DATA-INFORMED RESILIENCE PROTECTING CHILDREN AND YOUNG PEOPLE FROM HEAT STRESS VIA WEARABLE TECHNOLOGY IN PHYSICAL EDUCATION LESSONS – A DESIGN THINKING APPROACH

Kristy Howells, School of Sciences, Psychology, Arts and Humanities, Computer Engineering and Sports (SPACES), Canterbury Christ Church University, Kent, UK.

Pim Koolwijk, Research Group Healthy Lifestyle in a Supporting Environment, The Hague University of Applied Sciences, The Hague, The Netherlands.

Antonino Mulè, Faculty of Education, Free University of Bozen-Bolzano, Brixen-Bressanone, Italy.

Ivan Müller, Faculty of Medicine, University of Basel, Basel, Switzerland; UNESCO Chair on '*Physical Activity and Health in Educational Settings*'.

Susan Whatman, Faculty of Arts, Education and Law, Griffith University, Gold Coast, Australia.

Keywords : Heat literacy; Quality Physical Education; Climate change; Health; Pedagogy.

ABSTRACT

Climate change is reshaping the conditions under which children and young people learn and move. Rising temperatures and more frequent heatwaves expose pupils to increased physiological strain, heightening risks to health, wellbeing, and learning during Physical Education (PE). While heat-safety guidance exists, it remains largely reactive, threshold-based, and externally imposed, offering limited pedagogical support for teachers' real-time decision-making or children's understanding of their own physiological responses.

This paper conceptualises children's heat stress as a pedagogical design problem arising from persistent mismatches between physiological strain, perceptual awareness, and educational practice. Drawing on interdisciplinary literature and prior research on children's hydration and perceptual mismatches in physical activity (PA), the paper synthesises evidence on physiological vulnerability, differential risk (including obesity, diabetes, and medication-related thermoregulatory impairment), and educational impact.

Using Chambers et al.'s (2019) design thinking framework aligned with Quality Physical Education (QPE), the paper advances a wearable-informed pedagogical model. Wearable technologies are framed not as surveillance or performance tools but as educational mediators and instructional tools that make invisible physiological processes visible, interpretable, and discussable for learning, self-regulation, and safeguarding in PE. Benefits are critically evaluated alongside ethical, psychological, and equity-related constraints. An implementation-oriented infographic is presented as a knowledge mobilisation artefact for both teachers and researchers.
The paper concludes with a call for climate-resilient PE, positioning data-informed pedagogy as a means of enhancing children's heat literacy, supporting teachers' professional judgement, and reducing heat-related risk under conditions of environmental uncertainty.

INTRODUCTION

CLIMATE CHANGE, HEAT STRESS, AND PHYSICAL EDUCATION

Climate change is a defining condition of contemporary education, characterised by heightened risk and uncertainty (Sakschewski et al., 2025). Rising global temperatures and increasingly frequent heatwaves are now enduring features of children's environments rather than exceptional events. Schools, many of which were designed for temperate climates, must now operate safely under sustained thermal stress. PE is particularly exposed, as lessons occur indoors and outdoors, combining environmental heat with metabolically generated heat from PA, and often involve greater skin exposure. PE teachers are responsible for delivering safe, inclusive, and developmentally appropriate movement experiences, while safeguarding in physically demanding learning environments.

Heat stress arises in children when their thermoregulatory capacity cannot keep pace with the combined demands of movement and environmental heat, resulting in cumulative physiological strain that can impair wellbeing, cognition, attention, learning, and physical safety. Although professional bodies provide guidance on safe thresholds (Racinais et al., 2023), heat-related decision-making in schools remains largely perceptual and reactive, relying on ambient temperature, visual cues, or children's self-reports. These approaches are poorly equipped to detect "silent" physiological strain. UNICEF (2022) estimates that by 2050 almost every child (under 18) globally will be exposed to high heatwave frequency, indicating that heat stress is a widespread educational issue rather than a regional anomaly. Currently, 624 million are exposed to high heatwave duration, high heatwave severity, or extreme high temperature. Heat stress is not just limited to some parts of the world but impacts children globally and raises the need for this topic to be discussed and researched in more detail.

