Journal of Science and Medicine in Sport 24 (2021) 747–755

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Perspectives

The HEAT-SHIELD project — Perspectives from an inter-sectoral approach to occupational heat stress

Nathan B. Morris[a], Jacob F. Piil[a], Marco Morabito[b,c], Alessandro Messeri[b,c,d], Miriam Levi[e], Leonidas G. Ioannou[f,g], Ursa Ciuha[f], Tjaša Pogačar[h], Lučka Kajfež Bogataj[h], Boris Kingma[a,i], Ana Casanueva[j,k], Sven Kotlarski[j], Christoph Spirig[j], Josh Foster[l], George Havenith[l], Tiago Sotto Mayor[m], Andreas D. Flouris[g], Lars Nybo[a,*]

[a] Department of Nutrition, Exercise and Sports, University of Copenhagen, Denmark
[b] Institute of BioEconomy (IBE) - National Research Council c/o Area di Ricerca di Firenze, Italy
[c] Centre of Bioclimatology - University of Florence, Italy
[d] Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence (UNIFI), Italy
[e] Epidemiology Unit, Central Tuscany Local Health Unit, Italy
[f] Department of Automatics, Biocybernetics, and Robotics, Jožef Stefan Institute, Slovenia
[g] FAME Laboratory, Department of Exercise Science, University of Thessaly, Greece
[h] Department of Agronomy, Biotechnical Faculty, University of Ljubljana, Slovenia
[i] TNO, The Netherlands Organization for Applied Scientific Research, Unit Defence, Safety & Security, The Netherlands
[j] Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland
[k] Meteorology Group, Dept. Applied Mathematics and Computer Sciences, University of Cantabria, Spain
[l] Environmental Ergonomics Research Centre, School of Design and Creative Arts, Loughborough University, UK
[m] SIMTECH Laboratory, Transport Phenomena Research Centre, Engineering Faculty of Porto University, Portugal

ARTICLE INFO

Article history:
Received 16 November 2020
Received in revised form 11 February 2021
Accepted 1 March 2021
Available online 8 March 2021

Keywords:
Occupational medicine
Occupational hygiene
Occupational physiology
Environmental physiology
Public health
Occupational health

ABSTRACT

Objectives: To provide perspectives from the HEAT-SHIELD project (www.heat-shield.eu): a multi-national, inter-sectoral, and cross-disciplinary initiative, incorporating twenty European research institutions, as well as occupational health and industrial partners, on solutions to combat negative health and productivity effects caused by working on a warmer world.
Methods: In this invited review, we focus on the theoretical and methodological advancements developed to combat occupational heat stress during the last five years of operation.
Results: We outline how we created climate forecast models to incorporate humidity, wind and solar radiation to the traditional temperature-based climate projections, providing the basis for timely, policy-relevant, industry-specific and individualized information. Further, we summarise the industry-specific guidelines we developed regarding technical and biophysical cooling solutions considering effectiveness, cost, sustainability, and the practical implementation potential in outdoor and indoor settings, in addition to field-testing of selected solutions with time-motion analyses and biophysical evaluations. All recommendations were adjusted following feedback from workshops with employers, employees, safety officers, and adjacent stakeholders such as local or national health policy makers. The cross-scientific approach was also used for providing policy-relevant information based on socioeconomic analyses and identification of vulnerable regions considered to be more relevant for political actions than average continental recommendations and interventions.
Discussion: From the HEAT-SHIELD experiences developed within European settings, we discuss how this inter-sectoral approach may be adopted or translated into actionable knowledge across continents where workers and societies are affected by escalating environmental temperatures.

1. Occupational heat stress – a societal challenge calling for inter-sectoral solutions

It is quite clear that environmental heat stress has acute effects on humans, as it aggravates physiological strain, especially during

* Corresponding author.
E-mail address: nybo@nexs.ku.dk (L. Nybo).

https://doi.org/10.1016/j.jsams.2021.03.001

work- and exercise-conditions, where it accelerates the development of fatigue and impairs performance.[1] In addition, elevated environmental temperatures have important health implications for workers exposed for prolonged periods to occupational heat stress (OH-Stress): the combined effect of environmental heat stress and internal metabolic heat production, consequent of physical exertion.[2] However, in relation to public health, the focus has mainly been on the increased mortality rates during extreme heat events,[3] but workers are affected at much lower temperature levels due to the elevated metabolic heat production consequent of their work tasks, and having to often wear protective clothing which limits their abilities to dissipate heat to the environment. It has long been recognized that OH-Stress impairs worker health and performance and research into methods for improving heat tolerance date back to the 1960s.[4] Since then, numerous laboratory and exercise oriented studies have evaluated cooling methods, hydration, and heat acclimatisation protocols[5] to prevent or minimize heat-induced loss of performance[6,7]; whereas, to date, most occupational health and safety organizations have focused on outlining precaution procedures and creating work-rest cycles to prevent negative health effects.[8] The latter typically leading to a net loss of productivity, which, under some scenarios, is insufficient for preventing heat illness and injury.[9] Some solutions from sport/exercise orientated studies are potentially relevant and attractive for occupational settings, as they aim at preventing loss of performance and hence work efficiency.[7] However, both acclimatisation and cooling interventions may be time consuming and not always applicable or net-beneficial in occupational settings.[7]

Also, OH-Stress deviates from clinical and athletic forms of heat stress in that it threatens human wellbeing through multiple direct and indirect pathways.[2,10] The direct pathophysiological issues include cardiovascular disease and acute respiratory problems, and particularly, chronic kidney disease, especially for (but not limited to) agricultural workers.[10] Specifically, ~15% of those who typically work under heat stress experience acute kidney injury or kidney disease.[2] However, OH-Stress aggravates other less-recognised health concerns, such as mental health problems including depression, anxiety, and the risk of suicide; particularly for farmers on account of drought-related pressures.[10] Further, as many occupations susceptible to OH-Stress occur outdoors (particularly agriculture), workers are at greater risk for vector-borne illnesses.[10] Although current evidence is somewhat limited, vector-borne infectious diseases seem to be worsened by climate change due to some combination of altered soil microbial communities, moving microorganisms, potentially altered pathogen life cycles within vectors, incubation periods, and vector-human interactions.[11]

