| Nigeria | The study determined the effects of service learning and educational trips on primary school students' environmental knowledge. It also explored the effects of school location on environmental knowledge of the students. The results showed that community-based instructional activities and educational trips affected students' knowledge in environmental education in a positive way. | [43] |
| Turkey | The study investigated the changes in the knowledge levels, opinions and perceptions of middle school students, who participated in a nature education project on renewable energy aspects. The qualitative analyses indicated that significant improvements in participants' views toward renewable energy have been observed by the end of the nature education project. | [15] |
| USA | To investigate the different ways teachers implement a climate-focused curriculum to enhance students' climate change literacy and their impacts on students' learning and concluded that teaching strategies are equally important in educating students about climate change, as designing empirically based, innovative curricular resources, combining science with the earth's climate system and global climate change | [16] |
| USA | The review study summarised the challenges faced by both teachers and students in developing their knowledge about global climate change and suggested that the traditional curriculum should be infused with scientific, experimental, and data-driven approach so that students are able to visualise, comprehend and investigate the complex scientific phenomenon underlying the concept of global climate change and can develop a multi-dimensional understanding of the concept. | [12] |
| South Korea and Australia | Investigate the impact of climate change education programme on climate literacy among junior high school students. The programme was implemented in seven sessions, consisting of video conferencing between students of two different countries to facilitate exchange of ideas, playing the videos that showed different climate action programmes, storytelling by teachers about the concepts of earth's climate system and changing of climate and climate change sticker-making activity. The impacts were assessed by a climate change literacy questionnaire, and they concluded that students' perceptions and understanding of climate change was improved after attending the programme. | [14] |

that provide students with first-hand experiences relating to their own daily lives.

### 1.5. The Heat-Cool Initiative

Here, we report the outcomes of such a novel approach that merges climate change science with school education, using a co-creation method involving parents, teachers, researchers, and students in the formulation of an engaging climate-education programme utilising thermal imaging. We co-developed the 'Heat-Cool Initiative' so that primary and secondary school students could learn about climate change drivers and impacts with the use of thermal imaging cameras.

Using hand-held, user-friendly thermal imaging cameras to explore the physical concepts of thermodynamics and how indoor and outdoor objects are heating and cooling, students were able to create a visually rich and meaningful representation of the concept of heat and temperature [36]. Thermal imaging visualises long-wave electromagnetic radiation in the infrared spectrum. The resulting images are called thermograms and provide a real-time visualisation of heat transfer between physical objects and the environment.

The main idea behind designing Heat-Cool, was to teach complex scientific phenomena in engaging ways, using games and other activities and to make the students aware of the environmental issues. The principle behind designing Heat-Cool was to make students aware of the problem of global climate change and heating of earth's surface, by practical demonstration to the students, with the help of thermal imaging cameras. In line with the call for action in the Work Programme of COP26, this study uses empirical methods to improve the climate change literacy of school students, especially about the impact of heat on the physical environment and how behavioural change can make a positive impact. This was achieved through designing, implementing and assessing the impact of a new practical tool (Heat-Cool) that delivers on the call of the United Nations to use science and technology-driven climate change education to achieve the Sustainable Development Goals, especially Goal 4 (Quality Education) and Goal 13 (Climate Action).

In the Heat-Cool programme, the theoretical and practical curricular activities were designed to: (i) Establish the preliminary knowledge of students about climate change and related aspects through an initial quiz; (ii) Raise the awareness of students about how energy heats and cools our planet through thermal imaging sessions; (iii) Educate about climate change and global warming through engaging video resources; and (iv) Generate curiosity and interest for STEM subjects among students. The initiative tested the hypothesis that interactive learning increases climate literacy in students and hence stimulates their interest and engagement in STEM disciplines. This was assessed by using (a) The observations during sessions, assessment of thermal images and results of structured quizzes before and after the practical sessions, and (b) Observations of students during sessions and assessment of thermal images taken by them. In addition, we analysed the thermal images taken by the students to identify any age-related differences in depicted content. This would help inform the development of age-specific practical STEM education programmes that use infrared thermography as a tool to improve climate change literacy.

## 2. Methodology

The Heat-Cool Initiative was implemented at four schools in London and Guildford, United Kingdom, between October 2021 and March 2022 (Table 2). A total of 103 primary and secondary school students aged between 9 and 14 years participated in the programme. The initiative used a co-creation approach based on a Play, Observe and Ask framework [44,45] and citizen-science [46,47] that incorporated 'inclusion', 'collaboration', and 'reciprocation', for making learning a more enjoyable process. The activities of the Heat-Cool initiatives were divided into four distinct phases: Preparation, Implementation, Assessment and Engagement (Fig. 1). An additional 'Intermediate Phase' was implemented between Phases 1 and 2 to field test materials and methods during two public events that also contributed to an overarching engagement phase, as described in Section 2.4.

### 2.1. Preparation phase

During Phase 1, the researchers co-developed quizzes in consultation with the schoolteachers, designed content for active climate education and thermography sessions, prepared and tested the thermography equipment and designed step-by-step user manuals for the equipment. The quizzes were used to measure the improvement in students' understanding and knowledge regarding climate topics (climate literacy). Two quizzes were developed in accordance with the science programme of study in the National Curriculum in England[48]; see SI Section S2 for two cohorts of students studying in years 5–6 and 7–9, and thus reflected the assumed state of knowledge of primary and secondary school students. Importantly, both quizzes were designed to entail no preparation by students, thus allowing an effective assessment of the knowledge held by the students prior to the programme. The quiz designed for the primary school students consisted of 10 multiple-choice questions, whereas the quiz for the secondary school students consisted of a mix of 14 multiple-choice and 6 descriptive free-text questions (with a word limit of 50). Both quizzes are provided in the SI Tables S1 and S2. The quiz questions were formulated based on three elements that contribute to the 'cause-impact-mitigation' chain of the concepts and principles of climate change planning (Fig. 2, Table S3). The level of quiz difficulty was adjusted depending upon the year level of the students. For causes, the quiz asked questions (27%) about factors or reasons responsible for global climate change. For impacts, the questions asked (43%) dealt with manifestation of climate change and the effects of climate change; for example, the environmental and socio-economical problems we are facing due to climate change impacts. Lastly, questions (30%) about solutions asked how we can help stop, control, mitigate and adapt to the effects of climate change. Before deploying the quiz questions in the 'Heat-Cool' initiative, we tested them on a few students from primary and secondary schools (Section 2.4). Based on our first trial or the response of the students, we reformulated the questions for students' level of thinking and understanding; for example, using pictures, hints of answers from other optional questions, and keeping optimum numbers of questions to maintain the curiosity level.