Existing research tends to address thermoregulation, climate risk, or wearable monitoring in isolation. This paper integrates these strands by framing children's heat stress as a pedagogical design problem rather than solely a medical or environmental concern. A design thinking approach enables wearable technology to be understood as a pedagogical tool that shapes learning, behaviour, and values (Schnitzler et al., 2026), rather than as surveillance or performance monitoring.

Informed by Chambers et al.'s (2019) design thinking framework and tools such as S.C.A.M.P.E.R., developed at the *Future Matters: Reimagining Physical Education for a Changing World* AIESEP Specialist Seminar, children's heat stress is conceptualised as a wicked problem marked by uncertainty, uneven vulnerability, and the absence of a single technical solution (Chambers et al., 2025). Drawing on anticipatory perspectives, design thinking was used to surface tensions between environmental change, duty of care, and pedagogical decision-making, and to explore how wearable technologies might translate into more responsive and ethically grounded PE pedagogy (Chateauraynaud, 2013). This aligns with UNESCO's Fit for Life (2021) and Quality Physical Education (McLennan & Thompson, 2016) initiatives and international calls for climate-resilient schooling that extend beyond infrastructure to pedagogical transformation.

CHILDREN'S PHYSIOLOGICAL VULNERABILITY TO HEAT STRESS

Heat-safety guidance in youth sport and education is commonly structured around environmental thresholds, particularly the Wet Bulb Globe Temperature (WBGT) (Patel et al., 2013). Organisations such as the American College of Sports Medicine (ACSM, 2007), the International Olympic Committee (Racinais et al., 2023), Sports Medicine Australia (Tartarini et al., 2025), and the American Academy of Pediatrics (AAP, 2025) provide recommendations for training and competition in hot environments. ACSM and AAP recommend limiting moderate-to-vigorous physical activity (MVPA) at 27.5–30°C and ceasing activity at 30–32.3°C. However, WBGT was not designed to account for the dynamic variability of children's physiology, nor for the interaction between metabolic heat production, hydration status, and developmental capacity.

Children differ fundamentally from adults due to higher surface-area-to-mass ratios, reduced evaporative cooling efficiency, greater metabolic heat production during movement, slower acclimatisation increases children's vulnerability during MVPA and extreme heat (Morrison, 2022). Children have an underdeveloped thirst reflex compared to adults and can miss the physiological signs as to when they need to drink and hydrate (Howells & Coppinger, 2021). Consequently, children may accumulate significant thermal strain even when external conditions appear manageable.

Heat stress also affects children unevenly. Symptoms range from irritability and fatigue to dizziness, nausea, clammy pale skin, and excessive sweating (UK Health Security Agency, 2024). Children with obesity are at heightened risk due to increased insulation from adipose tissue, lower heat dissipation, and slower acclimatisation, causing them to heat more rapidly during activity. Those with diabetes face additional challenges related to dehydration and hyperglycaemia, impaired cardiovascular and thermoregulatory responses (Satow et al., 2025). Common childhood medications, including antihistamines, antibiotics, and some ADHD treatments, may induce side effects that inhibit sweat production, suppress thirst, and further impair thermoregulation.

These vulnerabilities are rarely visible in routine PE practice. Heat stress develops progressively and is shaped by interactions between physiology, hydration, medication, and environment. In school PE settings, where physical activity (PA) is organised and delivered collectively, and activity modification is typically applied uniformly, individual vulnerability can be obscured, rendering heat risk structurally invisible despite outward signs of coping. This structural invisibility reframes heat stress not as an individual failure of awareness, but as a pedagogical design problem requiring new forms of heat literacy that do not depend on diagnosis, disclosure, or stigma.