In addition to the direct health effects, it is equally important to consider the indirect effects that impaired productivity may have on individual and national socio-economic factors.[2,10] On an individual level, those working on piece-rate pay systems (i.e. where people are paid by the work produced, like pounds of rice harvested, rather than by the hour), will clearly have reduced personal incomes, thereby potentially influencing prevention of poverty-related malnutrition and other health issues.[12] Offsetting economic growth may also become a national issue in regions where labour supply in the most vulnerable sectors (outdoor industries relying on manual work) may be reduced by up to 30%, as productivity declines by more than 2% for every degree increase beyond 24 °C wet bulb globe temperature (WBGT)[2]; issues that will only worsen with climate change. Although often considered only a problem for "hot countries", decreases in worker productivity can begin to occur at relatively low temperature levels (~24 °C)[13] and it is often the non-acclimatised workers who are at the greatest risk for heat illness.[14] Further, with increasing geographical spread and increased frequency of heat waves,[15] as well as the growing population (particularly in traditionally hot countries), more than 2 billion workers across the world will be exposed to seasonal or year-round heat stress.[16,17]

Obviously, it is pertinent to tackle these temperature issues, both with local and global actions, as well as through collaboration among different disciplines, to improve heat resilience and mitigate the detrimental effects of rising environmental temperatures. For the workers regularly exposed to environmental heat, the problem is very concrete, and the need for solutions to protect their health is clear and personal. However, for the public and private managers, employers, and policy/decision makers, who often do not directly work in the heat, the issue is less clear and personal, and therefore these people may need convincing policy-relevant health data to emphasize the problem and cost-benefit analyses to prove that investing resources on cooling interventions will benefit the economic bottom line.[18]

To address these issues, the HEAT-SHIELD project (European Commission Horizon 2020 Grant 668786) was launched in 2016 with the dedicated aim to improve heat resilience in European workers by combining the knowledge of experts from a wide range of disciplines. The project aims to provide accurate guidance to the European community, ranging from the individual citizen to public and private policy makers, to better protect European health and productivity during present and future climatic heat scenarios. The present paper was invited to provide perspectives and lessons learned from the project and accordingly we will highlight the work focussed on improving weather warning systems by incorporating both meteorological and physiological factors relevant for determining the level of heat stress, translating laboratory and physiological research into ecologically valid settings, and disseminating this research to stakeholders within the industries of interest. Although the HEAT-SHIELD project focuses on the European workforce and economy, the lessons learned and the developed methodologies can be translated to hot weather scenarios around the world, to help improve the direct and indirect health of those working in the heat, globally.

2. How to accurately identify and predict OH-Stress

Accurate weather forecasting is important to be able to properly prepare and initiate adequate and timely hot weather responses. This is particularly true for areas at higher latitudes, where due to the seasonality of the climate, many workers are unacclimatised to hot weather and will be at greater risk of heat illness in the short-term.[14] At present, however, making accurate weather predictions is difficult, due to the insufficient availability of pertinent information. Specifically, in order to accurately assess whether OH-Stress will be an issue, and to what degree, six key factors are needed: the ambient temperature, humidity, wind speed, thermal (usually solar) radiation, the thermal insulation and the breathability of the clothing worn, and the amount of internal heat being produced by the workers, consequent of the metabolism needed to fuel their work.[19] In addition to the weather measurements, which will be outlined below, reference tables can be used to estimate the level of heat being produced for a given task.[20] Interestingly, however, many of the occupational metabolic equivalents had not been updated since the 1800s, but were recently updated as part of the HEAT-SHIELD project.[21] Clothing affects heat transfer with the environment by insulating the individual, usually limiting both heat loss through convection and radiation (dry heat transfer) as well as reducing evaporative heat losses (from sweat).[22–24]

Presently, the availability of weather information is variable, as European heat warning systems are diverse and mostly based solely on daily mean or maximum temperature.[25] Providing accurate forecasts of the other relevant environmental factors requires

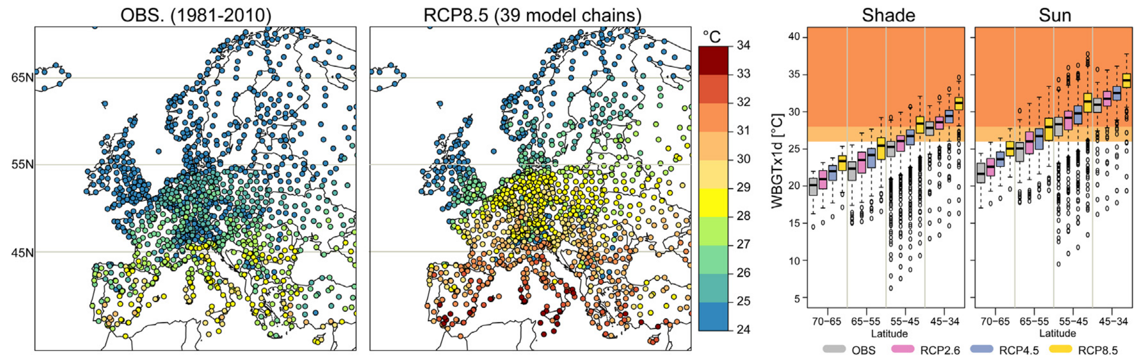

Fig. 1. Present and future projected climatological models of Europe (original work from previous HEAT-SHIELD publication).[29] (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

tailored postprocessing of general weather forecasts based on sufficiently long weather observation records.[26,27] This postprocessing often includes the correction of systematic climate model biases, which is essential to improve the representation of the inter-variable relationships among the environmental factors.[28] When the observation records used for the correction are point stations (as in HEAT-SHIELD), a downscaling from the coarse climate model resolution (here 12 and 50 km) to the local scale is implicitly performed.[29] As demonstrated in Fig. 1, sufficiently sensitive regional resolutions are also required, as environmental conditions in relatively close proximity can differ widely based upon local geographical factors such as bodies of water, presence/or absences of green spaces, etc.[28] Finally, indoor heat sources affect the accuracy of hot weather warning systems that only rely upon outdoor weather information.[30]

