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The impact of workplace heat and cold on work time loss

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Our findings are expected to inform policies aimed at improving workplace conditions and enhancing labor productivity across diverse industries globally. The Workplace Environmental Labor Loss functions quantify the impact of workplace temperature on work time loss, offering critical insights for health scientists and policymakers to minimize occupational health risks.

Abstract

Objective: We investigated the impact of workplace heat and cold on work time loss. **Methods:** Field experiments in different industrial sectors were conducted in multiple countries across all seasons between 2016 and 2024. Hundreds of workers were video-recorded and their full shifts (n = 603) were analyzed on a second-by-second basis (n = 16,065,501 sec). Environmental data were recorded using portable weather stations. The Workplace Environmental Labor Loss (WELL) functions were developed to describe work time loss due to workplace temperature. **Results:** The WELL functions revealed a U-shaped relationship whereby the least work time loss is observed at 18 °C (64 °F), and increases for every degree above or below this optimal temperature. **Conclusions:** The WELL functions quantify the impact of workplace temperature on work time loss, extending to temperatures previously believed to be unaffected.

Keywords: temperature, wbgt, occupational, labor, productivity, capacity

Learning Outcomes

- To investigate the impact of workplace temperature on work time loss.
- To discuss how this new evidence can influence future occupational heat-health policies.

Introduction

Ambient conditions affect the ability of people to work. A previous small-scale study showed that the thermal conditions of a workplace cause a re-allocation of time during a work shift, whereby workers spend less time on labor and more time on non-labor activities or vice versa (1). This is especially true in climate-vulnerable industries such as agriculture, construction, and tourism where workers can be exposed to high levels of thermal stress (2-4). Potential changes of work time supplied in these industries not only affect the lives of the billions of people employed (4) but also undermine food security and create substantial spillover effects on the global economy (5, 6). Therefore, it is important to better understand the impact of workplace heat and cold on work time loss to provide climate scientists and economists with the tools needed to model the impact of climate change on the economic growth, competitiveness, and living standards of countries.

Enhancing knowledge on how heat and cold affect work time loss is crucial for two more reasons. First, because the occurring climate change steadily amplifies the detrimental impacts of ambient conditions on working people (4, 7). Second, because most of the global estimates of climate change impacts on workers rely on two studies conducted in the 1960s: a field study with South African indigenous males shoveling broken rock for five hours inside a very hot and deep gold mine (8) and a laboratory study of three mine rescue male personnel walking on a treadmill for one hour inside an environmental chamber (9). While these studies were of outstanding quality at the time of publication, more than half a century ago, their relevance today is limited because work itself, the way it is performed, and the characteristics of the people who do it have drastically changed. Moreover, contemporary attitudes and perceptions toward occupational heat stress have evolved significantly, with more workers now aware of the adverse impacts of temperature on their capacity for work (10). This, of course, has important implications for current and future global estimates of climate change impacts and necessitates contemporary research to reflect current work practices among diverse populations. In this respect, the aim of this study was to investigate the impact of workplace heat and cold on work time loss.

Methods

We performed field experiments in Cyprus, Greece, Nicaragua, Qatar, Slovenia, and Spain during all seasons from 2016 to 2024. The experimental protocol (ClinicalTrials.gov ID: NCT04160728) for these field experiments was approved by the National Bioethical Review Board of Cyprus (protocol no: EEBK EP 2017.01.61), the Bioethical Committee of the Department of Physical Education and Sport Science of the University of Thessaly (protocol no: 1217), and the Qatar Ministry of Administrative Development, Labor and Social Affairs (protocol no: 40262271/1) in accordance with the Declaration of Helsinki. This study was reported in accordance with the STROBE guidelines for observational studies (STROBE checklist is available as Supplementary Digital Content, http://links.lww.com/JOM/B836).

Participant recruitment in Cyprus (n = 135), Greece (n = 90), Nicaragua (n = 9), Slovenia (n = 16), and Spain (n = 23) was carried out via word-of-mouth led by members of the local work cooperative. Participant recruitment in Qatar (n = 103) was carried out via invitation to local farmers by employees of the Qatar Ministry of Administrative Development, Labor and Social Affairs. As previously recommended (1), participants (both employees and employers) were blinded to the fact that they were participating in a scientific experiment to minimize the observer effect. Participants in Cyprus, Greece, Nicaragua, and Slovenia were informed that the researchers were creating a documentary, and that this would require a few days of filming their normal daily routine. In Qatar and Spain, employers and employees were informed that the study aimed to examine potential health implications of working in different environmental conditions. Importantly, all participants were informed about the true purpose of the study once data collection was completed. Also, they were informed that they could request their data to be removed and destroyed, and they were asked to give their written permission for their data to be analyzed and published. All workers gave written informed consent for their data to be analyzed and included in analyses and publications. Thereafter, they also provided information about their sex, nationality, age, height, and weight.

