

TECHNICAL REPORT

D3.5: Report on solutions to mitigate heat stress of construction sector workers



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TABLE OF CONTENTS

SUMMARY (with overview of identified/screened solutions)	3
1. INTRODUCTION	4
2. INDUSTRY SPECIFIC ISSUES FOR CONSTRUCTION WORKERS	5
Description of Study 1	5
3. IDENTIFIED/SCREENED SOLUTIONS FOR CONSTRUCTION WORKERS	12
Description of Study 2	12
4. REFERENCES	20
5. APPENDIX	22

SUMMARY (with overview of identified/screened solutions)

European workers in the construction sector are seasonally exposed to heat stress levels that undermine individual health (mild hyperthermia and dehydration) and affect productivity (4.7-fold increase in the lost labour time).

This report is dedicated to provide guidelines with screened (effective, feasible and sustainable) solutions and strategies to mitigate or minimize negative effects of excessive heat exposure. Occupational heat stress is very relevant in the construction industry because many tasks rely on manual work as the prevailing and, sometimes, only feasible method for performing complex tasks. Importantly, occupational heat stress is difficult to mitigate in construction, as artificial cooling or shadowing towards the sun would compromise health and safety regulations.

It is advisable that construction firms, from large multinational corporations to small local contractors, consider/**develop an appropriate heat adaptation plan** to protect both employer (by maintaining productivity) and employee (by minimizing health risks) benefits. This plan may be qualified by a designated person and benefit from consulting advanced warning weather systems to warn in advance when a period of hot weather is expected. Single or combined heat resilience methods appropriate/applicable for the specific work setting should be identified and translated into feasible actions and habits that workers can adopt during hot periods – with timely information at the beginning of the summer and regular follow-up reminders.

Staying hydrated is critical for maintained productivity and health in the construction industry. Unfortunately, most workers forget or fail to rehydrate from day-to-day. Thus, nine out of 10 construction workers arrive at work in a dehydrated state. This means they start the day at an elevated risk for hyperthermia and acute kidney injury, as well as low probability for performing at their best during their work shift. Construction workers should drink sufficient volumes before work (with 500-750 ml or volumes equal to three cups of water as an operational guideline). In addition, they should consume similar volumes of water every hour during work. When working under heat stress, this strategy demonstrates the best results for maintaining hydration (reducing the risk for kidney disease or acute kidney injury) and for reducing labour loss due to irregular work breaks. For this reason, it is important that strategies are put in place for workers to have access to cold/cool water throughout the day, even when working on different floors or remote areas of a construction site. These guidelines are on the condition that workers re-establish water and electrolyte (salt) balance from day to day. This may imply that during periods where workers are sweating profusely, healthy workers should add a larger amount of salt (electrolytes) to their diet/main meals. However, workers with heart, blood pressure, or other medical conditions should adopt this advice only when confirmed by their physician. If possible – and, particularly, during breaks – cooling the water by refrigeration, or better yet, by the addition of shaved/crushed ice will help lower the discomfort and heat stress experienced by the workers and improve work performance. Additionally, spreading water on the skin either during breaks or during work (if there is an abundance of water) can help increase evaporative cooling and help limit the rate of dehydration.

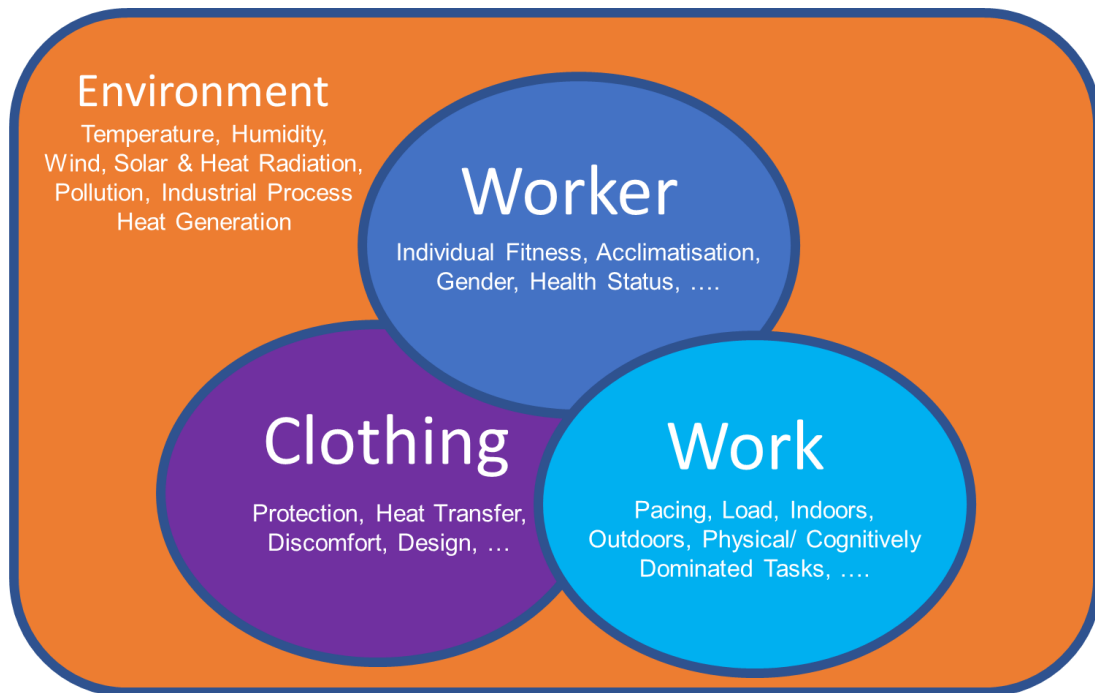
Clothing is important for construction workers because it can lower the worker's thermal stress. Construction workers require special protective clothing (gloves, helmet, boots, etc.), while clothing is also beneficial for protecting the construction worker from excessive sun exposure. However, clothing can also restrict heat loss as it provides a boundary layer that limits evaporation and convective and radiative heat loss. To facilitate heat loss, clothing worn during the work shift should be selected based upon promoting air flow across the skin and improving sweat evaporation (reducing clothing evaporative resistance). This can be accomplished by reducing the total amount of skin covered by clothing by wearing a t-shirt vs long sleeve (if indoors), wearing looser fitting clothing which allows for greater air flow underneath the clothing, and wearing clothing with a wider knitting pattern which allows for more air flow to pass through the clothing. Additionally, lighter colours should be selected on sunny days in outdoor environments to increase the reflection of solar radiation. In situations where long, rigid clothing must be worn (e.g. coveralls), ventilation patches can be incorporated into more protected areas such as under the arms and between the legs to help promote air flow through the garment.

It is crucial to **plan the workflow to allow workers time to adapt**. Workers will acclimatize to heat during the first days of hot weather, however depending on the initial fitness and previous exposure it will take at least one week before workers get used (physiologically adapted) to the increased heat. This acclimatization process will be hampered/take longer if the workers spend prolonged periods of time in artificially cooled environments when not working.

1. INTRODUCTION

1.1 It is quite clear that occupational heat stress can negatively affect workers health and their performance capacity, which subsequently may lower productivity and income for the individual and/or company costs directly related to lost working efficiency or indirectly via illness/sickness. The present report is part of a series of five papers (industry specific reports on each of the key EU sectors [manufacturing, construction, transportation, tourism and agriculture]). Overall the papers focused on defining, screening and optimizing appropriate technical and biophysical solutions to counter the negative impact of high thermal stress imposed by the combination of adverse environmental conditions, industrial heat production, the workers own/internal metabolic heat production, conditions and confounding factors such as protective clothing or other work-related factors that may conflict with heat dissipation.

Figure 1. Overview on occupational aspect of human heat balance.



1.2 Human function depends on a balance between internal (metabolic) heat production and heat-exchange with the environment. When a worker is physically active, the metabolic energy release will increase in proportion to the work intensity and hence increase heat production in the body. If not released to the environment, this heat will warm up the worker, increase heat strain, impair both physical and cognitive function and potentially provoke fatal overheating. Therefore, to keep workers safe and avoid decrements in functionality, the produced heat must be balanced by heat lost from the body (skin) to the environment, which can be by dry heat loss (primarily air convection and radiation) and/or by sweat evaporation. For occupational settings, it is characteristic that in addition to climatic conditions (with air temperature, solar radiation, humidity and wind speed as the factors of importance) the local environment may also be highly influenced by the industrial settings (see Figure 1). The warmer and more humid the environment (micro-climate around the worker), the more difficult it is to lose the heat. In addition, solar radiation or radiation from industrial processes, will further add to the heat load while wind/ventilation can benefit dry heat loss as long as the air temperature is below 35°C. In addition, wind can facilitate evaporation and hence benefit the overall heat balance even at higher environmental temperatures.

1.3 When considering solutions to lower heat stress any practice that may either lower workers internal heat production (e.g. optimizing the work procedures) or facilitate heat dissipation (including lessening of the constraining effects that e.g. clothing may impose) or directly cool the body (e.g. ingestion of cold drinks or ice) can be beneficial. This can range from behavioural and biological interventions/adaptations to technical solutions that may assist heat dissipation (e.g. increasing air flow, cooling vests or air conditioning) or lower the environmental heat load (e.g. reducing solar radiation). In accordance with this overall context, the present report considers the specific solutions

screened and identified as both effective and feasible to implement for workers in the construction sector.

- 1.4 This report on solutions for the construction sector focus on the industry specific issues, needs and exposure characteristics of workers from the construction sector in order to identify ways to mitigate the corresponding heat stress. The focus is in proposing adaptation measures including advanced hydration, shading alternatives, advanced work load planning and smart clothing solutions (i.e. ventilated garments), given the particular exposure of construction workers to both indoor and outdoor conditions. While assessing the capacity and potential of these adaptation measures to mitigate workers' heat stress, the report also puts special attention on determining the specific requirements of the different solutions, and their compatibility with the intended application environment. The feasibility aspect is particularly important.

2. INDUSTRY SPECIFIC ISSUES FOR CONSTRUCTION WORKERS

- 2.1 Currently, nearly one-third of the world's population is regularly exposed to climate conditions that exceed human thermoregulatory capacity leading to major increases in morbidity and mortality.¹⁻³ Even if aggressive mitigation measures are adopted, one-half of the world's population will be exposed to such conditions by 2100¹ and a number of studies report that the resulting occupational heat strain (OHS) will directly threaten workers' health, with corollary negative impacts on productivity, poverty, and socio-economic inequality.⁴⁻⁷
- 2.2 The OHS refers to physiological consequences of environmental heat stress and it massively influences the ability to live healthy and productive lives, as nearly one million "work life years" will be lost by 2030 due to occupational heat stroke fatalities, and 70 million "work life years" will be lost due to reduced labour productivity.^{8,9} Warning systems for extreme weather events have been recently piloted in some countries, but they are designed for the general population whose needs and exposure to heat are vastly different from those of workers. For instance, they typically advise individuals to stay indoors throughout the day or to remain in "cooling shelters" at public buildings.¹⁰ Such strategies are not compatible with the need to stay productive regardless of the prevailing environmental conditions.
- 2.3 OHS is a parameter that influences a number of industries worldwide. In the construction sector, OHS is very relevant because many tasks rely on manual work as the prevailing and, sometimes, only feasible method for performing complex tasks. OHS is difficult to mitigate in construction, as artificial cooling or shadowing towards the sun would compromise health and safety regulations. This may be the reason for the lack of previous studies on the impact of OHS in health and productivity outcomes in European construction workers.
- 2.4 To address the lack of knowledge regarding the effects of workplace heat on European construction workers, we conducted an observational evaluation to understand the nature of the problem. Our approach was to evaluate ~109 work hours via time-motion analysis on a second-by-second basis collected from 16 workers while performing different construction jobs on two different days. This study was labelled "Study 1" and is explained in detail in the following sub-sections.