To account for these issues, HEAT-SHIELD developed a novel OH-Stress warning system (available at https://heatshield.zonalab.it/), which incorporates the requisite environmental data; the workers' estimated metabolism, clothing, and heat acclimatisation status; and allows for estimations of local (e.g. indoor) environmental factors.[27] This warning system operates using WBGT[31,32]; since it is commonly used, incorporates all relevant meteorological parameters, and can be interpreted via international labour standards.[33] The warning system provides both short-term and long-term probabilistic predictions of heat stress risk (up to 6 weeks ahead) obtained from the ensemble forecasts of the European Centre for Medium Range Weather Forecasts.[34] The HEAT-SHIELD approach for OH-Stress warning using WBGT has been adopted by its sister project ClimApp (http://www.lth.se/climapp/about-climapp/) and extends the use case from occupational health to caretakers of children and elderly. The ClimApp smartphone application provides highly localized short-term weather information based on the user location (source: https://openweathermap.org/) and uses that to estimate the local WBGT index (ISO7243). Moreover, HEAT-SHIELD infographics on heat mitigation strategies are presented to the user based on the work activities, clothing level, and predicted sweat losses.

Accurate heat-health warning systems can also help to make robust climate projections on European scales to better characterize and prepare for future problems that may occur. Using a similar methodology as the HEAT-SHIELD platform, we exploited a large ensemble of state-of-the-art regional climate projections provided by the international CORDEX initiative[35] and its European branch EURO-CORDEX,[36,37] considering the effect of three different greenhouse gas emission scenarios on worker health and productivity across Europe. We observed future heat exposure will indeed exceed critical levels for physically active humans far more often than in today's climate in large parts of Europe (Fig. 1), and labour productivity might be largely reduced in southern Europe.[29] Indeed, Southern Europe might suffer from high heat stress risk even if the strongest global mitigation actions are implemented; the annual number of days with WBGT above 28 °C might increase by 5–20 days by the end of the century compared to the present, leading to consequent reductions in labour productivity of up to 30%.[29]

3. Applying laboratory-derived findings to ecologically valid environments

In a recent umbrella review of the cooling interventions literature we conducted, it was found that of the 36 included systematic reviews investigating the effects of cooling interventions on health and performance, only nine were conducted within an occupational context, whereas the rest stemmed from athletic studies.[7] As such, much of the evidence practitioners rely on to inform guidelines must be translated from athletic literature. From a physiological point of view, OH-Stress affects the body similar to the thermal stress experienced during exercise/athletic performance in the heat; however, some important parameters are different. To effectively manage OH-Stress, the similarities and differences need to be well understood, as given in Fig. 2A. Although some sports require protective equipment (e.g., American football, ice hockey and motor sports) athletes usually wear minimal clothing that is typically made of light, breathable materials. In contrast, for many workers, clothing is usually made of heavier materials to provide some protection from physical abrasions, or else specific personal protective equipment must be worn, which is often highly insulative, minimizing heat loss to the environment. Although athletic events typically involve very high metabolic rates (and hence metabolic heat production), they usually last for relatively short durations, compared to the low to moderately intensive, long lasting and frequent heat exposures of OH-Stress. These differences also affect the type of cooling strategies that can be applied, because while it may be acceptable to spend relatively large amounts of time, energy and money to precool an athlete with whole-body water immersion, these types of cooling interventions are far too costly, and infeasible to apply to an everyday worker, day after day (as discussed in more detail below).

Cultural factors may also influence cooling strategies for OH-Stress in ways not of a concern for athletics. For example, foreign workers from hotter, less developed countries have been found to be more positive about working in the heat than their native cool-country counterparts.[38] Conversely, in some countries, the traditional roles of women performing most of the housework puts them at greater risk for OH-Stress, as they exert themselves both at home and at the job site.[30] Further, many women do not to take rest breaks because they do not wish to appear weak, fearing their hourly income will be lowered.[39] Moreover, women have been

A

	Work	Sport
Clothing	Heavy, protective, with high insulation	Light with low insulation
Duration	Continuous 8-12h a day, for multiple days	Typically less than 2 hours in duration, with days or weeks between major events
Individual	Older, unfit, unlikely to be acclimatized, with possible medical conditions	Young, healthy, fit, and likely at least partially heat acclimatized
Resources availability (e.g. clean water and electricity available)	Can be high (interior work) or very low (field work)	Usually very high, close to infrastructure
Scheduling	Relatively fixed	Relatively flexible
Funding per person	Generally low	Generally high
Work/metabolic rate	Low to medium	Medium to very High