The active climate education and thermography sessions were co-designed after discussions with the schoolteachers about the cognition level of their students and a feasibility study was carried out during the intermediate phase (SI Section S1). Activities were semi-structured and built upon each other with increasing complexity. Each activity ($n = 5$) was scheduled for 30 min over a 5–6-week interval, totalling 2.5 h of engaged learning (Table 3).

A combination of a tablet computer (iPad model A2429, 10.2-inch, Apple Inc, Cupertino, CA, United States), a freely available thermal imaging app (FLIR One, version 4.2.0, Teledyne FLIR, Wilsonville, OR United States) and an attachable infrared camera (Flir One Pro, Teledyne FLIR) (together hereafter termed *imaging device*) were assembled. Four imaging devices were used in this project and a step-by-step manual was developed that explained their use (SI Section S5, SI Figure S1).

### 2.2. Implementation phase

Phase 2 was the 'hot phase' where the programme was implemented. The pre-session quizzes were completed by the students, before the five imaging sessions took place. Students' group in each school were divided into three or four subgroups and each subgroup received an imaging device before being guided through the five thermal imaging sessions. Researchers provided basic training to the students about how to properly use the imaging device and how to interpret the images, and

**Table 2**
Details of the studied schools and their characteristics.

| School type (Location) | School code | OFSTED rating[a] | Class | Number of students that took both quizzes | Duration of activities |
|---|---|---|---|---|---|
| Primary (London) | PS1 | Outstanding | Year 5 | 19 | 13 Oct - 01 Dec 2021 |
| Primary (Guildford) | PS2 | Good | Years 5–6 | 13(a)<br>13(b) | 02 Nov - 23 Nov 2021 |
| Secondary (Guildford) | SS1 | Not available | Year 7 | 16 | 29 Nov - 03 Dec 2021 |
| Secondary (Guildford) | SS2 | Outstanding | Year 7–9 | 10 | 2 Feb-2 Mar 2022 |

[a] https://reports.ofsted.gov.uk/.

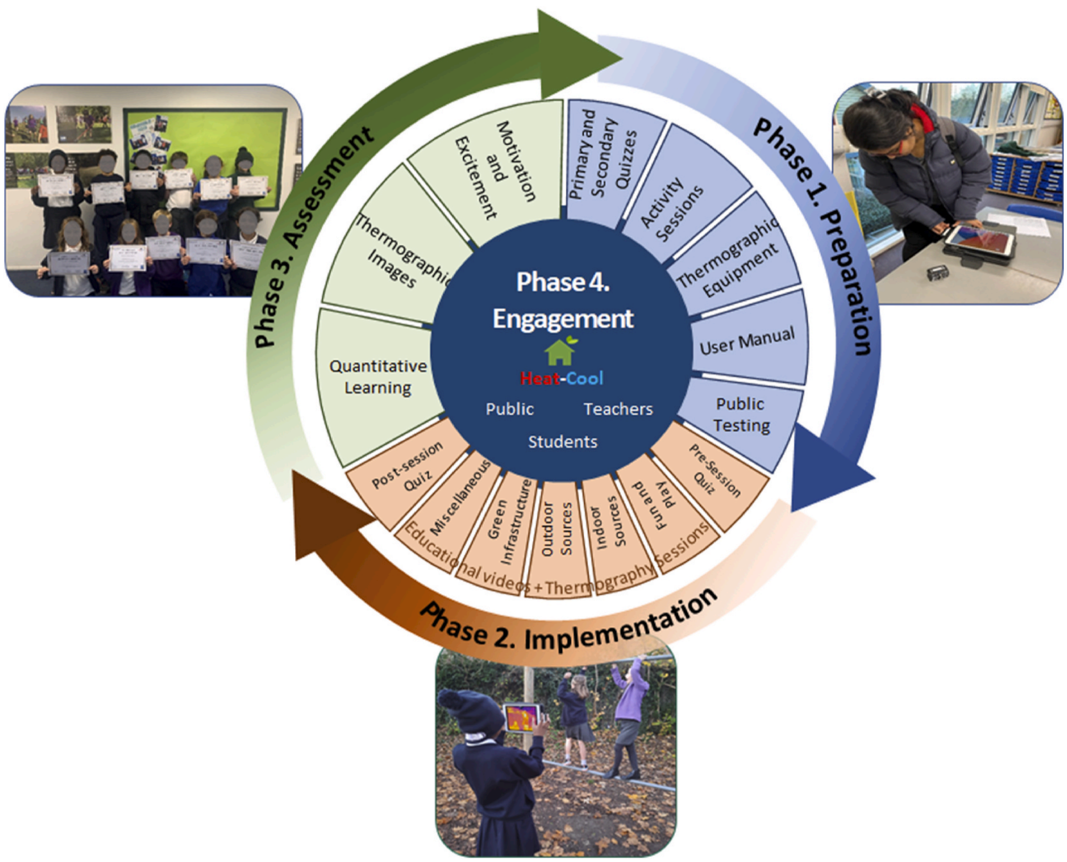


**Fig. 1.** Schematic diagram of the Heat-Cool study design, showing details of its various phases.

assisted the students with any technical issues. The five sessions were "Fun and play", "Indoor objects", "Outdoor objects", "Green Infrastructure" and "Miscellaneous", with each session spanning 30 min, as shown in Table 3. Researchers also explained what the objectives and focus of each session were. During each session, students used the imaging device to observe, take pictures or make videos of any structure (e.g., objects, places, people, vegetation) that they found relevant considering the focus of each session. Some examples of the images taken by the students can be seen in Fig. 3. After completing the five sessions, the students completed the post-session quizzes.

Two researchers observed the students' motivation, engagement and interest during these sessions using a scoring matrix (SI Section S6). The aim of this observational analysis (Section 3.3) was to capture the following aspects: (i) Motivation (when a student was energised or moved to perform a task or behave in a particular way [49]); (ii) Engagement (when a student actively committed or became occupied [50]); and (iii) Interest (when a student expressed their feelings about activities/learnings to others [51]. The observational matrix contained 10 scoring criteria (SI Figure S2) and was used for the qualitative analysis (Section 2.3). The underlying conceptual framework was adopted from Refs. [52,53], allowing the collection of open response and rating scale data on the three aspects - motivation, engagement and interest. In parallel with recording observational information, student groups were engaged by teachers in discussions about the relevance of their imaged objects to climate change, urban heat and how to mitigate or reduce this heat.