Description of Study 1

- 2.5 The study involved monitoring construction workers on two separate days (5-6/7/2017) in Zaragoza, Spain. The experimental protocol was approved by the University of Thessaly, School of Exercise Science Ethics Review Board (Protocol No. 1217) in accordance with the Declaration of Helsinki. Written informed consent was obtained from all volunteers prior to their participation in the study (in English or Spanish) before entering the study. They were free to deny participation or withdraw their consent at any point.
- 2.6 One day prior to the start of data collection, volunteers underwent a familiarization session which included information regarding all data collection procedures. Anthropometric characteristics were also recorded at that time. In total, 16 male workers participated in the study:
- 10 frame workers,
 - 4 brick layers,
 - 2 drivers (1 forklift driver; 1 crane driver).

- 2.7 Throughout the two study days, all volunteers were assessed from the beginning until the end of the work shift. The measurements performed were non-invasive, time-efficient, practical, and did not disturb the workers during their job.
- 2.8 During each recording day, each worker was monitored from the beginning until the end of the work shift by a researcher who observed the worker's activities. Also, we recorded skin temperature and environmental data throughout the work shift. No restrictions were placed on water/food consumption or any other kind of work- or non-work-related behavior. To ensure that we did not influence the workers' normal work routine, the temperature sensors used were miniature and wireless. Also, to minimize participant bias (i.e., work activities being affected because the workers were being observed), the true reason for the observations was hidden from the volunteers. Instead, they were informed that the investigators were interested to see the different types of work that they engage in. Of course, once the data collection was completed, all volunteers were informed about the true purpose of the observations and gave their permission to analyze and publish these data.
- 2.9 We recorded the workers' age and work experience. Anthropometric measurements included height and mass. Body surface area was calculated using the Du Bois formula.¹¹ We obtained urine samples in the beginning and the end of the work shift to evaluate urine specific gravity, a well-known indicator of hydration status.¹² We also administered different questionnaires to assess the workers' subjective perception of the heat-related issues and symptoms, as well as their level of job satisfaction.
- 2.10 Temperature at the skin surface was recorded every second at four sites using iBUTTON sensors (type DS1921H, Maxim/Dallas Semiconductor Corp., USA) to calculate the mean skin temperature $[T_{sk}; 0.47 \cdot \text{biceps} + 0.38 \cdot \text{quadriceps} + 4.56]$.¹³ About twenty minutes before the beginning of each work shift, we installed weather stations (Kestrel 5400FW, Nielsen-Kellerman, Pennsylvania, USA) about 40 m away from the different workplaces of the volunteers. Each weather station was used to measure air temperature (°C), humidity (%), wind speed (m/s), and the wet-bulb globe temperature (WBGT) (°C), continuously. The WBGT is a type of apparent temperature used to estimate the combined effect of temperature, humidity, wind speed (wind chill), and visible and infrared radiation (sunlight).
- 2.11 The real-time observation recordings were used to identify work-related behaviors. Work time spent on irregular work breaks (WTB) was defined as any unprescribed work cessation determined by the workers' own judgment, and not based on specific time intervals or instructions. Lunch time was not considered as WTB because it was prescribed by management. We also recorded the duration of uninterrupted work (WTL; continuous work without break) to delineate the impact of workplace heat on the frequency of breaks, which is different from the duration of WTB. It should be noted that the workers had sometimes access to shade from the surrounding buildings. Thus, the WTB was divided into two categories: the WTB during which the workers decided to rest in the shade (WTB_{shade}) and the WTB during which the workers chose to stay under the sun (WTB_{sun}). Based on these definitions, the following five work-related behaviors were identified in the time-motion analysis: (i) WTL, (ii) uninterrupted WTL, (iii) WTB_{shade}, (iv) WTB_{sun}, and (v) lunch.
- 2.12 Work-related behaviors were determined for each worker individually through time-motion analysis that was conducted on site in real-time by trained investigators. Experimenter bias was minimized via training the observers to rate by observing the same worker for 1 hour to ensure adequate agreement. For the same reason, the observers worked in close proximity and they were instructed to seek each other's advice in cases where they could not make a firm decision on their own. They were, thus, encouraged to give consensus group ratings of work-related behaviors.

Results

- 2.13 The reported work experience ranged from 1 to 21 years, with a mean of 14 years. Workers' age ranged from 21 to 56 years, with a mean of 43 years. Frame workers were younger (mean age: 40 years) compared to the brick layer workers and the drivers (mean age for both: 47 years). The mean body mass index (BMI) for the entire group of workers was 26.4, which indicates that, on average, they were overweight. The mean body mass index for the frame workers was 24.6, which indicates that their body composition was normal. The mean body mass index for the brick layer workers was 28.4, which indicates that they are overweight. Finally, the mean body mass index for the drivers was 29.5, which indicates that they are in the high levels of overweight and close to being obese (BMI≥30).

2.14 Detailed temperature and weather conditions for the two test days are shown in Figures 2 and 3. Day 1 was a hot day (temperature range: 21.8-37.3°C) with high levels of solar radiation (sunlight). Day 2 was a cool day (temperature range: 21.9-31.6°C) with low levels of solar radiation due to increased cloud coverage. The WBGT on Day 1 was high, ranging between 27°C and 29°C for the most part of the work shift. This is noteworthy since, according to the ISO Standard 7243 (1989), an individual cannot sustain working more than 45 minutes every hour when WBGT is between 28.6°C and 29.3°C (Figure 4). Therefore, it would not be surprising to see a loss of work time as high as 25% between 16:00 and 19:00, when WBGT is high. On the other hand, the WBGT on July 6 was normal (average: 22.5°C), ranging between 20°C and 24°C for most of the work shift. Therefore, any loss of work time during that day would probably not be attributable to the heat.

Figure 2. Environmental temperature (°C) and weather conditions (top panel) as well as WBGT (°C; bottom panel) throughout the work shift during Day 1.

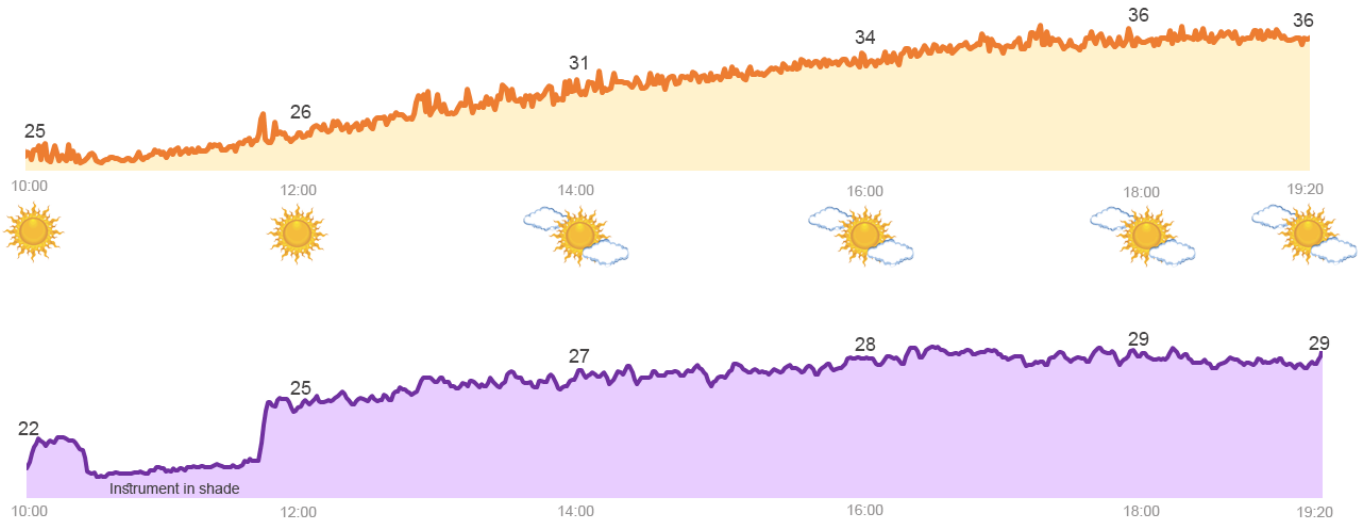


Figure 3. Environmental temperature (°C) and weather conditions (top panel) as well as WBGT (°C; bottom panel) throughout the work shift during Day 2.