B

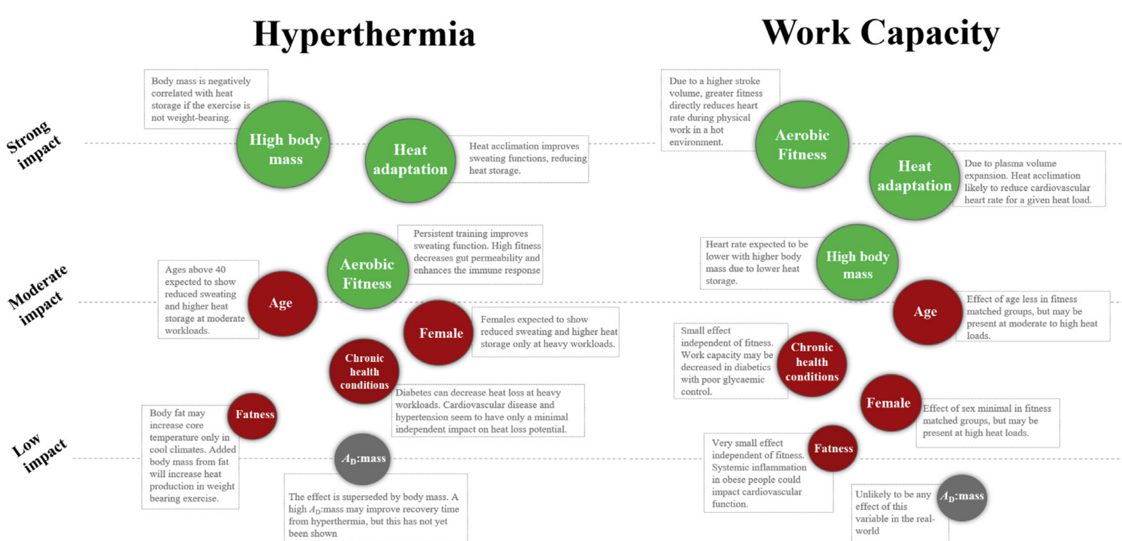

Fig. 2. Panel A: Differences between the factors causing and mitigating heat stress in occupational compared to athletic settings. Panel B: Personal characteristics that help to modify the level to which a person becomes hyperthermic or their work capacity is compromised due to occupational heat stress (original work from previous HEAT-SHIELD publication).[42] (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

demonstrated to be at greater risk for dehydration, due to voluntary fluid restriction to avoid having to use unhygienic (or non-existent) at-work toilet facilities.[40] Finally, lack of previous experience may be a concern, as men aged under 25 years working in agriculture are at greater risk for OH-Stress.[41]

Athletes and typical workers also differ greatly on personal characteristics that affect a person's heat tolerance. Indeed, to better characterise the influence of the factors on occupation-related hyperthermia and work capacity, we conducted an all-encompassing narrative review of the literature.[42] Fig. 2 illustrates the primary protective (green) and detrimental (red) characteristics for physical work capacity (2A) and hyperthermia (2B). High body mass, heat adaptation (acclimatisation), and high aerobic fitness are considered to have a *strong* impact because their positive influence is robust across the relevant range of work rates and climate types. While older age, being female, and some chronic health conditions have the potential to exert a negative influence, their *independent* effect is less robust because it depends on the work rate and environment. Identifying workers at particular risk for OH-Stress is critical for developing a comprehensive strategy to combat heat stress and has practical benefits by strategically deploying (or acquiring) personnel best suited to work in hot conditions. Additionally, extra supervision can be given to those identified as having characteristics that increase risk of hyperthermia (i.e., those above a certain age, or under a certain body mass). Finally, in addition to the more long-term personal characteristics outlined above, more acute factors are known to affect heat tolerance such as hypohydration,[43] certain medications,[44] and ongoing illness.[45]

It is also important to consider differences that may arise between laboratory testing and testing in ecologically valid situations. For example, for a long time whether hyperthermia affected cognitive performance was equivocal.[46] Recently, a series of HEAT-SHIELD studies developed a protocol that was sufficiently sensitive and reliable to detect difference in motor-cognitive performance in hyperthermic individuals.[47] Using this protocol, it was demonstrated that dehydration significantly worsens hyperthermia-related decrements in cognitive performance.[48] Fur-

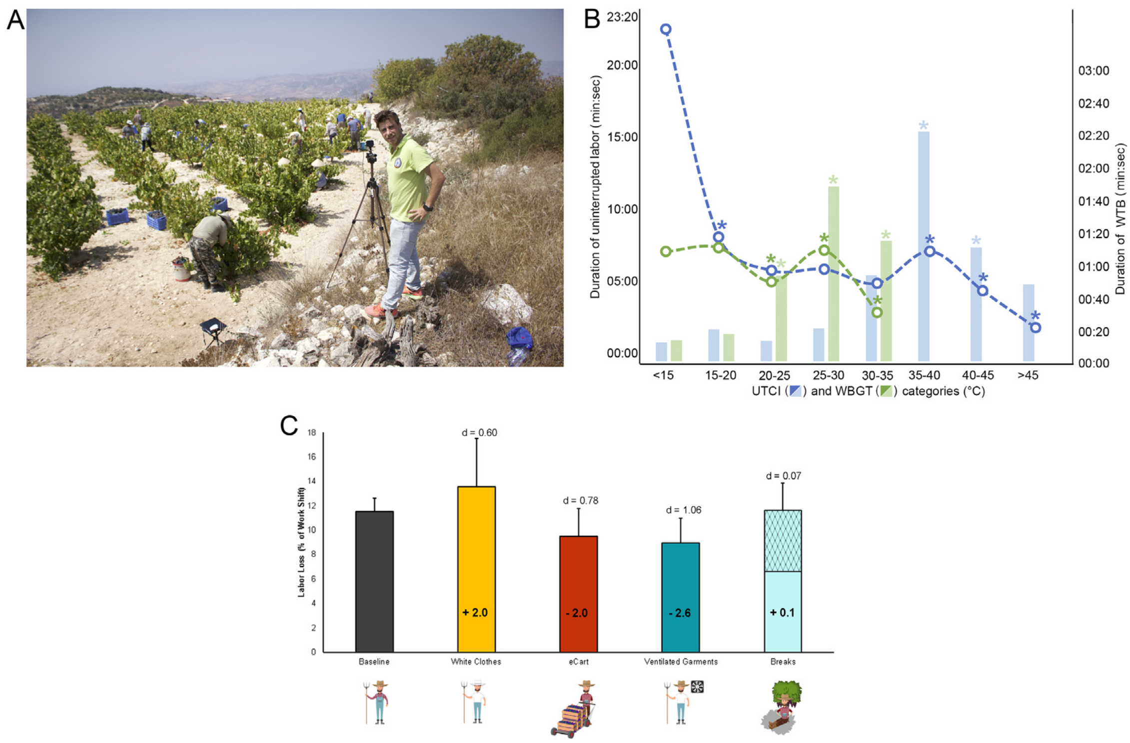

Fig. 3. Panel A: HEAT-SHIELD researcher setting up time-motion analysis system overlooking an agricultural work site in order to characterise productivity loss from unplanned breaks. Panel B: Relationship between productivity losses and Wet-Bulb Globe Temperature, as determined by time-motion analysis (original work from previous HEAT-SHIELD publication).[51] Panel C: Comparison of daily productivity losses when different cooling solutions are applied (modified figure from data under review).

ther, simulated solar radiation exposure, especially directed to the head, caused reductions in motor-cognitive performance at lower core temperatures compared to hyperthermia alone.[49] Moreover, in a systematic review of athletic performance in the heat, we identified that air-speed is very influential on physical performance, despite many laboratory based studies using air speeds well below realistic values, or else none at all.[50] These findings further support the importance of having access to all relevant weather and personal characteristics affecting worker heat balance, as highlighted in the earlier meteorological section.