### 2.3. Assessment phase

Quantitative and qualitative data analyses were the core activity during Phase 3. We used paired *t*-test to assess if the quiz scores of the students had improved after they participated actively in the thermal imaging sessions. While a total of 103 students completed at least one of the pre- and post-session quizzes, only scores from those students that completed both quizzes ($n = 71$) were used in these analyses. Differences of the scores were analysed at three different levels to determine if climate literacy had improved among all students (level 1), in the two different school types (level 2) and in individual classes (level 3). Significance for all tests was set at $p \leq 0.05$.

The thermal images taken by students during the sessions were used to assess their focus during the imaging sessions. Einarsdottir [54] reviewed several studies that discussed the use of children's

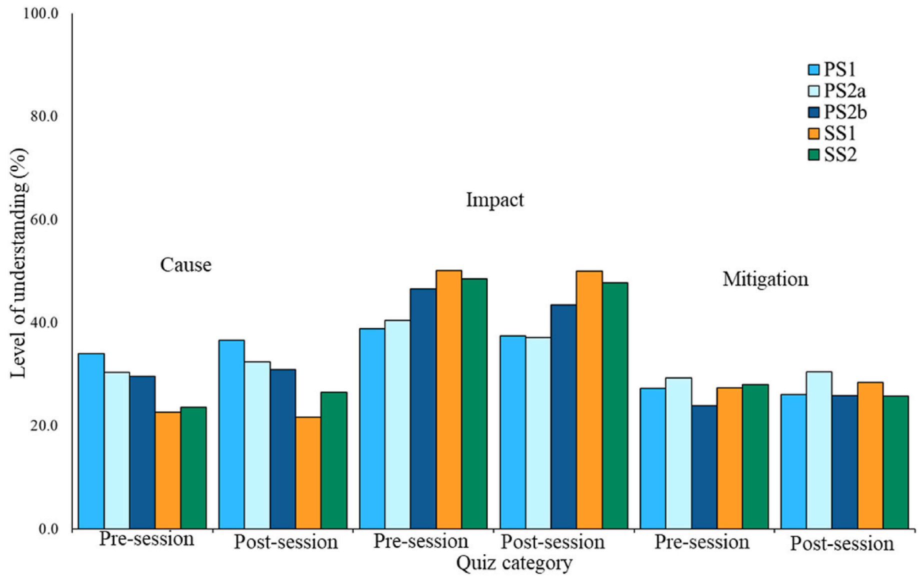


**Fig. 2.** Relative level of understanding as indicated by quiz scores of causes, impacts and mitigations strategies of climate change by primary school (PS1, PS2a) and secondary school (PS2b, SS1, SS2) students before and after the practical imaging sessions. Bars shown must be read as proportions of the overall (cumulative) level climate change literacy, where adding each bar per school and quiz type among the three categories will represent 100% of the current level of understanding.

**Table 3**
Sequence of activities where students would use thermal imaging cameras in semi-structured, 30-min sessions.

| Session Number | Session Title | Session Aim |
|---|---|---|
| 1 | Fun and play | Familiarise students with iPAD-IR camera, explain colour scheme of images and how to differentiate thermal properties of objects |
| 2 | Indoor objects | Visualise differences in surface temperature according to the proximity of an object to a heat source and material properties |
| 3 | Outdoor objects | Comprehend formation and absorption of heat by outdoor objects by assessing surface temperatures of parked vs. operating vehicles, different building materials and cast shade |
| 4 | Green Infrastructure | Enhance understanding of the cooling capacity of green infrastructure such as trees or hedges by imaging areas with and without green infrastructure in the same frame |
| 5 | Miscellaneous | Session was discretionary, allowing students to take any images of their interests in indoor and outdoor environments to assess if students now operated thermal cameras more targeted |

photographs as a method of data collection and concluded that the use of photographs in research with children has many advantages. For instance, the photographs taken by the children represent their perspective and a way for children to express their feelings and opinions. However, different age groups can have different interests, perceptions, interpretation, and enjoyment of their environment [55], which can influence the way the children take photographs or interpret them. Given that visual literacy can enhance learning [56], an analysis of the thermal pictures taken by the students can help to better understand the students' perspectives about the activity and the differences and similarities observed considering their perspective of the thermal image between schools and students' ages. The thermal images taken by students from each participating subgroup over five sessions (Table 3) were sorted into thirteen categories that broadly captured the main themes and objects that featured in the images (Table 4). Each category was created considering that the images within a category were similar to each other, but different from the other images within other categories; thus in reality each image was categorised into only one category [57]. Thereafter, the profile of each school was obtained through the percentage of the contribution of each category to the total of images taken by that school (Section 3.2). The data collected by the two researchers on the motivation and engagement of the students was subsequently analysed quantitatively using the following categories: very low (≤20% student in a student sub-group); low (>20–40%); medium (≥40–60%); high (≥60–80%); very high (≥80%). These categories were sorted into four levels, namely positive motivation, negative motivation, positive engagement, and negative engagement (SI Table S4). In addition, the students' activities (e.g., storytelling and demonstrations) and open responses from school representatives were used to measure their level of interest in the sessions [58].

### *2.4. Engagement phase*

During Phase 4, further engagement was carried out at each school with students and teachers, and with local community groups. All the participating students were given 'Heat-Cool Master' certificates. Three students from each school, nominated by the teacher based on their participation level in the activities, were given 'Heat-Cool Champion' certificates. After the study sessions, each school was asked to provide written feedback about how the project activities helped their students to understand the concept of heating and cooling in relation to climate change, together with any suggestions for improvements of the Heat-Cool Initiative. These quotes (see SI Section S6) were used in social media to engage the broader audience via news articles and other online platforms, such as Twitter [59–61].

The general public was engaged through two events, namely during the "Car Free Day" [62] and at the launch of "Zero Carbon Guildford" [63], where school representatives, parents and children visited the stall set up by the research team and observed the heating and cooling of the objects around them using the imaging device (SI Section S1). These events were organised, before the Heat-Cool sessions were carried out in the participating schools, to assess the feasibility of adopting imaging devices for school students and co-designing sessions with parents and school representatives. The researchers explained how the images should be interpreted with respect to the temperature and colour distribution representing different temperatures.