HEAT STRESS, WELLBEING, AND LEARNING

Heat stress undermines wellbeing and learning well before medical emergencies occur. Elevated temperatures impair attention, working memory, and executive function, with even modest increases in school-year temperatures associated with measurable learning losses (McClain, 2025). Behavioural changes such as irritability, lethargy, and reduced motivation often precede physical symptoms but are frequently misinterpreted in PE as disengagement or poor behaviour. As a result, children may continue and teachers may encourage them to exert themselves in conditions that compromise both their wellbeing and learning.

The educational significance of heat stress lies in its unequal distribution. Cuartas et al. (2025), following 19,607 children, found disproportionate impacts on those with limited access to cooling or hydration infrastructure and those with underlying vulnerabilities. Addressing heat stress is therefore both a safeguarding obligation and an equity imperative for education systems. As climate exposure intensifies, failure to address heat stress risks amplifying existing health and participation inequalities within PE.

PERCEPTUAL MISMATCH AS A PEDAGOGICAL DESIGN PROBLEM

A persistent challenge in managing heat stress in PE is the mismatch between perceived and actual physiological states. Children often lack interoceptive awareness to accurately judge PA intensity, hydration needs, or physiological strain (Howells & Coppinger, 2021, 2022). During play and sport, attention is externally focused, further obscuring internal cues.

In hot conditions, this perceptual gap becomes critical: skin and core temperatures may rise substantially without overt symptoms, creating a “silent” risk period (Satow et al., 2025). This mismatch should not be understood as individual failure but as a predictable outcome of developmental capacity and pedagogical contexts that rely on external observation. Reframing perceptual mismatch as a design problem shifts responsibility from children’s self-awareness to the learning environment, opening space for pedagogical tools such as wearable technology that translate internal physiological processes into shared, interpretable signals to inform real-time decision-making.

LIMITS OF EXISTING HEAT GUIDANCE IN PE

PE combines internal metabolic heat with environmental exposure, creating risks that are poorly captured by traditional pedagogical metrics such as speed, distance, or repetitions. A child moving slowly may be operating near maximal cardiovascular capacity, while a confident athlete may approach dangerous thresholds without visible distress.

Although heat-safety guidelines are essential for population-level risk management, they provide limited support for in-lesson decision-making. WBGT estimates environmental risk but does not account for individual variability in fitness, hydration, obesity, medication use, or engagement. Consequently, activities may continue below threshold values while some children experience substantial physiological strain, reinforcing false perceptions of safety (AAP, 2025). This highlights the need for complementary approaches that support dynamic individual interpretation of heat stress within PE lessons.

WEARABLE TECHNOLOGY AS PEDAGOGY: A DESIGN THINKING RESPONSE

Wearable technologies offer a bounded pedagogical response by supporting professional judgement where physiological risk is not visible. Their educational value lies not in data collection alone but in interpretation, governance, and integration into pedagogical decision-making (ADEME, 2021).

As pedagogical tools, wearables can scaffold heat literacy by linking sensation, action, and physiological consequence during PA. This supports pacing, hydration, and rest decisions within PE lessons (IHT Spirit, 2021). Over time, scaffolding can be reduced as children develop greater interoceptive awareness, narrowing the mismatch between perceived and actual PA (Howells & Coppinger, 2022), which is key in heat stress situations. It also enables teachers to make proportionate adjustments to task intensity, duration and grouping in real time.

For teachers, wearable-informed pedagogy enables differentiated, effort-based assessment relative to individual baselines rather than peer comparison or competition. This supports inclusion and allows differential vulnerability to be addressed pedagogically without diagnosis, disclosure, or stigma (AAP, 2025), while preserving professional judgement.