Following from this, it is evident that laboratory-derived findings regarding how heat stress may affect worker productivity could vary from ecologically valid settings, and therefore, it is critical to have in-field measurements of productivity. For some industries, this can be relatively straightforward, as the number of products made (e.g., chairs, iPhones, etc.) or amount of produce harvested (e.g., bushels of grain, apples, etc.) can be counted. However, for many occupations, there may not be immediate and consistent deliverables to measure. Therefore, we employed a novel time-motion analysis approach for measuring work performance, as seen in Fig. 3A. In brief, this method works by video-recording a work area and then retrospectively measuring the amount of time that the workers spend taking unplanned breaks.[51] For example, in one field study (Fig. 3B), there was a 2.1% increase in productivity loss for every 1 °C in the mean skin temperature of workers[51]. Subsequently, a monetary metric (e.g., dollars, Euros, etc.) can be given to the productivity losses by multiplying them by the workers' wages. Alternatively, this method can also determine how much less time is spent on unplanned breaks when a cooling intervention is applied. An example of such an approach can be found in Fig. 3C. Accordingly, a cooling intervention can be determined beneficial if the cost (both for initial set-up and operation) is less than the amount of money lost to reduced productivity.

4. Effectively disseminating accurate recommendations to stakeholders

The increasing scientific knowledge has very limited impact if it is not disseminated and used by those at greatest risk. When surveyed, 20% of Slovenian manufacturing workers and 60% of agricultural workers reported receiving heat health information from their advisers, whereas 75% of (primarily self-employed) tourist guides were aware of heat health information.[52] A similar number of Greek and Slovenian workers lacked heat health information (50 and 60% respectively), but of those who did possess know-how, the employer was the primary source.[53] Further, from a survey provided to employees, managers, and health and safety officials in Denmark, Italy, and Cyprus, 14% of respondents reported being unaware of any protective measures and 48% thought that the methods their companies employed to combat heat stress were ineffective.[18]

In contrast to cooling for sporting events with a relative short duration, implementation in occupational setting require additional resources or frequent repetition (Fig. 2A) for effective mitigation of OH-Stress over an entire work-shift. Further, feasibility of the job site, cost-benefit ratios and environmental sustainability must be considered. For example, air-conditioning is highly effective, but results in substantial greenhouse gas emissions,[54] and is further unfeasible for those working in large bays or outdoors areas, making it a poor choice as a cooling solution. To address these issues, we performed an umbrella review of all known cooling interventions and supplemented this review with a secondary analysis, in order to determine the level of evidence, effectiveness, cost, feasibility, and sustainability.[7] The best identified interventions were to allow workers time to (physiologically) acclimatise (particularly for the first two weeks of seasonal hot weather), ensure a readily-accessible supply of drinking water, allow for more planned breaks in shaded areas that were well ven-

Fig. 4. HEAT-SHIELD recommendations to combat occupational heat stress.

tilated, and optimize personal protective equipment and/or work clothing.[7] Further, original HEAT-SHIELD investigations have provided novel evidence for reorganizing the work schedule so that the least stressful tasks are performed in the middle of the day, the work day starts earlier, or a "siesta" is taken in the middle of the day to avoid peak hours.[55,56]

From the findings of the review, our original studies, and the combined expert opinion of the HEAT-SHIELD consortium, we created a list of what we consider to be the necessary basis of any heat action plan to combat OH-Stress (summarized in Fig. 4). However, communication with stakeholders is needed to identify weaknesses in company policies and to ensure that recommendations will actually be used.[57] To this end, we verified our recommendations at 7 different workshops in Italy, Denmark, Cyprus, Germany and Greece by presenting our recommendations to 115 stakeholders including employers/managers, employees, safety officers and policy makers and obtained feedback regarding the strengths and weaknesses of these recommendations.[18] Stakeholders were generally positive about our recommendations, with 88% of respondents agreeing that the presented guidelines would be effective and 57% of respondents stating that they perceived no barriers to implementing our recommendations. Of the recommendations presented, the three most favoured by stakeholders were providing drinking water, improving the thermal qualities of clothing, and optimizing the work schedule. Of the perceived barriers to implementation that were listed, cost was the most common (30%), followed by feasibility with certain job tasks and employer perceptions (15% each), and then cultural habits and fixed work hours (10% each).[18]

It is necessary to increase the knowledge of employers and workers through clear and simple steps to help them understand the escalation of the problem, so that they can start implementing mitigation and adaptation measures.[53] Health education in relation to heat stress would improve risk awareness and should therefore become a part of the education system, with the younger generations being competent as soon as they enter the labour market.[30] Targeted information campaigns are needed for adults, as many misunderstandings still exist[57] and trade unions can further play a very strong role in effective dissemination. The media should be encouraged to become more active and make use of examples of good practise, such as increasing productivity when companies adopt effective methods to alleviate heat stress.[57]

Another method for disseminating heat health information is through direct delivery of personalised information via internet-based tools such as the HEAT-SHIELD web platform, described above, or else through smartphone applications such as the HEAT-SHIELD sister project ClimApp (freely available at google play and Apple App store – Android: https://play.google.com/store/apps/details?id=com.climapp.app, iOS: https://apps.apple.com/us/app/climapp/id1458460604). In this way, not only do people have access to weather forecasting, but notifications, with best-practise cooling recommendations that can be delivered automatically to their phones or email when hot weather is approaching. These platforms further facilitate accurate information dissemination by incorporating International Organization for Standardization guidelines (such as ISO7243 and ISO7933) and rapidly translating this advice into different languages. Further, information can be customized to account for several individual and behavioural aspects, such as the worker's activity level, the type of clothing worn by the workers and in particular if they have to wear personal protective equipment that may trap heat and perspiration on the body's surface. The personal physical characteristics (height and weight) and the level of acclimatisation to heat of the worker can also be accounted for as well as the indoor environment.