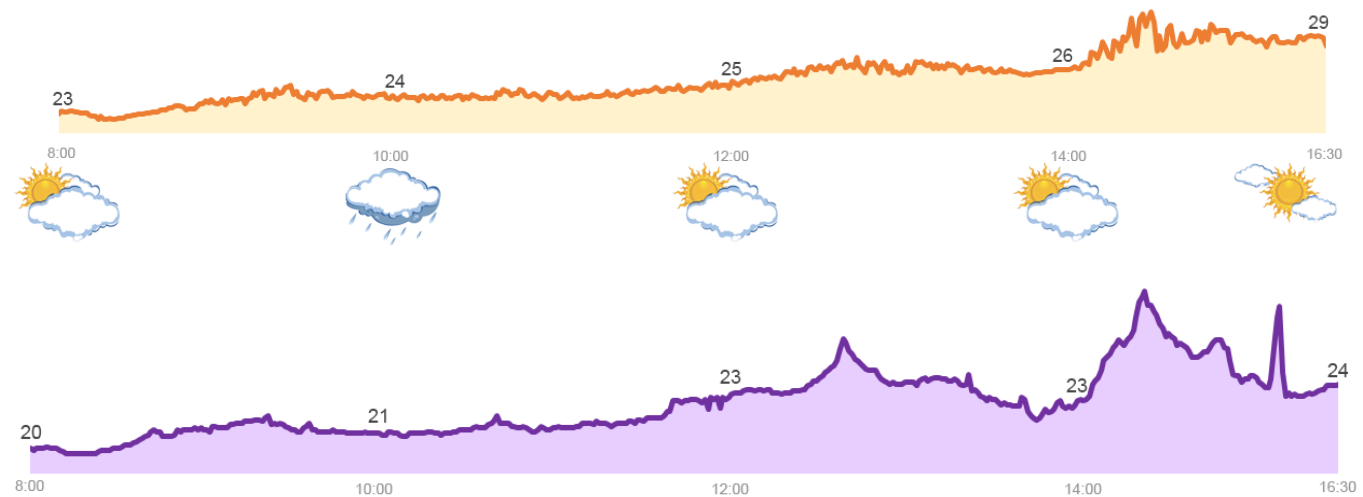
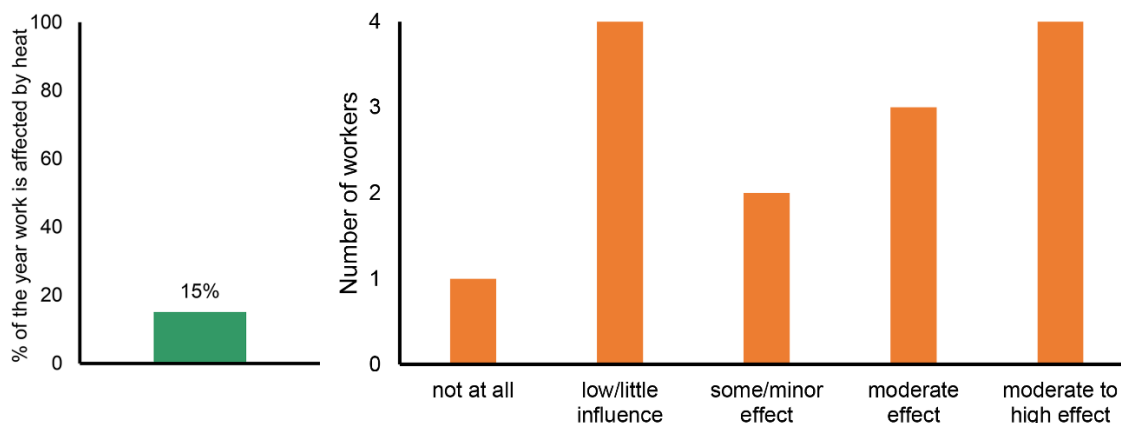


Figure 4. Hourly work capacity for an acclimatized worker carrying out moderate activity (300W) at different WBGT levels.

WBGT °C heat exposure				
<28.6	29.3	30.6	31.8	>38
60 min/hr	45 min/hr	30 min/hr	15 min/hr	0 min/hr

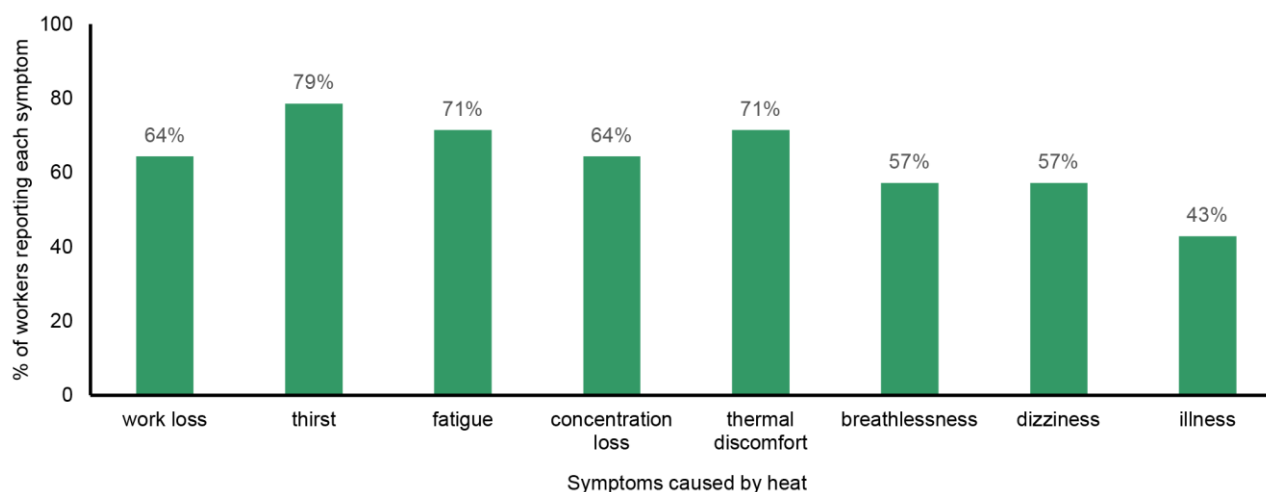
2.15 As reported by the workers, 15% of the work done in a year (i.e. 55 days) is affected by heat (Figure 5). During these hot days, 50% of the workers feel that the intensity of the heat effect is moderate or high.

Figure 5. Average percentage of yearly work that is affected by the heat (left panel) and intensity of the heat effect during those hot days (right panel), as reported by the workers.



2.16 Almost 2/3 of the workers reported working less during a hot day (Figure 6). During such days, nearly 80% reported feeling thirsty, while more than 2/3 were fatigued, uncomfortable, and had low concentration. Also, about 60% of the workers reported feeling breathlessness and dizziness, while about 40% reported having been ill due to the heat.

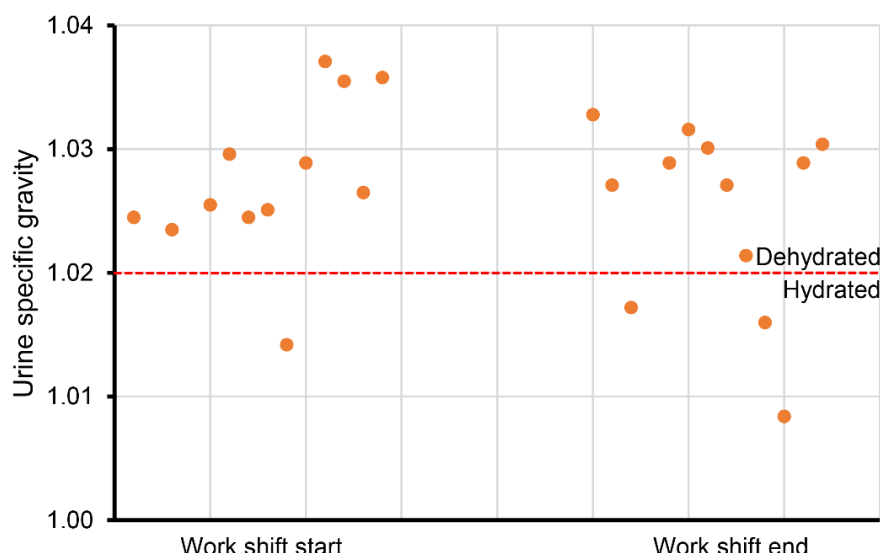
Figure 6. Percentage of workers reporting different symptoms caused by heat in the workplace.



2.17 The urine samples taken to assess the workers' hydration status showed that 92% of them start their work shift in a dehydrated state (Figure 7). At the end of the work shift, 82% of the workers are still dehydrated.

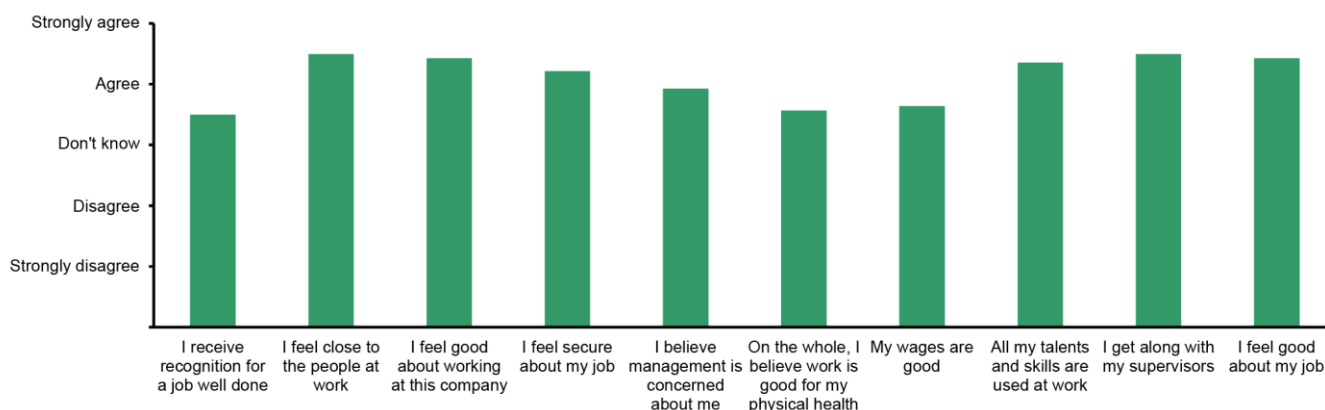
2.18 These findings are particularly important since dehydration leads to an increase in body temperature because the body reduces its sweat production. Also, dehydration increases the overall perception of fatigue. As a result, dehydrated workers are far more likely not to perform their duties adequately but also to cause/get involved in a work accident. Finally, chronic dehydration (almost daily dehydration for several months) can lead to kidney function disorders.

Figure 7. Urine specific gravity values at the start (left panel) and the end (right panel) of the work shift. The cut off value separating hydrated and dehydrated workers is indicated with a dotted red line.



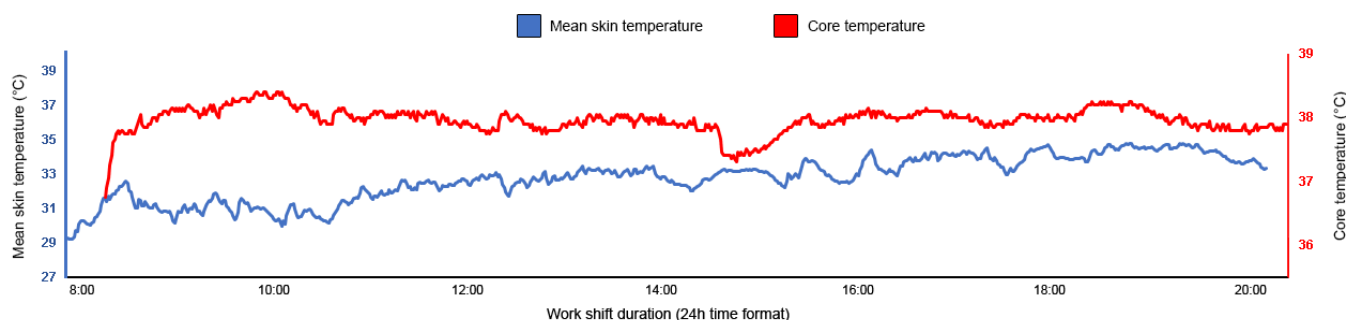
2.19 The majority (71%) of the workers reported receiving recognition for a job well done, while only 14% reporting that this is not the case (Figure 8). All workers reported feeling close to the people at work, and nearly all (93%) felt good about working in this company and secure about their job. Nearly 80% of the workers felt that the management cares about them, yet 30% felt that this work is not good for their health and only 57% were satisfied with their wage. On the other hand, nearly all (85%) workers felt that all their talents and skills are used at work and they all reported getting along with their supervisors and feeling good about their job.