PSYCHOLOGICAL, ETHICAL, AND EQUITY CONSIDERATIONS

Integrating wearables in PE raises psychological, ethical, and equity concerns. Risks include anxiety, obsessive monitoring, and negative social comparison if data are framed competitively (Wort et al., 2021). Ethical issues relate to informed consent, data privacy, and the creation of digital health records for minors. Practical constraints include cost, access, accuracy, distraction, and safety in some activities.

Responsible implementation, therefore, requires bounded, intermittent, teacher-mediated use focused on effort and safety rather than competition or body metrics. Equity considerations are central: reliance on personal devices risks widening inequalities, necessitating school-owned equipment alongside investment in shade, hydration, and environmental mitigation.

IMPLEMENTATION AND FUTURE DIRECTIONS

The proposed model complements frameworks such as UNICEF's B.E.A.T. the Heat (2024) by embedding heat literacy within routine PE practice. Making physiological strain visible before symptoms escalate strengthens preventative intent and supports real-time action. To guarantee that this approach is both transparent and scalable, implementation must be addressed across multiple operational layers, moving beyond individual classroom practice to a wider systemic change. Specifically, at the teacher and classroom levels, focus should remain on integrating real-time biometric feedback into lesson planning, enabling immediate intensity and duration adjustments based on individual physiological strain rather than arbitrary thresholds. This can be supported at the school leadership level by prioritising the purchase of school-owned wearable devices to ensure equitable access and to enable them to become part of learning, not an add-on extra. This would enable teachers to create their own adaptive curriculum and body of knowledge based on information from wearables, allowing them to make decisions tailored to their regional climate challenge. Also, for school leadership to invest in resilient infrastructure, such as permanent shade structures and accessible, safe hydration stations. A systems response approach to be weather-aware and to timetable PE lessons appropriately for when they could be delivered safely. Finally, at the policy and system level, it is essential for preservice teachers within teacher education to be taught how to respond to biometric feedback so that wearables can be integrated seamlessly within the spectrum of teaching approaches already in use in PE, and to standardise heat-safety training while establishing clear governance safeguards regarding data privacy and the ethical management of digital health records for minors.

Future research should examine how heat literacy informed by wearables develops across childhood and adolescence, as responsibility for self-regulation shifts with age, in an equivalent way to how, for example, children with type 1 diabetes become more responsible for their readings and responses with age. Understanding how pedagogical responsibility transitions across developmental stages is essential for supporting lifelong PA under increasingly unfavourable climatic conditions. This research should also establish robust evaluation frameworks to monitor the long-term psychological impacts of data-informed pedagogy on children's relationships with PA. In the short term, priorities may include developing training modules focused on “heat literacy” and piloting wearable-integrated lessons that monitor internal physiological responses to ensure student safety, while simultaneously developing children's own knowledge of how they feel and how to respond to those sensations. Medium-term goals may focus on funding and scaling school infrastructure, such as integrating wearable data with cooling stations and shaded play areas to provide comprehensive protection. In the long term, heat-resilient PE frameworks should be fully embedded in national curricula, ensuring that pedagogical responsibility transitions effectively across developmental stages and schooling sectors. This empowers students to take full ownership of their physiological self-regulation, ensuring they can safely sustain lifelong PA under increasingly unfavourable climatic conditions. Future research on how knowledge of heat literacy is developed for pupils and teachers, using wearables within national PE curricula, leading to resilient school policy and beyond, is important to follow longitudinally to examine lessons learned from the heat literacy development.

CONCLUSION

This paper advances a pedagogical reorientation that makes heat stress visible, interpretable, and teachable within PE. As climate change redefines the material conditions of schooling, PE cannot rely on temperate-era pedagogies of effort, endurance, and visible performance. By positioning heat stress

as a learnable phenomenon rather than an invisible background risk, the paper opens new directions for research, teacher education, curriculum design, and climate-resilient schooling.
Wearable-informed pedagogy enables teachers to respond to emerging physiological strain before visible harm occurs, supporting safeguarding in conditions where self-regulation cannot be assumed. In doing so, it shifts heat stress in PE from reactive guidance toward structured, data-informed, climate-resilient practice.