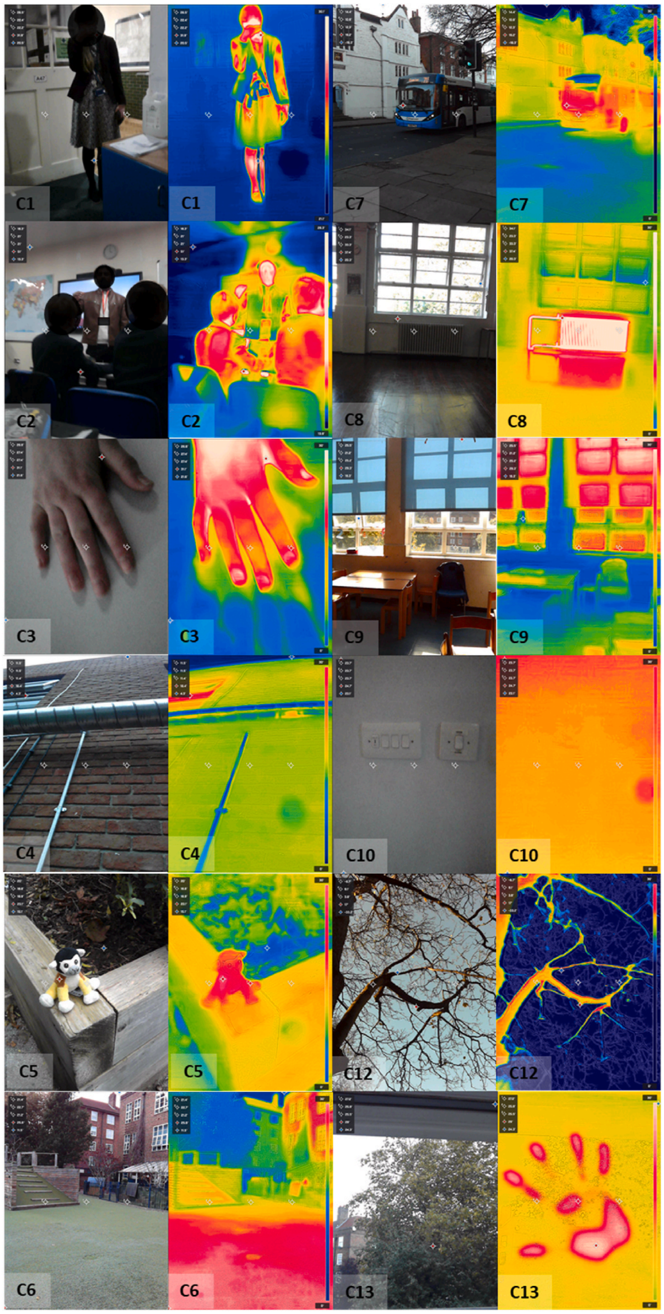


**Fig. 3.** Examples of thermographs (infrared thermal images) taken by students considering the 13 categories: C1) Human Body (individuals); C2) Human Body (group); C3) Human Body (Parts); C4) Outdoor structures; C5) Outdoor Objects; C6) Outdoor spaces; C7) Motorised Vehicle; C8) Indoor objects; C9) Indoor spaces; C10) Miscellaneous; C12) Nature; C13) Ghost print. Note that the original temperature range of the picture has been changed so that they all have the same range (0–30 °C). Emissivity of all thermographs was set to 0.95. C11 is the video category and therefore not added to the examples above.

**Table 4**
Categories used for the systematic analyses of infrared images collected by students during five active sessions. Examples for each category are provided.

| Category No. | Description | Example |
|---|---|---|
| C1 | Human body (individual) | Only one individual |
| C2 | Human body (group) | Two or more individuals |
| C3 | Human body (parts) | One or more body parts (e.g., hands, legs) |
| C4 | Outdoor structures | E.g., walls, building, windows |
| C5 | Outdoor objects | E.g., table, chair, bicycle, racket |
| C6 | Outdoor spaces | Outdoor scenes (e.g., playground, sitting areas, parking) |
| C7 | Motorised vehicles | E.g., Cars, trucks, vans and other motorised vehicles |
| C8 | Indoor objects | E.g., Chairs, radiator, lights |
| C9 | Indoor spaces | E.g., Classrooms, assembly hall, corridor |
| C10 | Miscellaneous | Images with no thermal differences (e.g. images that visually do not seem to have a difference in temperature) or other unidentifiable images. |
| C11 | Videos | Videos taken by students |
| C12 | Nature | E.g., plant, clouds, sky, trees |
| C13 | Ghost prints (body) | E.g., Handprint or other bodyprint |

## 3. Results and discussion

### 3.1. Quantitative assessment of learning

Statistical analyses of the quiz scores revealed that the climate change literacy of the participating students increased significantly ($p = 0.005$) after they had participated in the thermal imaging sessions (Table 5). Among all primary and secondary school students, the average of the post-session quiz scores increased by 5% (Fig. 4). Of the 71 students that completed both quizzes, the scores improved for 42, declined for 21 and remained unchanged for eight. Five of these eight students, however, scored 90 points or higher in both quizzes, indicating they already had a very good understanding of issues related to climate change. While five students (5 primary schools, 0 secondary schools) scored 90 points or more in the pre-session quiz, 15 students scored 90 points or more in the post-session quiz (13 primary schools, 2 secondary schools).

Separate analyses of the scores from primary and secondary schools showed a significant improvement of climate change literacy for both school types (primary schools: $p = 0.021$, secondary schools: $p = 0.022$). However, the analyses also revealed that although the secondary school students had generally a better understanding of the topic, as evidenced by higher mean pre- and post-session scores compared to primary school students (Table 5), the improvement in quiz scores was greater for primary school students. The mean difference between the two average quiz scores for primary school students was +5.8, which is nearly twice that of the secondary school students (+3.3; Table 5).

When analysing the scores of individual classes, it became obvious that knowledge about climate change causes, impacts and mitigation strategies differed markedly among primary school classes yet were relatively similar between the two participating secondary school classes (Table 5). Differences in pre- and post-session quiz scores were most pronounced between PS 1 (mean difference = 10.53) and PS 2b (mean difference = −0.08). Hence, the significant improvement in this school type was predominantly driven by the excellent scoring on the post-session quiz at PS 1. Even though the mean difference in average pre- and post-session quiz scores was equal between the two secondary school classes, the improvement in climate change literacy was only significant at SS 1 due to greater consistency in their scoring (smaller standard error, see Table 5).

The findings in this study are consistent with previous research [64–66], which showed that student's performance improved after some engagement and teaching activities. This result is similar to the previous studies carried out [67,68] in which multiple linear regression models were used to describe the academic performance indicators of the students. These studies found that climate change education had a positive impact on the student' awareness, understanding and interests towards science and technology related subjects, which is in line with the findings of several other studies e.g. Refs. [69,70].