Figure 8. Workers' perception regarding job satisfaction.



2.20 Individual data for mean skin and core temperatures throughout Day 1 from a representative frame worker are illustrated in Figure 9. This worker was found dehydrated at the beginning and at the end of the work shift. During work, his core temperature remained relatively stable (with fluctuations based the amount of work and breaks taken) between 37.7°C and 38.3°C, indicating mild hyperthermia. His skin temperature increased progressively from 29°C to 33°C during the work shift, indicating a minor level of hyperthermia.

Figure 9. Mean skin (blue) and core (red) temperature during Day 1 from a representative frame worker.



During the study, mean skin temperature ranged from 28.1°C to 36.28°C with an average of 32.2±1.3°C, while mean core temperature ranged from 36.5°C to 37.9°C with an average of 37.4±0.7°C. The average mean skin and core temperatures throughout both days are illustrated in Figure 10, while the separate values for Day 1 and Day 2 are illustrated in Figure 11. In both days, core temperature remained relatively stable (with fluctuations based on the amount of work and breaks taken) during the majority of the work shift between 37.3°C and 37.8°C, indicating mild hyperthermia. Skin temperature increased progressively from 30°C to 33°C during the work shift, indicating a minor level of hyperthermia.

Figure 10. Average of mean skin (blue; left axis) and core (red; right axis) temperatures of all workers throughout the two study days.

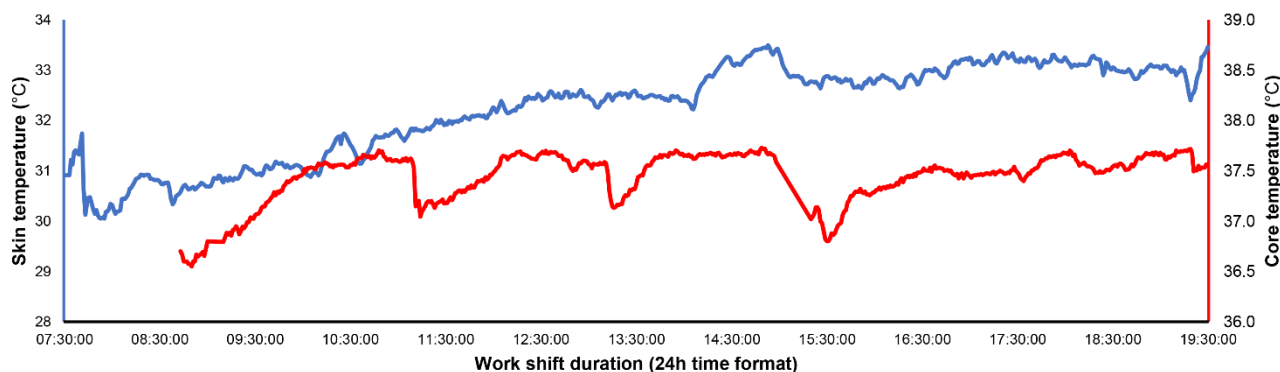
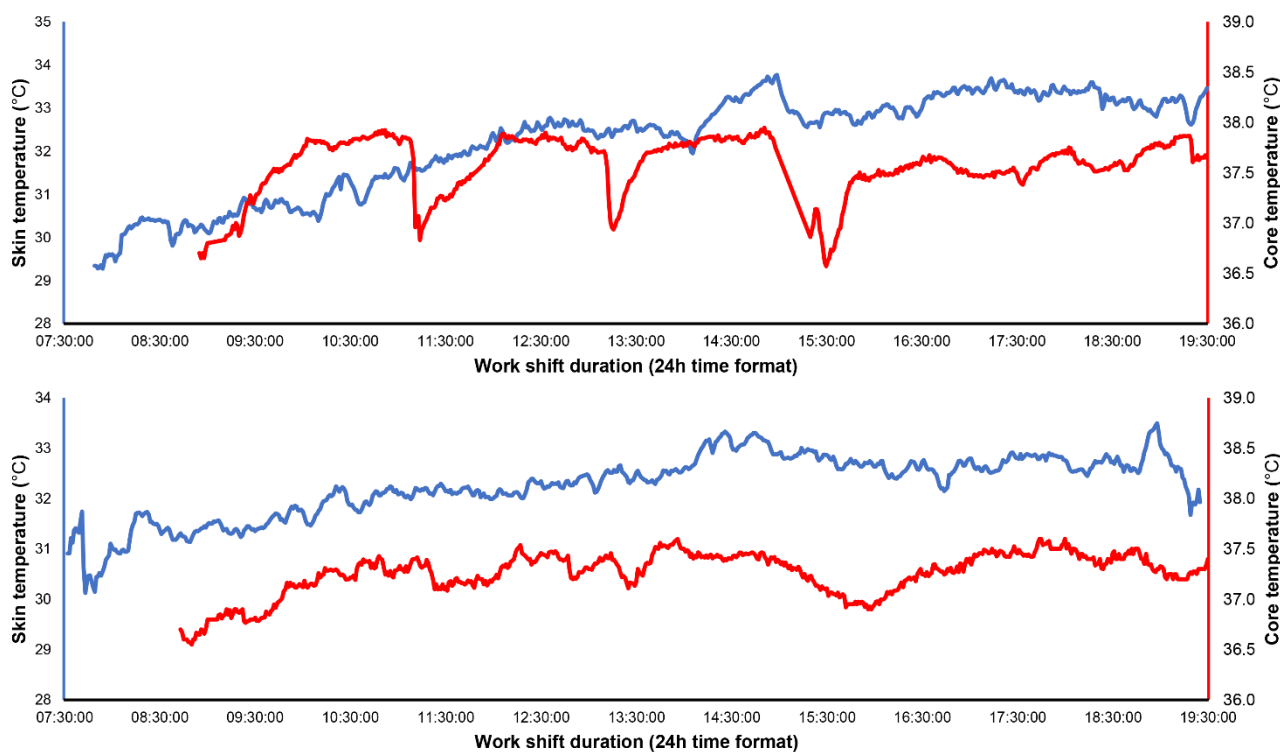


Figure 11. Average of mean skin (blue; left axis) and core (red; right axis) temperatures of all workers during Day 1 (warm day; top panel) and Day 2 (cold day; bottom panel) of the study.

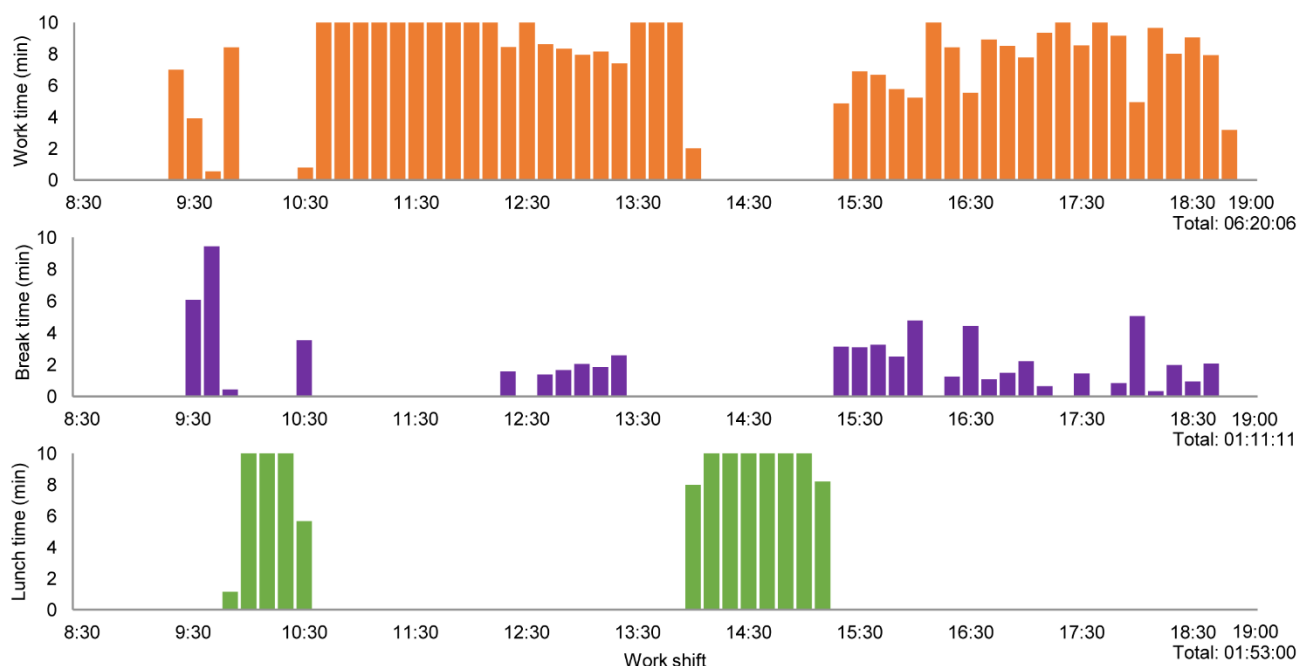


2.21 Work-related behaviours were identified through task analysis conducted by a trained researcher, on-site and in real-time. Work time spent doing work was defined as the time that a worker spends towards completing a task, not including breaks nor other work-related.

2.22 Work time, break time, and management-provided rest breaks during Day 1 from a representative frame worker are illustrated in Figure 12. A total of 9 hours, 24 minutes, and 17 seconds of this worker's work shift time were evaluated. During this time, the worker:

- worked for 6 hours, 20 minutes, and 6 seconds (67% of the evaluated work shift time),
- took irregular breaks for 1 hour, 11 minutes, and 11 seconds (13% of the evaluated work shift time),
- took regular breaks for 1 hour and 53 minutes (20% of the evaluated work shift time).

Figure 12. Work time (orange bars), break time (purple bars), and management-provided rest breaks (green bars) during Day 1 from a representative frame worker.



2.23 In total, 108.6 hours of work shift time (adding all the workers tested) were analyzed in the 2-day study. During this time, the workers spent:

- 84.7 h working (78 % of time),
- 6.8 h on irregular breaks (7.1 % of time),
- 17.1 h on regular breaks (15.6 % of time).

The frame workers spent:

- 75.2% of the time performing work,
- 9.0% of the time taking irregular breaks,
- 15.8% of the time taking regular breaks.

The brick layers spent:

- 80.3% of the time performing work,
- 4.1% of the time taking irregular breaks,
- 15.6% of the time taking regular breaks.

The drivers spent:

- 77.3% of the time performing work,
- 7.7% of the time taking irregular breaks,
- 15.0% of the time taking regular breaks.