Figure 1 operationalises this framework into an infographic, a knowledge mobilisation artefact, linking children's physiological vulnerability and perceptual mismatch to concrete wearable-informed pedagogical strategies in PE lessons and system-level responses to support both teachers and researchers alike.

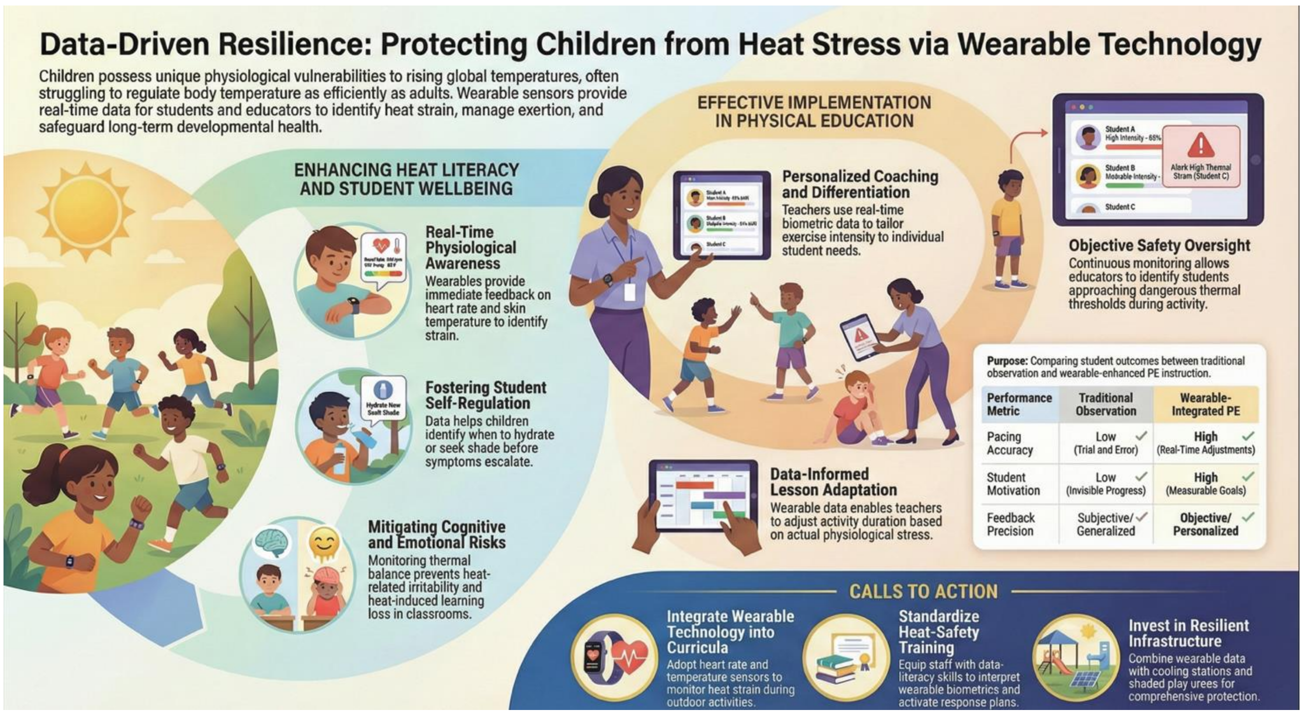

Figure 1 - Data-Informed Resilience: An Implementation Model for Protecting Children from Heat Stress via Wearable Technology in PE lessons (source: Howells et al., 2026).

Acknowledgments
The content of this research work is supported by UNESCO Switzerland and the UNESCO Chair on '*Physical Activity and Health in Educational Settings*.' We would like to thank Prof Fiona Chambers, Prof Christophe Schnitzler, Prof Kelly Salchow-MacArthur, and Prof Olivier Vors for their expert advice on the design thinking process. We would also like to thank AIESEP for running the Specialist Seminar on the Future of Physical Education, enabling the authors to come together as a team.