5. Global translation and future research

Despite the fact that the majority of OH-Stress research has been conducted at the Northern hemisphere,[2] clearly the problem does not primarily affect these nations, as future climate models project exposure to excessive heat stress to be widespread in tropical or subtropical, low-income and middle-income countries.[58] Therefore, we believe it is the moral duty of researchers from the globally Northern nations to translate their findings to other global areas lacking the financial resources to fund equivalent levels of research. Luckily, OH-Stress research is highly transferrable, as there is no such thing as a universal OH-Stress prevention strategy; even within Europe, heat action plans need to be activated at different temperature thresholds due to differences in local climate and the inherent level of heat acclimation of the different populations.[59] Therefore, in designing OH-Stress prevention strategies, often referred to as heat action plans, it is more important to ask the right questions rather than give specific information. Specifically, these should include: What is the weather going to be like in the coming days? What are the local factors that may contribute to heat stress? Can the working attire be optimized? Can the work schedule be optimized? Do the workers have access to water, and if not, how can water be supplied? When should additional breaks be provided? And which workers are most at risk?

In addition to generally increasing the amount of OH-Stress research in developing nations, several avenues of OH-Stress research have immediate need of attention. For example, occupations exposed to long stretches of moderate heat stress, such as agriculture and construction,[21] require much more attention in general,[7] as do older workers and/or those affected by cardiovascular or respiratory chronic diseases. In terms of protective and risk factors for heat illness (as well as cooling interventions), whether these factors have counteractive or additive effects is largely unknown.[2,10] For example, whether having a high body mass can counteract the negative impact of ageing or else whether both being old and having low aerobic fitness has an additive or multiplicative negative impact on either work capacity or hyperthermia risk. Another avenue for future work is to include longer term exposures, which better reflects the actual heat stress experienced during a full working day, as most studies to date are conducted with exposures of ∼60 min in duration, thereby not reflecting a typical 8-h working day.[60]

6. Conclusion

Global climate change, and particularly OH-Stress, is a societal challenge that threatens public health, both through direct negative effects for the individual worker exposed, as well as through the indirect effect of reduced income, consequent of reduced worker productivity. The HEAT-SHIELD project has worked for the past five years to combat these issues through a pan-European, inter-sectoral approach involving climatologists, epidemiologists, occupational hygienists, physiologists, engineers, employers, employees, health officers and policy makers. The first approach to combatting OH-Stress, is to accurately assess and be warned of the threat by the use of advanced weather warning systems that account for environmental, local, and personal factors. It must subsequently be understood how this threat affects workers, and to identify which workers are most at risk. Although some workers may be at greater risk than others, all workers will be at some level of risk and need to be protected. To this end, cooling interventions must be used that are effective, feasible, sustainable, and cost-effective. Further, the recommendation of cooling interventions and heat action plans needs to be done in collaboration with stakeholders and policy makers, to ensure personal adherence both through personal and legislative incentives. Information on heat-health practices (and the laws that support them) are only effective if people are aware of them, and therefore, effective public dissemination strategies are needed. Finally, environmental conditions, personal practices and acclimatisation to heat, working conditions, and resource availability will differ widely, both within and between countries. As such, there is no such thing as a global heat action plan, but rather, global heat action plan questions that must be asked to come up with individualized ideal solutions.

Funding

The study has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement No 668786.

References

1. Nybo L, Rasmussen P, Sawka MN. Performance in the heat—physiological factors of importance for hyperthermia-induced fatigue. *Compr Physiol* 2014:657–689. http://dx.doi.org/10.1002/cphy.c130012.
2. Flouris AD, Dinas PC, Ioannou LG et al. Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. *Lancet Planet Health* 2018; 2(12):e521–e531. http://dx.doi.org/10.1016/S2542-5196(18)30237-7.