2.24 In total, across the 2-day study, 6.8 hours were lost on irregular breaks (7.1% of the total evaluated work shift time). Given the substantial difference in the levels of workplace heat between the two study days (described in detail in paragraph 2.14), we investigated potential effects of heat on the time lost to activities other than work. During Day 1 (hot day), the workers spent:

- 49.5 h working (76 % of time),
- 5.6 h on irregular breaks (10.1 % of time),
- 10 h on regular breaks (15.3% of time).

During Day 2 (cool day), the workers spent:

- 35.2 h working (81 % of time),
- 1.2 h on irregular breaks (2.7 % of time),
- 7.1 h on regular breaks (16.3 % of time).

2.25 Overall, there was an additional 7.4 percentage points (4.4 h, or 4.7-fold difference) of work shift time lost on irregular breaks during Day 1 (a hot day) compared to Day 2 (a cool day).

Discussion

2.26 To our knowledge, this is the first study to investigate the effects of workplace heat on European construction workers. Our study was conducted on two different days where we used time-motion analysis of a total of ~109 work hours on a second-by-second basis collected from 16 workers while performing different construction jobs. Day 1 was a hot day (temperature range: 21.8-37.3°C) with high levels of solar radiation (sunlight), whereas Day 2 was a cool day (temperature range: 21.9-31.6°C) with low levels of solar radiation due to increased cloud coverage.

2.27 In total, the worksite was a safe place to work and the company had assessed and addressed a number of risks that may impact the health, safety, and welfare of its employees, visitors, contractors, and suppliers. Specifically, in the worksite evaluated, it was clear that the company:

- provided safe work premises,
- had assessed risks of injury and implemented appropriate measures for controlling them,
- ensured safe use and handling of goods and substances,
- provided and maintained safe machinery and materials,
- assessed workplace layout and provided safe systems of work,
- provided a suitable working environment and facilities.

2.28 These are important because creating a safe working environment is critical to the long-term success of a business because it can:

- help the company retain staff,
- maximise employee productivity,
- minimise injury and illness in the workplace,
- reduce the costs of injury and workers' compensation,
- ensure the company meets its legal obligations and employee responsibilities.

2.29 While recognizing the above, this evaluation demonstrated that further improvements are necessary with respect to the thermal stress experienced by the workers as well as the impact on their health and productivity. Specifically, almost 2/3 of the workers reported working less during a hot day, with nearly 80% reporting feeling thirsty, and >2/3 feeling fatigued, uncomfortable, and with low concentration. Also, about 60% of the workers reported feeling breathlessness and dizziness, while about 40% reported having been ill due to the heat. Despite these reported symptoms, a total of 92% of the workers started their work shift in a dehydrated state, with 82% of the workers remained dehydrated at the end of the work shift.

2.30 The above results impacted the workers' productivity. In total, across the 2-day study, 7.1% of the total evaluated work shift time was lost on irregular breaks (i.e., spontaneous work cessation determined by workers' own judgment). More importantly, however, there was an additional 7.4 percentage points (4.7-fold difference) of work shift time lost on irregular breaks during Day 1 (a hot day) compared to Day 2 (a cool day).

3. IDENTIFIED/SCREENED SOLUTIONS FOR CONSTRUCTION WORKERS

3.1 Combining the industry specific issues identified in Study 1 with a systematic review conducted by HEAT-SHIELD partners on the available solutions to mitigate heat stress (see Appendix), we designed Study 2 to test the effects and feasibility of implementing different solutions for construction workers to adapt to workplace heat. Our approach was to evaluate ~247 work hours via time-motion analysis on a second-by-second basis collected from 11 workers while performing different construction jobs and assess the effectiveness of different adaptation measures to alleviate the impact of workplace heat on labour effort. This study was labelled "Study 2" and is presented in the following sub-sections.

Description of Study 2

3.2 In Study 2, we used the results from Study 1 and identified/screened solutions to address the identified problems. Our approach was to evaluate ~247 work hours via time-motion analysis on a second-by-

second basis collected from 11 workers while performing different construction jobs and assess the effectiveness of different adaptation measures to alleviate the impact of workplace heat on labour effort.

3.3 Three adaptation measures were tested in a random order:

1. Planned breaks: during this intervention, the workers were provided with two 7-min breaks scheduled at 12:30 and at 16:30. During these breaks, the workers were free to do as they pleased though an advisory was given to rest and hydrate in the shade.
2. Ice slushy: during this intervention, the workers were provided with a 300 ml mixture of crushed ice and water every hour from 10:00 until the end of the work shift (18:00).
3. Hydration: during this intervention, the workers were provided with a 750 ml of water every hour from 09:00 until the end of the work shift (18:00). Also, their arms (if wearing a t-shirt), neck, and face were sprinkled with water on an hourly basis.

3.4 The study involved monitoring construction workers on four separate days (3-6/9/2018) in Murcia, Spain. The experimental protocol was approved by the University of Thessaly, School of Exercise Science Ethics Review Board (Protocol No. 1217) in accordance with the Declaration of Helsinki. Written informed consent was obtained from all volunteers prior to their participation in the study (in English or Spanish) before entering the study. They were free to deny participation or withdraw their consent at any point.

3.5 One day prior to the start of data collection, volunteers underwent a familiarization session which included information regarding all data collection procedures. Anthropometric characteristics were also recorded at that time. In total, 16 male workers participated in the study:

- 6 frame workers,
- 2 iron workers,
- 3 crane drivers.

3.6 Throughout the four study days, all volunteers were assessed from the beginning until the end of the work shift. The measurements performed were non-invasive, time-efficient, practical, and did not disturb the workers during their job.

3.7 During each recording day, each worker was monitored from the beginning until the end of the work shift by a researcher who observed the worker's activities. Also, we recorded skin temperature and environmental data throughout the work shift. No restrictions were placed on water/food consumption or any other kind of work- or non-work-related behavior. To ensure that we did not influence the workers' normal work routine, the temperature sensors used were miniature and wireless. Also, to minimize participant bias (i.e., work activities being affected because the workers were being observed), the true reason for the observations was hidden from the volunteers. Instead, they were informed that the investigators were interested to see the different types of work that they engage in. Of course, once the data collection was completed, all volunteers were informed about the true purpose of the observations and gave their permission to analyze and publish these data.

3.8 We recorded the workers' age and work experience. Anthropometric measurements included height and mass. Body surface area was calculated using the Du Bois formula.¹¹ We obtained urine samples in the beginning and the end of the work shift to evaluate urine specific gravity, a well-known indicator of hydration status.¹²

3.9 Temperature at the skin surface was recorded every second at four sites using iBUTTON sensors (type DS1921H, Maxim/Dallas Semiconductor Corp., USA) to calculate the mean skin temperature [T_{sk} ; $0.3 \text{ (chest + arm)} + 0.2 \text{ (thigh + leg)}$].¹⁴ About twenty minutes before the beginning of each work shift, we installed weather stations (Kestrel 5400FW, Nielsen-Kellerman, Pennsylvania, USA) about 40 m away from the different workplaces of the volunteers. The weather station was used to measure air temperature (°C), humidity (%), wind speed (m/s), and the WBGT (°C), continuously.

3.10 As with Study 1, the real-time observation recordings were used to identify work-related behaviors. Work time spent on irregular work breaks (WTB) was defined as any unprescribed work cessation determined by workers' own judgment, and not based on specific time intervals or instructions. Lunch time was not considered as WTB because it was prescribed by management. We also recorded the duration of uninterrupted WTL (i.e., continuous work without break) to delineate the impact of workplace heat on the frequency of breaks, which is different from the duration of WTB. It should be noted that the workers had sometimes access to shade from the surrounding buildings. Thus, the WTB

was divided into two categories: the WTB during which the workers decided to rest in the shade (WTB_{shade}) and the WTB during which the workers chose to stay under the sun (WTB_{sun}). Based on these definitions, the following five work-related behaviors were identified in the time-motion analysis: (i) WTL, (ii) uninterrupted WTL, (iii) WTB_{shade}, (iv) WTB_{sun}, and (v) lunch.

3.11 Work-related behaviors were determined for each worker individually through time-motion analysis that was conducted on site in real-time by trained investigators. Experimenter bias was minimized via training the observers to rate by observing the same worker for 1 hour to ensure adequate agreement. For the same reason, the observers worked in close proximity and they were instructed to seek each other’s advice in cases where they could not make a firm decision on their own. They were, thus, encouraged to give consensus group ratings of work-related behaviors.

Results

3.12 The reported work experience ranged from 2 to 31 years, with a mean±sd of 17.6±7.9 years. Workers’ age ranged from 22 to 53 years, with a mean±sd of 41.9±8.9 years. Frame workers were slightly older (mean age: 43.3±11.0 years) compared with iron workers (mean age: 41.5±9.2 years) and the crane drivers (mean age for both: 39.3±5.8 years). The mean body mass index for the entire group of workers was 27.3±4.7, which indicates that, on average, they were overweight. The mean body mass index for the frame workers was 26.2±4.7, which indicates that they were overweight. The mean body mass index for the iron workers was 29.7±6.4, which indicates that they were are in the high levels of overweight and close to being obese (BMI≥30). Finally, the mean body mass index for the crane drivers was 27.9±4.8, which indicates that they were overweight.

3.13 Detailed temperature and weather conditions for the four test days are shown in Figures 13-16. Overall, the weather conditions and the associated environmental heat stress were similar across the four test days.

Figure 13. Environmental temperature (°C; top panel) and WBGT (°C; bottom panel) throughout the work shift during the Baseline condition.