Abbreviations
AAP: American Academy of Pediatrics.
ACSM: American College of Sports Medicine.

ADEME: Agence de l'Environnement et de la Maîtrise de l'Énergie (French Environment and Energy Management Agency).
ADHD: Attention-Deficit/Hyperactivity Disorder (ADHD).
AIESEP: Association Internationale des Écoles Supérieures d'Éducation Physique (International Association of Physical Education in Higher Education).
IHT: Interactive Health Technologies.
MVPA: Moderate-to-Vigorous Physical Activity.
PA: Physical Activity.
PE: Physical Education.
QPE: Quality Physical Education.
S.C.A.M.P.E.R.: Substitute, Combine, Adapt, Modify, Put to new use, Eliminate, Rearrange.
UNESCO: United Nations Educational, Scientific and Cultural Organization.
UNICEF: United Nations Children's Fund.
WBGT: Wet Bulb Globe Temperature.

REFERENCES

ADEME. (2021). *Transition(s) 2050: Choose your future*. https://www.ademe.fr/en/futures-in-transition/.

AAP, Bergeron, M.F., Devore, C.D., & Rice, S.G. (2025). Council on Sports Medicine and Fitness and Council on School Health. *Pediatrics*, 128(3), e7141-e747. https://doi.org/10.1542/peds.2011-1664.

ACSM, Armstrong, L.E., Casa, D.J., Millard-Stafford, M., Moran, D.S., Pyne, S.W., & Roberts, W.O. (2007). American College of Sports Medicine Position Stand. Exertional heat illness during training and competition. *Medicine & Science in Sports & Exercise*, 39(3), 556-572. Doi: 10.1249/MSS.0b013e31802fa199.

Chambers, F.C., Jones, A., Murphy, O., & Sandford, R.A. (2019). *Design thinking for digital wellbeing: Theory and practice for educators*. Routledge.

Chambers, F.C., Aldous, D., Whatman, S., & Schnitzler, C. (2025). Building the Case for Planet-Centric Health and Physical Education for Society 6.0. In V.A. Goodyear & A. Bundon. (Eds.), *Routledge Handbook of Digital Technologies in Sport, Exercise and Physical Education*, (pp. 324-338). Routledge.

Chateauraynaud, F. (2013). Regard analytique sur l'activité visionnaire. Dans Sous la direction de D. Bourg, P. Joly et A. Kaufmann *Du risque à la menace: Penser la catastrophe* (p. 287-310). Presses Universitaires de France. https://doi.org/10.3917/puf.bourg.2013.02.0287

Cuartas, J., Balza, L.H., Camacho, A., & Gómez-Parra, N. (2025). Ambient heat and early childhood development: a cross-national analysis. *The Journal of Child Psychology and Psychiatry.* https://doi.org/10.1111/jcpp.70081

UNESCO. (2021). *Fit for Life*. https://www.unesco.org/en/fit4life.

Howells, K., & Coppinger, T. (2021). Children's Perceived and Actual Physical Activity Levels within the Elementary School Setting. *International Journal of Environmental Research and Public Health*, 18(7), 3485. https://doi.org/10.3390/ijerph18073485

Howells, K., & Coppinger, T. (2022). The Forgotten Age Phase of Healthy Lifestyles Promotion? A Preliminary Study to Examine the Potential Call for Targeted Physical Activity and Nutrition Education for Older Adolescents. *International Journal of Environmental Research and Public Health*, 19(10), 5970. https://doi.org/10.3390/ijerph19105970

IHT Spirit. (2021). *Heart Rate Monitors Give Students a Better Connection to PE Class*. https://ihtusa.com/journal/heart-rate-monitors-give-students-a-better-connection-to-pe-class/.