By grouping the average results of quiz questions from before and

**Table 5**
Maximum, minimum, mean difference, correlation, standard error, and p-value for pre-and post-session scores.

| | DF | Pre-session score (min, max) | Post-session score (min, max) | Mean Difference | Correlation | SE | p |
|---|---|---|---|---|---|---|---|
| All students | 70 | 65.58 (10,100) | 70.44 (10,100) | 4.86 | 0.68 | 1.84 | **0.005** |
| PS only | 44 | 61.22 (10,100) | 66.98 (10,100) | 5.76 | 0.66 | 2.76 | **0.021** |
| SS only | 25 | 73.12 (54,88) | 76.42 (36,97) | 3.31 | 0.70 | 1.55 | **0.022** |
| PS 1 | 18 | 54.21 (10,80) | 64.74 (10,100) | 10.53 | 0.47 | 5.59 | **0.038** |
| PS 2a | 12 | 76.15 (40,100) | 80.77 (30,100) | 4.62 | 0.78 | 3.69 | 0.117 |
| PS 2b | 12 | 56.54 (22,82) | 56.46 (20,75) | −0.08 | 0.77 | 2.96 | 0.510 |
| SS 1 | 15 | 71.94 (54,86) | 75.25 (45,91) | 3.31 | 0.74 | 1.83 | **0.045** |
| SS 2 | 9 | 75.00 (60,88) | 78.30 (55,97) | 3.30 | 0.65 | 2.92 | 0.144 |

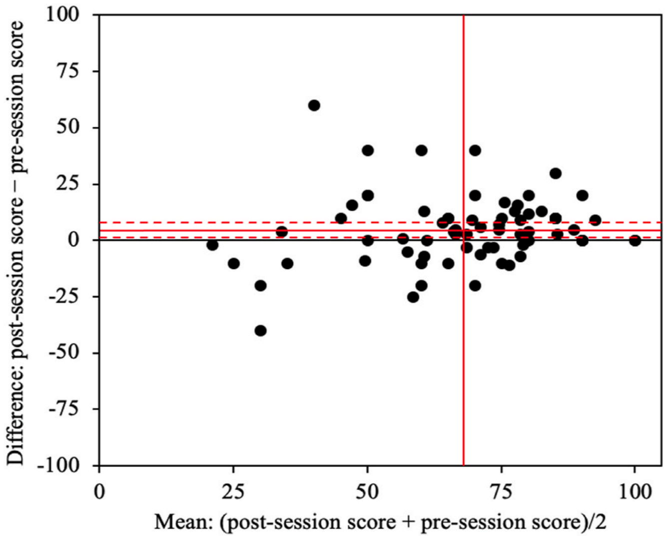


**Fig. 4.** Test scores of all students that completed the pre- and the post-session quiz (n = 71). Dots above the solid black line indicate improved scores, those below indicate lower scores in the post-session quiz. The horizontal solid red line depicts the level of improvement in climate change literacy among all students from primary and secondary schools. The horizontal dashed red lines show 95% confidence intervals. The vertical solid red line shows the overall mean score of both quizzes.

after the interactive sessions into the three categories of cause, impact, and mitigation, it became clear that in primary and secondary schools, the knowledge about impacts was greater than the knowledge about causes and mitigation strategies related to climate change (Fig. 4). This finding should be of concern, as it reflects previously documented combination of fear about climate change impacts coupled with low factual knowledge about climate change and what young people can do to actively reduce related impacts [71].

Overall, the quiz results demonstrated that initiatives such as Heat-Cool are effective to help to improve climate change education and therefore can play a significant role in spreading awareness and contributing to the achievement of SDGs #4 and #13. Therefore, starting the climate change education in primary schools for the early years is likely to contribute to a greater number of students wishing to specialise in the climate change field or more broadly related STEM disciplines, in their future work life. Apart from this, the Heat-Cool initiative may also boost students' basic understanding of climate science, including the carbon cycle, and the effects of greenhouse gases and their physical and socio-economic impacts, such as extreme climate conditions, and related losses of lives and property.

### *3.2. Thermography analysis*

The pictures and videos taken by the students were diverse in content and were separated into 13 categories that broadly captured the main themes and objects featured in the images. These categories and their descriptions can be seen in Table 4 and some examples of the images taken by the students can be seen in Fig. 3. The number of thermal images taken, and the time spent in filming videos by the students at each school were used as indicators of their involvement and excitement within the sessions (Table 6). The total images taken by subgroups per minute in the student cohort (hereafter called "Picture index") was the highest (3 images per minute) for the SS1, followed by 2 images per minute for the PS1 and 1 image per minute for both PS2 and SS2. In addition, each students' subgroup in PS1 and SS1 spent approximately 7% and 8% of activity time, respectively, on making short films (videos), while PS2 and SS2 spent only 2 and 3% of activity time, respectively during sessions.

Most of the images captured by PS1 students were categorised under "Human body (group)". Similarly, for PS2, it was "Motorised vehicles'' and "Human body (individual)"; for SS1, it was "Human body (group)" and "Outdoor spaces"; and for SS2, it was "Indoor objects" and "Outdoor spaces" (Fig. 5). This is consistent with the results presented in SI Figure S3 that PS1 took more pictures during session 1 (32% - Fun and Play), while PS2 and SS1 took more pictures during session 4 (51% and 63% respectively - Green infrastructure). SS2 took more pictures during session 2 (40% - Indoor objects). All schools showed a low percentage of images categorised as "Miscellaneous" or related to nature and outdoor spaces. This may indicate that the students were interested in finding objects, places and people that showed a high thermal contrast and could provide meaningful images or even greater desire for social interaction during the activities.

Pictures can be considered analogues of experience and, therefore, can be used to communicate experiences in a concrete way [72]. PS1 had a higher percentage of pictures taken of people compared with other categories, possibly indicating that their influence on the environment was more interesting compared with objects and spaces. On the other hand, the schools that took more pictures of objects and spaces seemed to have more interest in their surroundings and thermal objects and may have followed the proposed sessions more strictly. The difference in age may have influenced students' interests, perceptions, and the way in which they interpreted and enjoyed their environment, as discussed by Ref. [73]. Here, they found that different age groups presented different characteristics for a positive place, differentiating between age groups regarding what they considered appealing and enjoyable.