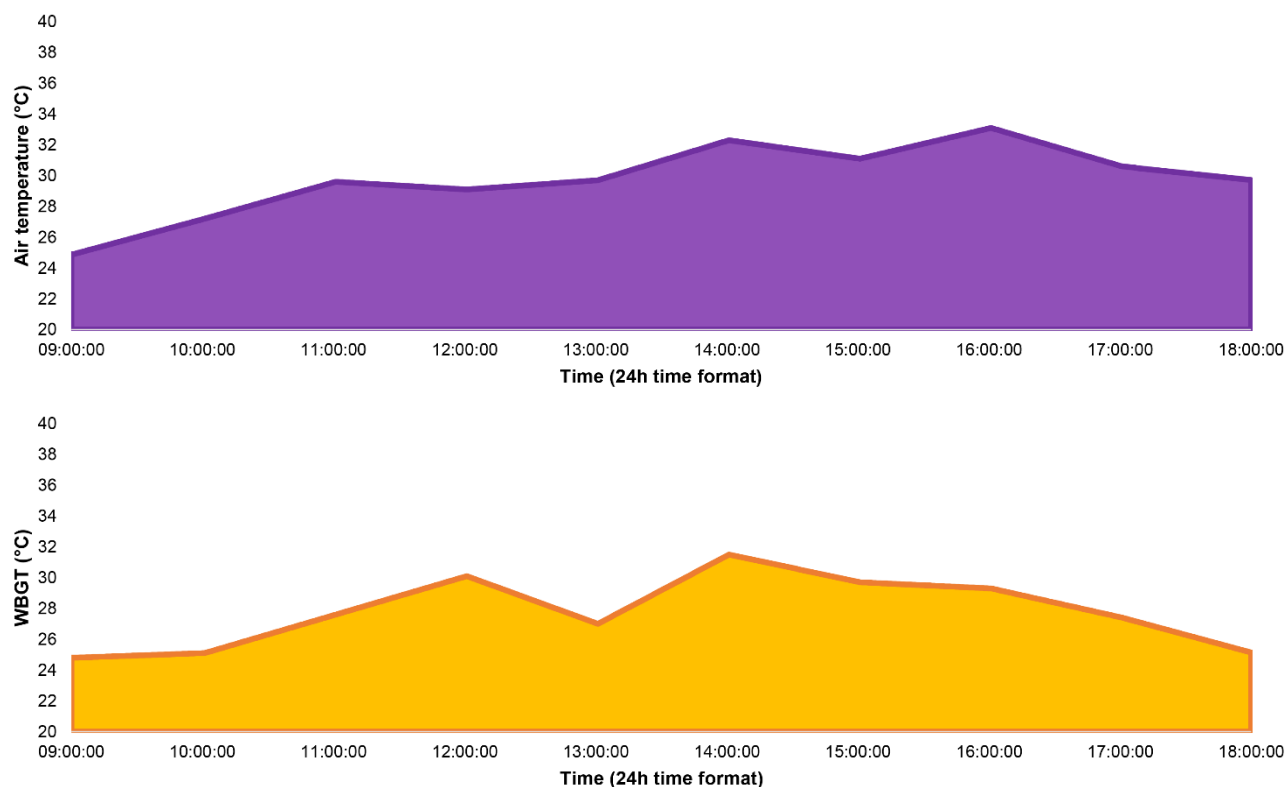


Figure 14. Environmental temperature (°C; top panel) and WBGT (°C; bottom panel) throughout the work shift during the Planned Breaks condition.

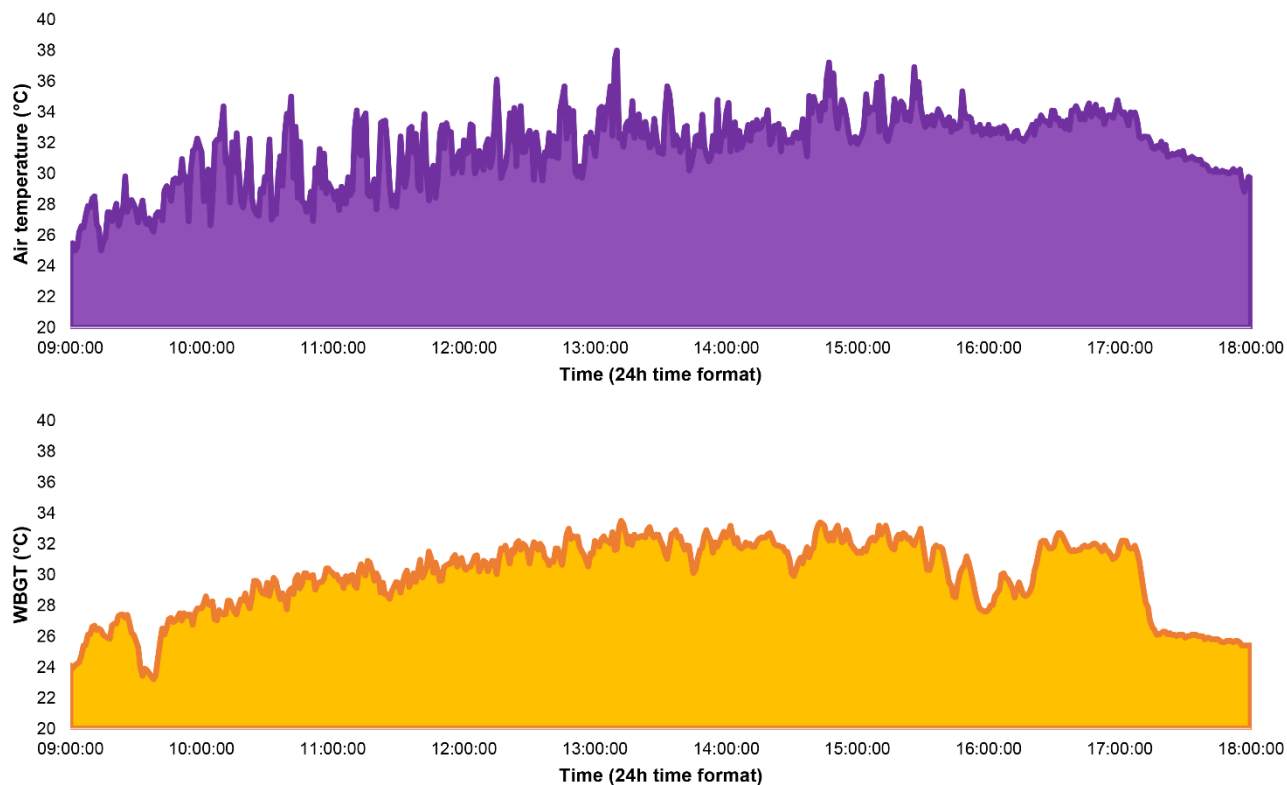


Figure 15. Environmental temperature (°C; top panel) and WBGT (°C; bottom panel) throughout the work shift during the Ice Slushy condition.

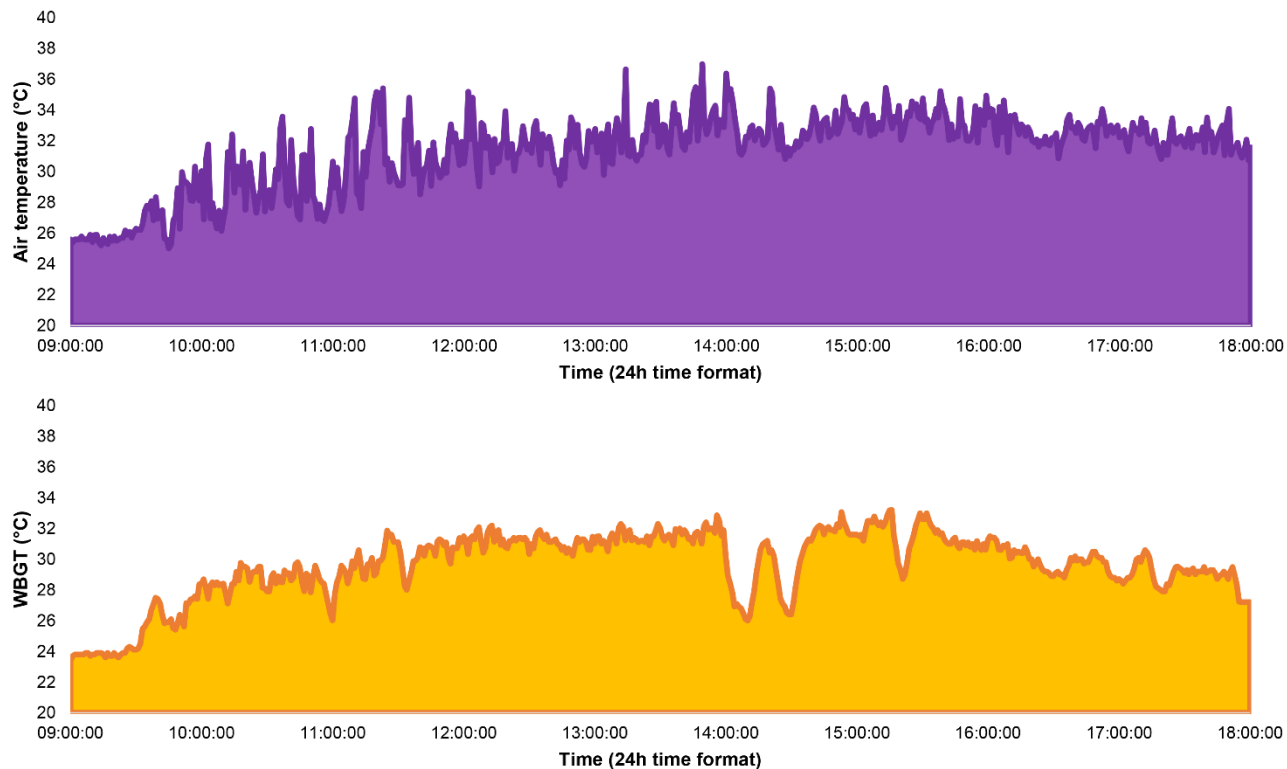
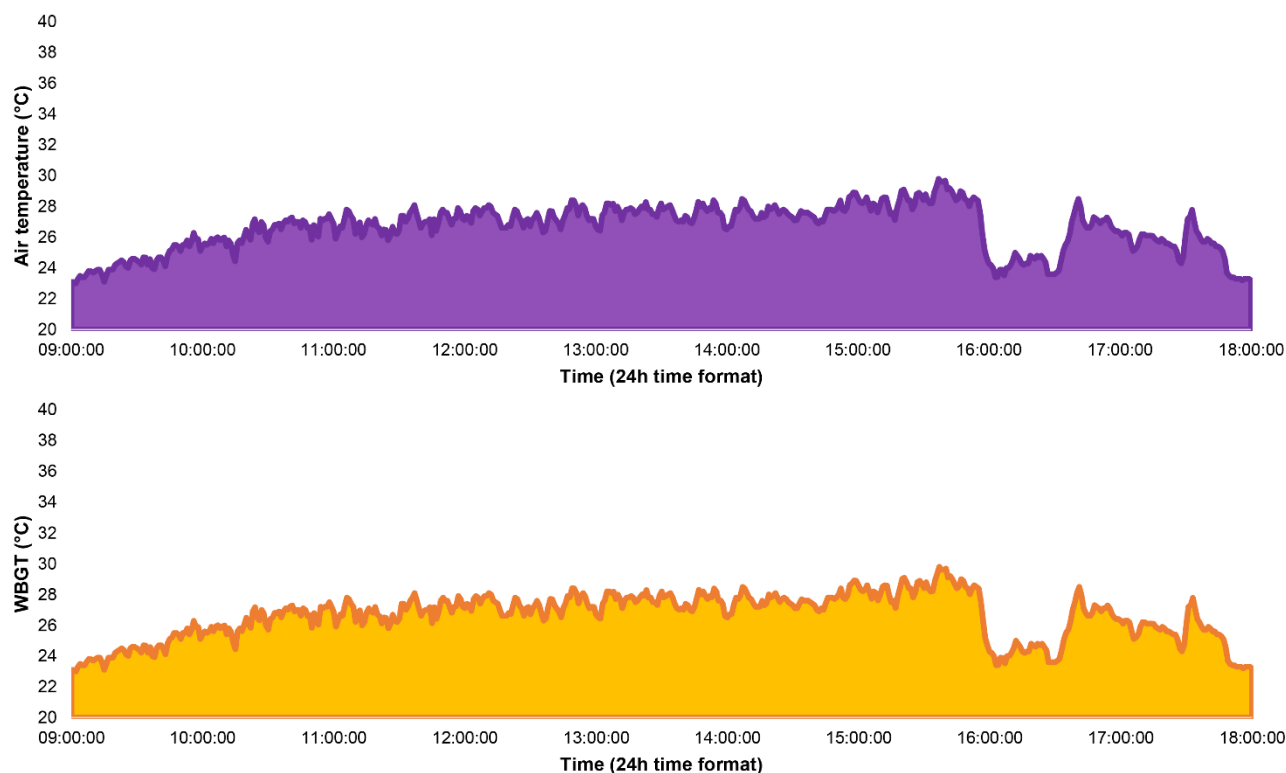