McClain, J. (2025). *Excessive Heat Harms Young Children's Development, Study Suggests*. https://www.nyu.edu/about/news-publications/news/2025/december/-excessive-heat-harms-young-children-s-development--study-sugges.html.

McLennan, N., & Thompson, J. (2016). *Quality Physical Education (QPE): guidelines for policy makers.* UNESCO.

Morrison, S.A. (2022). Moving in a hotter world: Maintaining adequate childhood fitness as a climate change countermeasure. *Temperature*, *10*(2), 179-197. doi: 10.1080/23328940.2022.2102375

Patel, T., Mullen, S.P., & Santee, W.R. (2013). Comparison of Methods for Estimating Wet-Bulb Globe Temperature Index From Standard Meteorological Measurements. *Military Medicine*, 178(8) 926-933. https://doi.org/10.7205/MILMED-D-13-00117

Racinais, S., Hosokawa, Y., Akama, T., Bermon, S., Bigard, X., Casa, D.J., Grundstein, A., Jay, O., Massey, A., Migliorini, S., Mountjoy, M., Nikolic, N., Pitsiladis, Y.P., Schobersberger, W., Steinacker, J.M., Yamasawa, F., Zideman, D.A., Engebretsen, L., & Budgett, R. (2023). IOC consensus statement on recommendations and regulations for sport events in the heat. *British Journal of Sports Medicine,* 57(1), 8-25. doi: 10.1136/bjsports-2022-105942.

Sakschewski, B., Caesar, L., Andersen, L.S., Bechthold, M., Bergfeld, L., Beusen, A., Billing, M., Bodirsky, B.L., Botsyun, S., Dennis, D.P., Donges, J.F., Dou, X., Eriksson, A., Fetzer, I., Gerten, D., Häyhä, T., Hebden, S., Heckmann, T., Heilemann, A., et al. (2025). *Planetary Health Check 2025: A Scientific Assessment of the State of the Planet*, Planetary Boundaries SCIENCE.

Satow, M., Wibowo, R., Bose-O'Reilly, S., Koller, D., Daanen, H., & Rakete, S. (2025). Impact of summer heat on male children's physiological responses during football training. *Environmental Research*, 286, 122725. https://doi.org/10.1016/j.envres.2025.122725

Schnitzler, C., Chambers, F., & Lefèvre, L. (2026). *Future Matters: Reimagining Physical Education for a Changing World. A Preparatory Guide for the AIESEP Specialist Seminar*. HEP Vaud University, Lausanne, Switzerland.

Tartarini, F., Smallcombe, J.W., Lynch, G.P., Cross, T.J., Broderick, C., & Jay, O. (2025). The Sports Medicine Australia extreme heat risk and response guidelines and web tool. *Journal of Science and Medicine in Sport,* 28(9), 690-699. doi: 10.1016/j.jsams.2025.03.006.

UK Health Security Agency. (2024). *Looking after children and those in early years settings before and during hot weather: teachers and other educational professionals*. https://www.gov.uk/guidance/looking-after-children-and-those-in-early-years-settings-before-and-during-hot-weather-teachers-and-other-educational-professionals#health-risks-from-heat.

UNICEF. (2022). *Protecting Children from Heat Stress. A technical note. Healthy Environments for Healthy Children*. https://www.unicef.org/media/139926/file/Protecting-children-from-heat-stress-A-technical-note-2023.pdf.

UNICEF. (2024). *Beat the heat. Child health amid heatwaves in Europe and Central Asia*. https://www.unicef.org/eca/reports/beat-heat-2024.

Wort, G.K., Wiltshire, G., Peacock, O., Sebire, S., Daly-Smith, A., & Thompson, D. (2021). Teachers' Perspectives on the Acceptability and Feasibility of Wearable Technology to Inform School-Based Physical Activity Practices. *Frontiers in Sports and Active Living*, 18(3). https://doi.org/10.3389/fspor.2021.777105.