3. Semenza JC, Rubin CH, Falter KH et al. Heat-related deaths during the July 1995 heat wave in Chicago. *N Engl J Med* 1996; 335(2):84–90. http://dx.doi.org/10.1056/NEJM199607113350203.
4. Wyndham CH, Strydom NB, Morrison JF et al. Criteria for physiological limits for work in heat. *J Appl Physiol* 1965; 20(1):37–45. http://dx.doi.org/10.1152/jappl.1965.20.1.37.
5. Strydom NB, Wyndham CH, Williams CG et al. Acclimatization to humid heat and the role of physical conditioning. *J Appl Physiol* 1966; 21(2):636–642.
6. Bongers CCWG, Hopman MTE, Eijsvogels TMH. Cooling interventions for athletes: An overview of effectiveness, physiological mechanisms, and practical considerations. *Temperature* 2017; 4(1):60–78. http://dx.doi.org/10.1080/23328940.2016.1277003.
7. Morris NB, Jay O, Flouris AD et al. Sustainable solutions to mitigate occupational heat strain – an umbrella review of physiological effects and global health perspectives. *Environ Health* 2020; 19(1):95. http://dx.doi.org/10.1186/s12940-020-00641-7.
8. OSHA. OSHA's Campaign to Prevent Heat Illness in Outdoor Workers | Using the Heat Index - About Work/Rest Schedules | Occupational Safety and Health Administration. Available at: https://www.osha.gov/SLTC/heatillness/heat_index/work_rest_schedules.html. Accessed 1 September 2020.
9. Armed FHSB. Update: heat illness, active component, US Armed Forces, 2016. *MSMR* 2017; 24(3):9.
10. Levi M, Kjellstrom T, Baldasseroni A. Impact of climate change on occupational health and productivity: a systematic literature review focusing on workplace heat. *Med Lav* 2018; 109(3):163–179. http://dx.doi.org/10.23749/mdl.v109i3.6851.
11. Brisbois BW, Ali SH. Climate change, vector-borne disease and interdisciplinary research: social science perspectives on an environment and health controversy. *EcoHealth* 2010; 7(4):425–438.
12. Nilsson M, Kjellstrom T. Climate change impacts on working people: how to develop prevention policies. *Glob Health Action* 2010; 3(s3):5774. http://dx.doi.org/10.3402/gha.v3i0.5774.
13. Parsons K. Heat stress standard ISO 7243 and its global application. *Ind Health* 2006; 44(3):368–379. http://dx.doi.org/10.2486/indhealth.44.368.
14. Tustin AW, Lamson GE, Jacklitsch BL et al. Evaluation of occupational exposure limits for heat stress in outdoor workers — United States, 2011–2016. *Morb Mortal Wkly Rep* 2018; 67(26):733–737. http://dx.doi.org/10.15585/mmwr.mm6726a1.
15. Morabito M, Crisci A, Messeri A et al. Increasing heatwave hazards in the southeastern European Union capitals. *Atmosphere* 2017; 8(7):115.
16. Masson-Delmotte TWV, Zhai P, Pörtner HO et al. IPCC, 2018: summary for policymakers, In: *Global Warming of 1.5 C. An IPCC Special Report on the Impacts of Global Warming of 1.5 C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global.* World Meteorol Organ Geneva Tech Rep, 2018.
17. International Labour Office. *Working on a Warmer Planet: The Impact of Heat Stress on Labour Productivity and Decent Work*, Geneva, ILO, 2019.
18. Morris NB, Levi M, Morabito M et al. Health vs. wealth: employer, employee and policy-maker perspectives on occupational heat stress across multiple European industries. *Temperature* 2020:1–18. http://dx.doi.org/10.1080/23328940.2020.1852049.
19. Gao C, Kuklane K, Östergren P-O et al. Occupational heat stress assessment and protective strategies in the context of climate change. *Int J Biometeorol* 2018; 62(3):359–371. http://dx.doi.org/10.1007/s00484-017-1352-y.
20. Ainsworth BE, Haskell WL, Whitt MC et al. Compendium of physical activities: an update of activity codes and MET intensities. *Med Sci Sports Exerc* 2000; 32(9; SUPP/1):S498–S504.
21. Poulianiti KP, Havenith G, Flouris AD. Metabolic energy cost of workers in agriculture, construction, manufacturing, tourism, and transportation industries. *Ind Health* 2019; 57(3):283–305.
22. Dorman LE, Havenith G. The effects of protective clothing on energy consumption during different activities. *Eur J Appl Physiol* 2009; 105(3):463–470. http://dx.doi.org/10.1007/s00421-008-0924-2.
23. McLellan TM, Havenith G. Protective clothing ensembles and physical employment standards. *Appl Physiol Nutr Metab Physiol Appl Nutr Metab* 2016; 41(6):121–130. http://dx.doi.org/10.1139/apnm-2015-0474.
24. Neves SF, Campos J, Mayor TS. Effects of clothing and fibres properties on the heat and mass transport, for different body heat/sweat releases. *Appl Therm Eng* 2017; 117:109–121.
25. Casanueva A, Burgstall A, Kotlarski S et al. Overview of existing heat-health warning systems in Europe. *Int J Environ Res Public Health* 2019; 16(15):2657. http://dx.doi.org/10.3390/ijerph16152657.
26. Monhart S, Spirig C, Bhend J et al. Skill of subseasonal forecasts in europe: effect of bias correction and downscaling using surface observations. *J Geophys Res Atmos* 2018; 123(15):7999–8016. http://dx.doi.org/10.1029/2017JD027923.
27. Morabito M, Messeri A, Noti P et al. An occupational heat–health warning system for Europe: the HEAT-SHIELD platform. *Int J Environ Res Public Health* 2019; 16(16):2890.
28. Casanueva A, Kotlarski S, Herrera S et al. Climate projections of a multivariate heat stress index: the role of downscaling and bias correction. *Geosci Model Dev* 2019; 12:3419–3438.
29. Casanueva A, Kotlarski S, Fischer AM et al. Escalating environmental summer heat exposure—a future threat for the European workforce. *Reg Environ Change* 2020; 20(2):40. http://dx.doi.org/10.1007/s10113-020-01625-6.
30. Ciuha U, Pogačar T, Bogataj LK et al. Interaction between indoor occupational heat stress and environmental temperature elevations during heat waves. *Weather Clim Soc* 2019; 11(4):755–762. http://dx.doi.org/10.1175/WCAS-D-19-0024.1.
31. Bernard TE. Prediction of workplace wet bulb global temperature. *Appl Occup Environ Hyg* 1999; 14(2):126–134. http://dx.doi.org/10.1080/104732299303296.