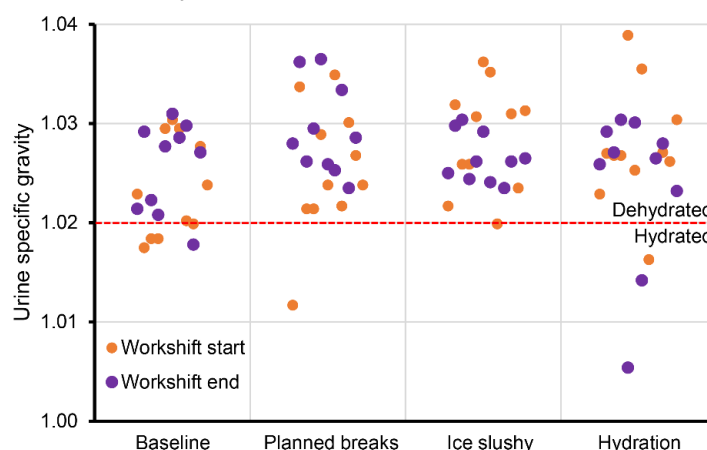
Figure 16. Environmental temperature (°C; top panel) and WBGT (°C; bottom panel) throughout the work shift during the Hydration condition.



3.14 The urine samples taken to assess the workers' hydration status during all days showed that 84% of them start their work shift in a dehydrated state (Figure 17). At the end of the work shift, 84% of the workers are still dehydrated. During the normal baseline condition, urine specific gravity was 1.023 ± 0.005 at the start (63% of workers at risk for dehydration) and 1.026 ± 0.005 at the end (90% of workers at risk for dehydration) of the work shift. During the planned breaks condition, urine specific gravity was 1.025 ± 0.007 at the start (91% of workers at risk for dehydration) and 1.029 ± 0.005 at the end (100% of workers at risk for dehydration) of the work shift. During the ice slushy condition, urine specific gravity was 1.028 ± 0.005 at the start (91% of workers at risk for dehydration) and 1.027 ± 0.003 at the end (100% of workers at risk for dehydration) of the work shift. Finally, during the hydration condition, urine specific gravity was 1.028 ± 0.006 at the start (91% of workers at risk for dehydration) and 1.024 ± 0.008 at the end (80% of workers at risk for dehydration) of the work shift.

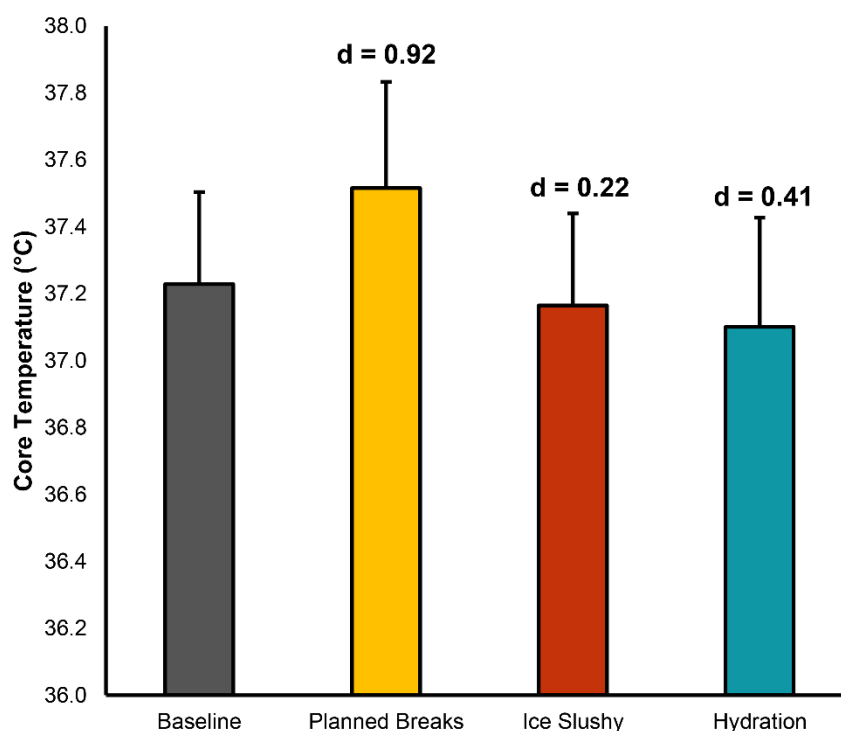
3.15 These findings are particularly important, since dehydration leads to an increase in body temperature because the body reduces its sweat production. Also, dehydration increases the overall perception of fatigue. As a result, dehydrated workers are far more likely not to perform their duties adequately but also to cause/get involved in a work accident. Finally, chronic dehydration (almost daily dehydration for several months) can lead to kidney function disorders.

Figure 17. Urine specific gravity values at the start (orange) and the end (purple) of the work shift. The cut off value separating hydrated and dehydrated workers is indicated with a dotted red line.



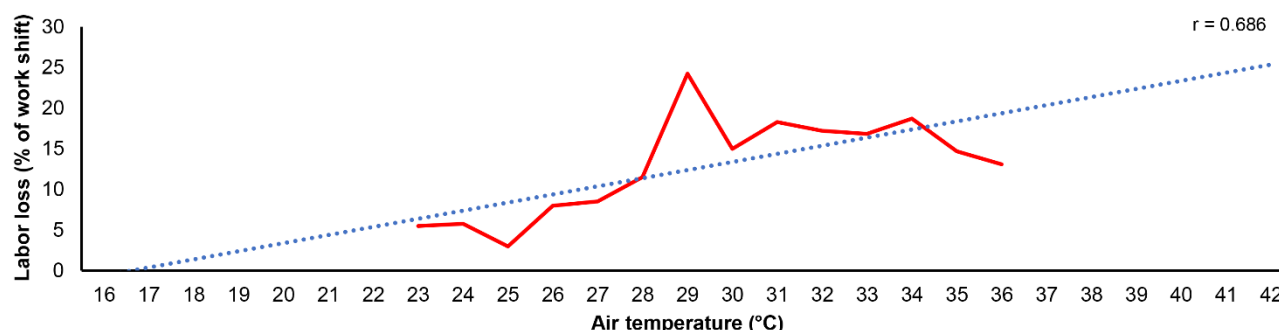
3.16 During the study, the core temperature of the workers ranged from 36.7°C to 38.3°C with an average of $37.4 \pm 0.4^\circ\text{C}$, indicating mild hyperthermia (Figure 18). During the Baseline condition, the core temperature of the workers ranged from 36.7°C to 38.1°C with an average of $37.4 \pm 0.3^\circ\text{C}$. During the Planned breaks condition, the core temperature of the workers ranged from 36.7°C to 38.2°C with an average of $37.5 \pm 0.3^\circ\text{C}$. During the Ice slushy condition, the core temperature of the workers ranged from 36.7°C to 38.3°C with an average of $37.4 \pm 0.5^\circ\text{C}$. Finally, during the Hydration condition, the core temperature of the workers ranged from 36.7°C to 37.9°C with an average of $37.1 \pm 0.3^\circ\text{C}$.

Figure 18. Average core temperatures of all workers during each of the different conditions of the study.



3.17 The loss of labour effort escalated from 5%, during low occupational heat stress (23-25°C air temperature), to 15.8% during high occupational heat stress (26-34°C air temperature) (Figure 19). The air temperature during work was positively correlated with labour loss ($r=0.686$, $p<0.05$).

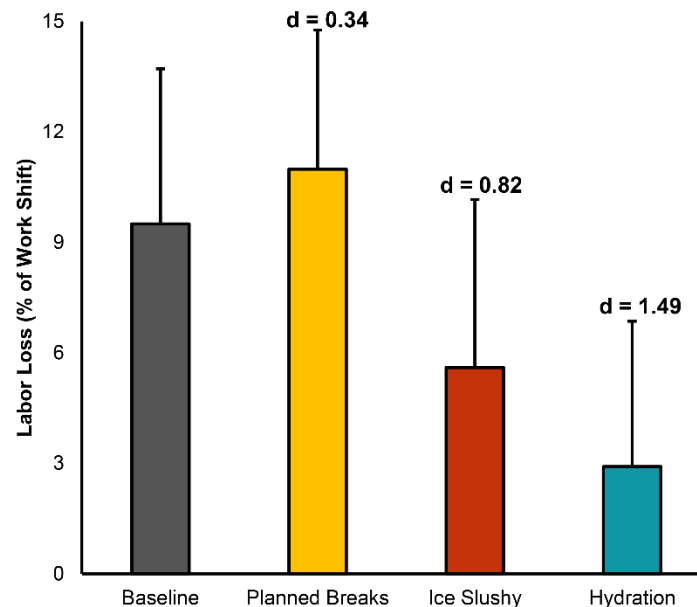
Figure 19. Association between environmental (air) temperature and loss of labour time during the baseline condition as well as the two study days of Study 1.



3.18 The results for labour loss (i.e., percentage of work shift time lost due to irregular work breaks) during the baseline assessment and the three interventions used to test different adaptation measures are illustrated in Figure 20. Specifically, we found that the percentage of work shift time lost due to irregular work breaks during the baseline assessment was $9.4 \pm 4.2\%$. The labour loss values observed when the workers were provided with planned breaks was $10.9 \pm 3.8\%$, as the time required to take

those breaks was added to the labour loss. When the workers were provided with ice slushies, the labour loss was reduced to $5.6 \pm 4.5\%$. Finally, when the workers were provided with additional water through the hydration strategy, the labour loss was reduced to $2.9 \pm 3.9\%$. Based on these results, providing sufficient (in the present case at least 750 ml per hour) of water to the workers appears to be the most effective adaptation measure to reduce the labour loss during construction work in the heat.

Figure 20. Labour loss (i.e., percentage of work shift time lost due to irregular work breaks) during the baseline assessment and the three interventions used to test different adaptation measures.