**Table 6**
Number (*n*) of thermal images and videos taken by the students per school. A Picture Index (images taken per group per minute) and the Relative Video Time (% of time spent filming during all sessions) were estimated based on a total time that students spent using the imaging devices during the sessions.

| Number of pictures | Schools | | | |
|---|---|---|---|---|
| | PS1 | PS2 | SS1 | SS2 |
| Pictures (n) | 1076 | 626 | 176 | 317 |
| Videos (n) | 34 | 8 | 9 | 5 |
| Video time (minutes) | 12.8 | 3.5 | 1.6 | 2.2 |
| Picture Index (n minute$^{-1}$) | 2 | 1 | 3 | 1 |
| Relative Video Time (%) | 7% | 3% | 8% | 2% |

Visual literacy and the use of visual elements (e.g., pictures and photographs) may enhance learning and yield positive results [72]. In the light of this, the activity proposed in this paper can be expected to have a positive impact on STEM learning of the students. Moreover, images and pictures can be an exceptional tool for learning and teaching especially if used in conjunction with active learning, which is considered as a good way to impact and increase students' knowledge and understanding [74,75].

The taking of photographs may also be a source of excitement [76] and a way to engage the students with the subject. In that case, several pictures taken by the students may be used to illustrate the student engagement and excitement during the activity (Fig. 5 and SI Figure S4). The interaction of the students with the camera to create their own thermal images can be observed in Fig. 5 (C13), where a student used his hand to make a thermal image, or in SI Figure S5a, where the student took a picture of his shoe to show the thermal imprint on the object. Another example was of some students who took pictures of a sink with running water, allowing the observation of the difference between the temperature of the cold water and the sink and their hand (SI Figure S5b).

### 3.3. Observational analysis

Student engagement levels in educational environments affect their learning during classroom teaching [77,78]. For instance, by interviewing and observing 88 students and their 10 teachers, [79] studied

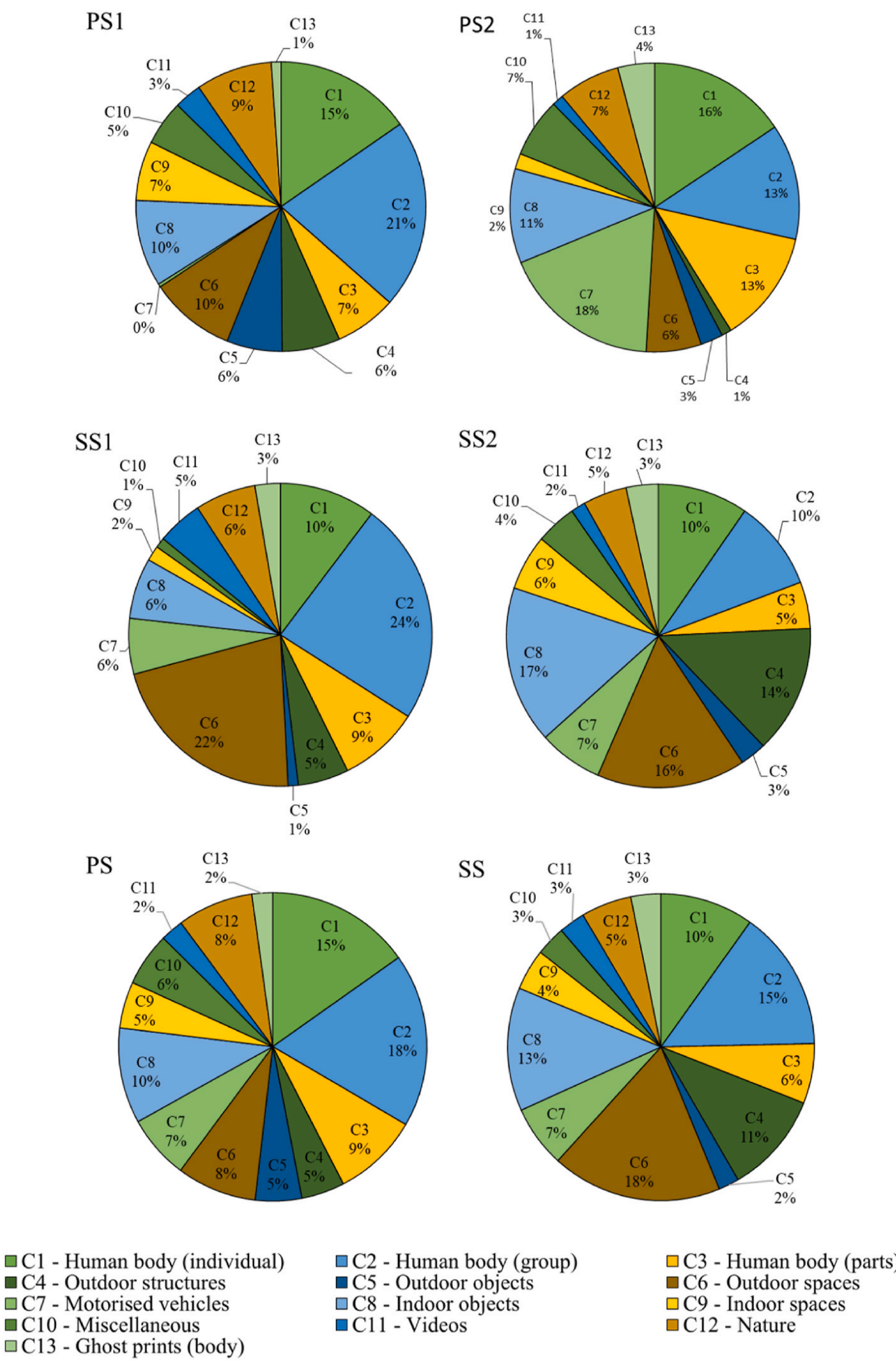


**Fig. 5.** Percentage of the students' taken thermal image contribution for each category (13 categories) considering (a) each school (PS1, PS2, SS1, SS2), (b) primary school and secondary school.

the impact of digital resources (games, web-based learning modules and videos) on student motivation for learning mathematics. They found that students' exposure to these digital resources was able to motivate students in learning mathematics. However, they did not quantify the impact of an increase in students' motivation on their learning. In the Heat-Cool programme after the first session that provided instruction and training (Section 2.1), the students were observed to be comfortable in utilising the thermal equipment during sessions 2–5 (Table 3). Fig. 6 depicts the percentage shared by students in overall responses for the level of motivation and engagement across all schools. The total 79 participating students were divided in 75 subgroups (3–6 students' groups in each session) during the total 20 sessions across the four schools (Table 2). While observing motivation levels (Fig. 6a), it was observed that more than 94% of students' subgroups (70 student subgroups) showed positive motivation towards paying attention to the teacher's instructions and completing the requested tasks, followed by questions asked (60 student subgroups), understanding of the tasks (52 student subgroups) and discussion (52 student subgroups) in most of the