32. Liljegren JC, Carhart RA, Lawday P et al. Modeling the wet bulb globe temperature using standard meteorological measurements. *J Occup Environ Hyg* 2008; 5(10):645–655. http://dx.doi.org/10.1080/15459620802310770.
33. ISO B. *7243: Ergonomics of the Thermal Environment—Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index*, Int Org Stand Geneva Switz, 2017.
34. Vitart F, Balsamo G, Buizza R et al. *Sub-Seasonal Predictions*, European Centre for Medium-Range Weather Forecasts, 2014.
35. Giorgi F, Jones C, Asrar GR. Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorol Organ WMO Bull* 2009; 58(3):175.
36. Kotlarski S, Keuler K, Christensen OB et al. Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geosci Model Dev* 2014; 7(4):1297–1333. http://dx.doi.org/10.5194/gmd-7-1297-2014.
37. Jacob D, Teichmann C, Sobolowski S et al. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Reg Environ Change* 2020; 20(2):51. http://dx.doi.org/10.1007/s10113-020-01606-9.
38. Messeri A, Morabito M, Bonafede M et al. Heat stress perception among native and migrant workers in Italian industries—case studies from the construction and agricultural sectors. *Int J Environ Res Public Health* 2019; 16(7):1090. http://dx.doi.org/10.3390/ijerph16071090.
39. United Nations Development Programme, Published online April 2016, retrieved on 7 October 2020 from *Climate Change and Labor: Impacts of Heat in the Workplace*, U N Dev Program, 2016 https://www.undp.org/content/undp/en/home/librarypage/climate-and-disaster-resilience-/tackling-challenges-of-climate-change-and-workplace-heat-for-dev.html.
40. Venugopal V, Rekha S, Manikandan K et al. Heat stress and inadequate sanitary facilities at workplaces–an occupational health concern for women? *Glob Health Action* 2016; 9(1):31945.
41. Binazzi A, Levi M, Bonafede M et al. Evaluation of the impact of heat stress on the occurrence of occupational injuries: meta-analysis of observational studies. *Am J Ind Med* 2019; 62(3):233–243. http://dx.doi.org/10.1002/ajim.22946.
42. Foster J, Hodder SG, Lloyd AB et al. Individual responses to heat stress: implications for hyperthermia and physical work capacity. *Front Physiol* 2020; 11:1147. http://dx.doi.org/10.3389/fphys.2020.541483.
43. Gonzalez-Alonso J, Mora-Rodriguez R, Below PR et al. Dehydration reduces cardiac output and increases systemic and cutaneous vascular resistance during exercise. *J Appl Physiol* 1995; 79(5):1487–1496. http://dx.doi.org/10.1152/jappl.1995.79.5.1487.
44. Stöllberger C, Lutz W, Finsterer J. Heat-related side-effects of neurological and non-neurological medication may increase heatwave fatalities. *Eur J Neurol* 2009; 16(7):879–882. http://dx.doi.org/10.1111/j.1468-1331.2009.02581.x.
45. Dineen SM, Ward JA, Leon LR. Prior viral illness increases heat stroke severity in mice. *Exp Physiol* 2020; 106(1):244–257. http://dx.doi.org/10.1113/EP088480.
46. Taylor L, Watkins SL, Marshall H et al. The impact of different environmental conditions on cognitive function: a focused review. *Front Physiol* 2016; 6:372.
47. Piil JF, Lundbye-Jensen J, Trangmar SJ et al. Performance in complex motor tasks deteriorates in hyperthermic humans. *Temperature* 2017; 4(4):420–428. http://dx.doi.org/10.1080/23328940.2017.1368877.
48. Piil JF, Lundbye-Jensen J, Christiansen L et al. High prevalence of hypohydration in occupations with heat stress—perspectives for performance in combined cognitive and motor tasks. *PLoS One* 2018; 13(10):e0205321. http://dx.doi.org/10.1371/journal.pone.0205321.
49. Piil JF, Christiansen L, Morris NB et al. Direct exposure of the head to solar heat radiation impairs motor-cognitive performance. *Sci Rep* 2020; 10(1):7812. http://dx.doi.org/10.1038/s41598-020-64768-w.
50. Junge N, Jørgensen R, Flouris AD et al. Prolonged self-paced exercise in the heat—environmental factors affecting performance. *Temperature* 2016; 3(4):539–548. http://dx.doi.org/10.1080/23328940.2016.1216257.
51. Ioannou LG, Tsoutsoubi L, Samoutis G et al. Time-motion analysis as a novel approach for evaluating the impact of environmental heat exposure on labor loss in agriculture workers. *Temperature* 2017; 4(3):330–340. http://dx.doi.org/10.1080/23328940.2017.1338210.
52. Pogačar T, Žnidaršič Z, Črepinšek Z et al. Aggravated occupational heat stress recognition and mitigation in Slovenia, In: *Clim. Change Adapt. East. Eur.* Springer, 2019. p. 267–277.
53. Pogačar T, Žnidaršič Z, Kajfež Bogataj L et al. Heat waves occurrence and outdoor workers' self-assessment of heat stress in Slovenia and Greece. *Int J Environ Res Public Health* 2019; 16(4):597. http://dx.doi.org/10.3390/ijerph16040597.
54. The Economist Intelligence Unit. The cooling imperative: forecasting the size and source of future cooling demand. *The Economist* 2019.
55. Masanotti G, Bartalini M, Fattorini A et al. Work in harsh hot environment: risk evaluation on thermal stress in a farm during green pruning activity. *BJSTR* 2019; 16:12103–12111.
56. Morabito M, Messeri A, Crisci A et al. Heat-related productivity loss: benefits derived by working in the shade or work-time shifting. *Int J Product Perform Manag* 2020; 70(3):507–525. http://dx.doi.org/10.1108/IJPPM-10-2019-0500.
57. Pogačar T, Žnidaršič Z, Kajfež Bogataj L et al. Steps towards comprehensive heat communication in the frame of a heat health warning system in Slove-

nia. *Int J Environ Res Public Health* 2020; 17(16):5829. http://dx.doi.org/10.3390/ijerph17165829.
58. Andrews O, Le Quéré C, Kjellstrom T et al. Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study. *Lancet Planet Health* 2018; 2(12):e540–e547. http://dx.doi.org/10.1016/S2542-5196(18)30240-7.
59. Lowe D, Ebi KL, Forsberg B. Heatwave early warning systems and adaptation advice to reduce human health consequences of heatwaves. *Int J Environ Res Public Health* 2011; 8(12):4623–4648. http://dx.doi.org/10.3390/ijerph8124623.
60. Smallcombe J, Foster J, Hodder S et al. Quantifying physical work capacity in the heat: one hour vs full day exposure. *Int. Conf. Environ. Ergon* 2019. p. 128.