Discussion

3.19 To our knowledge, this is the first study to investigate the effects of different adaptation measures to mitigate workplace heat on European construction workers. Our study was conducted on four different days where we used time-motion analysis of a total of ~247 work hours via time-motion analysis on a second-by-second basis collected from 11 workers while performing different construction jobs and assess the effectiveness of different adaptation measures to alleviate the impact of workplace heat on labour effort.

3.20 In total, the worksite was a safe place to work and the company had assessed and addressed a number of risks that may impact the health, safety, and welfare of its employees, visitors, contractors, and suppliers. Specifically, in the worksite evaluated, it was clear that the company:

- provided safe work premises,
- had assessed risks of injury and implemented appropriate measures for controlling them,
- ensured safe use and handling of goods and substances,
- provided and maintained safe machinery and materials,
- assessed workplace layout and provided safe systems of work,
- provided a suitable working environment and facilities.

3.21 These are important because creating a safe working environment is critical to the long-term success of a business because it can:

- help the company retain staff,
- maximise employee productivity,
- minimise injury and illness in the workplace,
- reduce the costs of injury and workers' compensation,
- ensure the company meets its legal obligations and employee responsibilities.

3.22 While recognizing the above, this evaluation demonstrated that further improvements are necessary with respect to the thermal stress experienced by the workers as well as the impact on their

health and productivity. For instance, staying hydrated is critical for maintained productivity and health in the construction industry. Unfortunately, workers forget or fail to rehydrate from day-to-day. Thus, nine out of 10 construction workers arrived at work at a dehydrated state. This means that they started the day at an elevated risk for hyperthermia and acute kidney injury as well as low probability for performing at their best during their work shift.

3.23 During the baseline assessment of the study, $9.4 \pm 4.2\%$ of the total evaluated work shift time was lost on irregular breaks (i.e., spontaneous work cessation determined by workers' own judgment). This was increased to $10.9 \pm 3.8\%$ when the workers were provided with planned breaks (when adding the time required to take those breaks). When the workers were provided with ice slushies, the labour loss was reduced to $5.6 \pm 4.5\%$. Finally, when the workers were provided with additional water through the hydration and sprinkling strategy, the labour loss was further reduced to $2.9 \pm 3.9\%$.

3.24 Based on the above results, construction workers should drink at least 750 ml (three cups of water) before starting work in the morning to mitigate arriving to work in a dehydrated state. During their work shift, they should consume 750 ml of water per hour. When working under heat stress, this strategy demonstrates the best results for maintaining hydration (reducing the risk for kidney disease or acute kidney injury) and for reducing labour loss due to irregular work breaks. For this reason, it is important that strategies are put in place for workers to have access to cold/cool water throughout the day, even when working on different floors or remote areas of a construction site. During periods where workers are sweating profusely, healthy workers should add a larger amount of salt (electrolytes) to their diet. However, workers with heart, blood pressure, or other medical conditions should adopt this advice only when confirmed by their physician. If possible – and, particularly, during breaks – cooling the water by refrigeration, or better yet, by the addition of shaved/crushed ice will help lower the discomfort and heat stress experienced by the workers and improve work performance. Additionally, spreading water on the skin either during breaks or during work (if there is an abundance of water) can help increase evaporative cooling and help limit the rate of dehydration.

3.25 In view of other interventions evaluated in the systematic review conducted by HEAT-SHIELD partners on the available solutions to mitigate heat stress (see Appendix), it is important to note that appropriate clothing can lower the construction worker's thermal stress. These workers require special protective clothing (gloves, helmet, boots, etc.), while clothing is also beneficial for protecting the construction worker from excessive sun exposure. However, clothing can also restrict heat loss as it provides a boundary layer that limits evaporation and convective/dry heat loss. To facilitate heat loss, clothing worn during the work shift should be selected based upon promoting air flow across the skin and improving sweat evaporation (reducing clothing evaporative resistance). This can be accomplished by reducing the total amount of skin covered by clothing by wearing a t-shirt vs long sleeve (if indoors), wearing looser fitting clothing which allows for greater air flow underneath the clothing, and wearing clothing with a wider knitting pattern which allows for more air flow to pass through the clothing. Additionally, lighter colours should be selected on sunny days in outdoor environments to increase the reflection of solar radiation. In situations where long, rigid clothing must be worn (e.g. coveralls), ventilation patches can be incorporated into more protected areas such as under the arms and between the legs to help promote air flow through the garment.

3.26 One final point is that it is crucial to plan the workflow to allow workers time to adapt. Workers will acclimatize to heat during the first days of hot weather, however depending on the initial fitness and previous exposure it will take at least one week before workers get used (physiologically adapted) to the increased heat. This acclimatization process will be hampered/take longer if the workers spend prolonged periods of time in artificially cooled environments when not working.

4. SUMMARY OF RECOMMENDED SOLUTIONS FOR CONSTRUCTION WORKERS

4.1 Based on the present evidence, it is advisable that construction firms, from large multinational corporations to small local contractors, consider/develop an appropriate heat adaptation plan to protect both employer (by maintaining productivity) and employee (by minimizing health risks) benefits. This plan may be qualified by a designated person and benefit from consulting advanced warning weather systems to warn in advance when a period of hot weather is expected.

4.2 Construction workers should drink at least 750 ml (three cups of water) before starting work in the morning. During their work shift, they should consume 750 ml of water per hour. When working under

heat stress, this strategy demonstrates the best results for maintaining hydration (reducing the risk for kidney disease or acute kidney injury) and for reducing labour loss due to irregular work breaks. For this reason, it is important that strategies are put in place for workers to have access to cold/cool water throughout the day, even when working on different floors or remote areas of a construction site. During periods where workers are sweating profusely, healthy workers should add a larger amount of salt (electrolytes) to their diet. However, workers with heart, blood pressure, or other medical conditions should adopt this advice only when confirmed by their physician. If possible – and, particularly, during breaks – cooling the water by refrigeration, or better yet, by the addition of shaved/crushed ice will help lower the discomfort and heat stress experienced by the workers and improve work performance. Additionally, spreading water on the skin either during breaks or during work (if there is an abundance of water) can help increase evaporative cooling and help limit the rate of dehydration.

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- 4.4 It is crucial to plan the workflow to allow workers time to adapt. Workers will acclimatize to heat during the first days of hot weather, however depending on the initial fitness and previous exposure it will take at least one week before workers get used (physiologically adapted) to the increased heat. This acclimatization process will be hampered/take longer if the workers spend prolonged periods of time in artificially cooled environments when not working

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HEAT-SHIELD research under preparation for publication:

Sustainable solutions to mitigate environmental heat stress – occupational and global health perspectives

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Introduction: Occupational heat stress influences the well-being and productivity of billions of people. As climate change will aggravate these conditions, identifying effective solutions is of critical concern. However, implementation in industrial settings, economic viability and ecological sustainability from a global health perspective are of equally important consideration. We conducted an umbrella-review to identify methods that relieve thermal stress and/or improve performance in the heat and evaluate the “implementation potential” of the procedure.



Methods: A systematic review of systematic reviews was conducted in PUBMED, Web of Science and SPORTdiscus, employing the following eligibility criteria: 1) ambient temperature above 28°C or hypohydrated participants, 2) healthy adults, 3) reported outcomes for physical or cognitive performance, thermal comfort or core temperature, 4) written in English, 5) and published before July 2018.

Results: An overview of the results is provided in Table 1. In total, 45 reviews fulfilled the criteria (36 were exercise-oriented, 6 were occupationally-oriented and 3 included both aspects) including 19 papers with meta-analyses. Lowering environmental heat stress was most effective for maintaining performance in the heat, it was also most expensive and least feasible, correspondingly necessitating more personalised interventions. The most effective interventions in the literature were phase-change and liquid-cooled garments, cold water immersion, heat acclimation, cold fluid ingestion and maintaining hydration status. Albeit effective, cold water immersion and liquid perfused garments are unfeasible under most occupational settings. On the other hand, highly feasible and sustainable methods such as taking periodic breaks, providing shade and using electric fans currently lack experimental and meta-analytical evidence in the literature.

Conclusions: Presently, the literature is overwhelmingly dominated by exercise-oriented studies conducted in laboratory settings and disregard whether the method is feasible to implement in real-life settings (occupational or recreational) or suitable and sustainable for mass application. Future studies are needed which are occupationally-oriented, useable in the field and are scalable.

Summary table: Assessment of different cooling interventions identified from the literature.

Intervention	Strength of evidence	Productivity/ Performance/ Physiological impact	Economic Cost	Feasibility/ Implementation (indoor/outside)	Environmental sustainability
<i>Environmental manipulation</i>					
Air conditioning		+++	\$\$\$		
Ventilation		- to ++	\$		
Shading		0 to ++	\$		
<i>External cooling</i>					
Cold water immersion		+ to ++	\$\$		
Phase change garments		+ to +++	\$\$		
Cooling packs		0 to ++	\$\$		
Ice towels		+++	\$\$		
Skin wetting		- to +++	\$		
Menthol application		0 to +++	\$		
Vacuum glove		0 to +	\$\$\$		
<i>Internal cooling</i>					
Ice slurry ingestion		+ to +++	\$		
<i>Mixed method cooling</i>					
External and internal cooling		++ to +++	\$ to \$\$		
<i>Hydration</i>					
Hyperhydration		++	\$		
Maintenance		++ to +++	\$		
Rehydration		++ to +++	\$		
<i>Clothing</i>					
Liquid & air-cooled		+++	\$\$\$		
Compression		- to +	\$\$		
Elevated design		++	\$\$		
<i>Heat acclimation</i>					
Long term		+++	\$ to \$\$\$		
Medium		++ to +++	\$ to \$\$\$		
Short		+ to ++	\$ to \$\$\$		
<i>Nutrition</i>					
Carbohydrate		0 to +	\$		
Amino acids		0 to ++	\$		
Electrolytes		++	\$		
<i>Pacing strategies</i>					
Breaks		0 to +++	\$	 to 	
Pacing		0 to +++	\$	 to 	
Scheduling		?	\$	 to 	

Summary table of a Heat-Shield-conducted systematic review of systematic reviews on all available interventions that have been employed to improve physical and cognitive performance as well as physiological and perceptual responses to heat stress (see appendix 1). Pages () denote strength of evidence, with  denoting meta-

analyzed data, 📄📄 denoting systematically analyzed data and 📄 denoting first level evidence only. Summative scores (-,0,+) denote effect on performance ranging from detrimental (-), neutral (0) to various levels of effectiveness (+=mildly beneficial, ++=moderately beneficial and +++= very beneficial). Approval signs (👎, 👍) denote how feasible the given intervention would be to employ in a standard agricultural environment ranging from nearly impossible to employ (👎👎👎) to essentially no additional effort to employ required (👍👍👍). Finally leaves (🍃) denote environmental sustainability ranging from not sustainable (🍃) to essentially no additional burden on the environment (🍃🍃🍃).