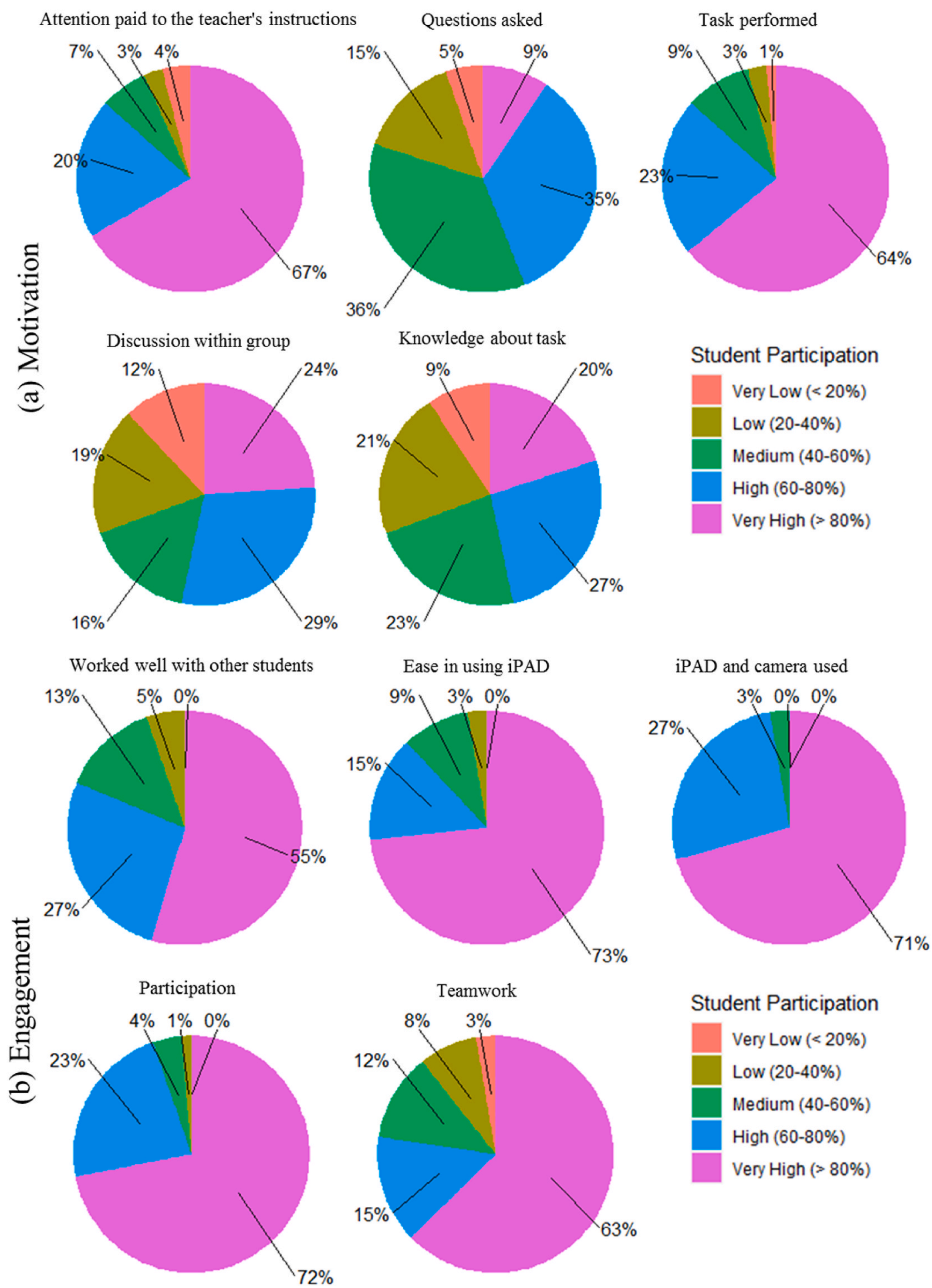


**Fig. 6.** Pie charts showing observed (a) motivation level, and (b) engagement level among students in different subgroups over all the schools. The colour indicates the percentage of students' participation in each task.

sessions. Thus, these observational data suggest that motivation levels during different sessions (Section 2.2) were generally positive. Further supporting qualitative observations were made by the headteacher from SS1 (SI Section S6; Response-1). However, on numerous occasions, a lower number of students were also observed discussing their experiences within their group (23 student subgroups) in the sessions. The reason behind these lower number of students' discussions about the difference in thermal properties of different objects (Section 3.2) during sessions might be due to the short period of each session or students' involvement in visualising different objects, and hence leaving lesser time for discussions. For instance, some students became over excited and, in some instances, sought to run towards moving or high thermal objects such as moving buses and cars, indoor radiators and metal objects in sunlight where teachers needed to immediately intervene.

Furthermore, Fig. 6b demonstrates that in more than 67 student subgroups (89%), most students worked well together, used thermal cameras, participated in tasks, and found it easy to use thermal cameras. Therefore, the student subgroups were found to be positively engaged in the tasks throughout all the sessions. A similar observation was also quoted by the headteacher of PS2 (SI Section S6; Response-2). According to Ref. [80], this positive engagement might be caused due to behavioural engagement (physical participation), cognitive engagement (willingness to put forth effort), and emotional engagement (the student's activation of positive and negative feelings and effects in the surrounding environment). Most of the students who participated in sessions had never used a thermal camera to visualise temperature differences between objects before, but they all found it simple to use and were able to complete the tasks for each session. These similarities amongst school children from various schools and ages implies that the Heat-Cool programme seems to be suitable as a STEM learning activity for climate change education in schools more broadly.

As suggested by Ref. [58], students tell stories, do demonstrations, and explore beyond the set tasks to express their interest. During sessions, students appeared to be eager to show what they have learned throughout the sessions. For instance, a student was so enthusiastic about what they had learned during the sessions that they explained to their teacher that if they put their hand on the cold window, it would heat up the window's surface. Then they proceeded to demonstrate it to the teacher by asking them to put their hand on the window and hold it there for 10 s. Then the student snapped a photo of the window and showed their teacher the warm spot where the hand had been (Fig. 3. C13). Observation from a teacher from SS2 also evidenced the student's interest during sessions (SI Section S6; Response-3). In addition, the students were taking different routes (Table 4) to explore the new technology for expressing their interest, as is discussed in Section 3.2. Furthermore, teachers' experiences indicate that no equivalent material is accessible in the educational curriculum to boost school students' interest in the STEM subjects. For instance, a deputy headteacher from PS1 also confirmed these research outcomes in their open response (SI Section S6; Response-4). These expressions indicate the potential of Heat-Cool sessions and the new technology to support learning and interest in STEM.

Overall, the consistent distribution of observed responses across the four schools indicated that the developed sessions could be integrated with the current curriculum of both primary and secondary schools. During the sessions, students generally showed positive motivation and engagement towards activities related to capturing thermal properties of surrounding objects. In addition, students also expressed their interest in exploring the new technology and understanding of climate science. Schools found this approach to be interactive, target-oriented and useful for their students to help them improve their understanding about the issues of climate change and the mitigation measures. Policy makers and educators, thus, need to introduce similar approaches in the educational curriculums and hence integrate technology in students' learning and raise their interest in STEM.

## 4. Conclusions

This study was aimed at improving the awareness of students and knowledge related to climate change, heating, and cooling of planet earth, and at infusing their curiosity in STEM. This study was successful in creating an opportunity to demonstrate that a citizen science-based environment education programme, combined with the use of instruments such as an infrared camera, is a good way of enhancing the knowledge of students on climate change and broader environmental issues. Our multi-faceted approach for achieving the objectives of this project were integrated in the pre-sessions quiz, thermal camera-based activities by primary and secondary school students, and the post-session quiz. The pre-session quiz assessed the knowledge of students on the subject before the practical sessions and the post-session quiz was designed to evaluate and analyse the effect of these sessions' activities on students' learning and understanding. The performance of the students was quantitatively analysed and compared using descriptive statistics, and paired t-tests. This study provides both quantitative and qualitative analysis of the role of the Heat-Cool initiative in raising the awareness and enhancing students' knowledge of climate change drivers and their impact.

The following conclusions can be drawn from this work:

The majority of students demonstrated an improvement in knowledge related to heat and climate change, as a result of participating in the Heat-Cool programme, although this effect was not uniform across different school levels and classes. Students were excited to work with thermal cameras and the interpretation of thermal images encouraged them to take part in the activities in individual sessions. The number of pictures taken by the students, the interaction among them, and the images of objects and of fellow students to understand thermal profiles, indicate that the project activities were successful in infusing curiosity in students about the subject.

The results of thermal image analysis indicate that the profile of pictures taken in each school varied, especially considering the age of the students. Moreover, the activities triggered excitement and involvement as indicated by the high number (2195) and type (13 different categories) of pictures taken. The results of the observational analysis showed that the students were highly motivated ($\geq$94% subgroups) and engaged ($\geq$89% subgroups) towards the session's activities and indicated their interest in technology and climate change-related learning. Thus, increasing students' motivation and engagement in learning sessions is likely to have a positive impact on their knowledge about climate change.

This educational initiative is likely to increase students' motivation and engagement in STEM subjects. The engaging sessions of the 'Heat-Cool Initiative' had a positive impact on students learning about the heating and cooling of planet earth. This positive impact calls for much greater support of applied STEM learning in primary and secondary schools. Expansion of such learning activities across schools in the UK and internationally should be underpinned by progressive, new policies in the education sector. Nation-wide support programmes that provide financial incentives for schools and operational and intellectual help for teachers will be needed. Targeted investment in STEM education and policy frameworks that enhance climate change literacy in primary and secondary schools are needed now more than ever before. This initiative also has potential to enhance students' critical thinking and basic life skills such as problem-solving, information management, consensus building, teamwork, communication, and critical and creative thinking; these are important for all educational subjects and social life, in general.

Our experience through the Heat-Cool initiative implementation in primary and secondary schools, suggests that climate change education should be taught as part of the school curriculum; tomorrow's leaders should be prepared for tomorrow's issues, and students must be sufficiently educated for the future that they will inherit. Thus, the focus on educational initiatives should also cover broader purposes such as shaping future citizens and leadership beyond education, in line with the OECD's concept of global competencies. Environmental education courses based on engaging pedagogical methodologies, curriculum, and evaluation strategies, are required to increase climate literacy in schools. The combination of the above strategies within Heat-Cool sessions could exploit the full potential of climate change education in primary and secondary schools.

While there were many positive aspects of the Heat-Cool initiative, there were also several limitations that future research should address. Firstly, the number of participating students and related pre-activity and post-activity quizzes was limited. To support the development of national and international curricular activities that aim at enhancing STEM interest in school children, it will be necessary to widen the implication and rigorous analysis of the Heat-Cool Initiative across a much broader sample of schools. The classification of thermal images and observations made during the activities were carried out subjectively by the researchers, which may have introduced an unknown bias and error. Moreover, although the quiz was designed to address a wide range of climate change topics (SI Sections S3 and S4), it included a limited number of questions, which did not exhaust the topic of climate change. Therefore, the assessment of students' learning through the quizzes could be further enhanced by broadening the question base by including questions related to associated climate change topics such as the role of green infrastructure in mitigation of flooding, reduction of urban overheating, and improving air quality.

The students were curious about these associated topics and raised them with the session coordinators during Heat-Cool sessions. This indicates that students may have also learned about these topics during the sessions despite not being covered by the quiz. Such observations will require further investigation and refining of the sessions. Regardless of potential future improvements, our robust results demonstrate that a programme like Heat-Cool will generate positive learning outcomes, signified by an increase of quiz scores after the activities by 5% in a highly diverse cohort of students. Policymakers and practitioners in school education should take note of these tender signs of positive change and translate them into much needed action to reverse the declining interest in STEM topics in the future generations of earth stewards.

## Credit author statement

**Prashant Kumar**: Conceptualization, Funding acquisition, Writing - original draft, Resources, Supervision, Project administration, Methodology, Writing - review & editing. **Jeetendra Sahani**: Data collection, Methodology, Writing - original draft, review & editing. **Nidhi Rawat**: Data collection, Methodology, Writing - original draft, review & editing. **Sisay Debele**: Methodology, Quantitative analysis of data, Writing - original draft, review & editing. **Arvind Tiwari**: Data collection, Methodology, Qualitative analysis of data, Writing - original draft, review & editing. **Ana Paula Mendes Emygdio**: Methodology, Qualitative analysis of data, Writing - original draft, review & editing. **K.V. Abhijith**: Data collection, Methodology, Formal analysis, Writing - review & editing. **Vina Kukadia**: Methodology, Writing - review & editing. **Kathryn Holmes**: Methodology, Writing - review & editing. **Sebastian Pfautsch**: Writing - original draft, Methodology, Writing - review & editing.

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## Declaration of competing interest

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

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

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