A total of 376 (females: 100; males: 276) manual workers (agriculture: 227; construction: 95; tourism: 54) participated in the study. These workers were experienced (assessed during their primary source of income work) and acclimatized (continuously living and working in the area). Their personal characteristics were as follows: age: 38.3 ± 12.1 years (n = 360), height: 1.69.1 ± 0.09 m (n = 368), weight: 72.2 ± 15.5 kg (n = 366), body mass index: 25.1 ± 4.4 kg/m^2 (n = 366), body surface area: 1.82 ± 0.21 m^2 (n = 366). Also, they originated from 16 different nationalities: Albania: 2, Bangladesh: 50, Cyprus: 32, Egypt: 8, Ghana: 3, Greece: 78, India: 57, Kenya: 7, Nepal: 2, Nicaragua: 9, Philippines: 13, Romani group: 10, Romania: 50, Slovenia: 16, Spain: 21, and Vietnam: 18. In agriculture, they performed various jobs in vineyards, orchards, rose farms, sugarcane farms, potato farms, and botanical gardens, as well as applying fertilizer, operating tractors, harvesting straw, trimming trees, cutting forest trees, and plowing fields. In construction worksites, our participants worked as carpenters, masons, riggers, electricians, scaffolders, bricklayers, crane operators, and forklift operators. In the tourism industry, our volunteers worked as gardeners, maids, cooks, chefs, drivers, laundry workers, and pool boys, among many other jobs. In total, our participants were assessed over 603 full shifts, with some of them being assessed during more than one shift. To avoid interference with the aim of the study, which was to assess the impact of workplace heat and cold on work time loss, work shifts were carefully selected to exclude those with work-rest regimes (provision of planned breaks based on environmental conditions) in place.

To assess work time loss in Cyprus, Greece, Nicaragua, and Slovenia we filmed the workers' activities throughout their normal work shift and, thereafter, we performed time-motion analysis to extract the time that each worker allocated on work- and non-work-related activities on a second-by-second basis, as previously described (1, 11). Specifically, about 20 minutes before the beginning of each work shift, video cameras (Hero 5 black, GoPro, California, USA) were installed about 40 m away from the workplace of the participants. The video cameras were set at 2.7 k resolution and 60 frames per second with a wide field of view to continuously record worker activities. The video recordings were used to extract detailed, second-by-second, information about what each worker did during his/her work shift following previous methodology (1). Based on previous methodology (11), the same video recordings were also used to estimate the metabolic rate characterizing the intensity of each identified work- and non-work-related task performed by workers, according to the compendium of physical activities (12). In all monitored worksites, there were no standard clothing requirements and workers wore typical attire suitable for the season and their type of work.

In Cyprus, Greece, Nicaragua, and Slovenia, task analysis was performed separately for each worker by four trained and experienced investigators who analyzed all video recordings within a period of one calendar year after data collection. To minimize the risk of errors due to fatigue, each investigator was taking a 1-hour break every two hours of task analysis. Thereafter, an independent analyst re-analyzed all task data against the video recordings for validity purposes. In Qatar and Spain, we carried out the same task analysis in real-time using a smartphone application developed for this study, where one investigator was recording the activities performed by one or two workers throughout their work shift. It is important to note that, as mentioned in a previous paragraph, all task analysis methodologies are subject to the "observer" effect (13), where workers may alter aspects of their behavior (e.g., avoid taking breaks and/or work more intensely) due to their awareness of being studied (14). To minimize the "observer" effect, we always performed one day of sham measurements at the beginning of data collection in each worksite, so that the workers were familiarized with the research team and the data collection methods.

Throughout each work shift, we obtained environmental data using portable weather stations (Kestrel 5400FW, Nielsen-Kellerman, Pennsylvania, USA) installed in advance at a height of 1.2 m above the ground about 40 m away from the workplace of the participants. In workplaces where employees were expected to work in multiple locations (e.g., waiters who have to enter the restaurant, take orders, and serve customers dining outdoors), multiple weather stations were installed across the working area. Each second of work was matched with the corresponding environmental temperatures throughout the shift, whether indoors, outdoors, in vehicles, under shade, or in direct sunlight. The weather stations measured air temperature and Wet-Bulb Globe Temperature (WBGT) a thermal stress indicator combining all four environmental factors (air temperature, humidity, wind velocity, and radiant heat). The WBGT is the most widely adopted thermal stress indicator and was recently found to be the most effective index for quantifying the physiological heat strain experienced by workers (15-17).

The collected environmental and task analysis data were used to develop two Workplace Environmental Labor Loss (WELL) functions based on WBGT and ambient temperature. For the development of the WELL functions, the work time loss (i.e., time allocated to non-work-related activities excluding breaks provided by management, such as the lunch break) for every degree of WBGT and ambient temperature was modelled using the task analysis and weather station data from our field studies. Specifically, the percent of work time loss was determined at each degree (rounded to the nearest integer) of WBGT and ambient temperature, for each individual worker. Thereafter, the average percent of work time loss for all workers across each WBGT and ambient temperature degree was calculated. Regression of means was used to determine the quantitative effect of ambient conditions on the capacity of workers to carry out their job. Based on previous recommendations (18), this technique was adopted to ensure that individual differences in how people response to heat or cold stress (14, 19, 20) would not result in underestimation or dismissal of the impacts of occupational heat or cold stress on the group performance. To generate the WELL functions, we used three degree (cubic) polynomial regressions [Numerical Python (NumPy) extension (21)], using the average percent of work time loss for each WBGT and ambient temperature degree. Using the same technique, we developed two additional models (upper and lower bounds) for each WELL function to describe inter-individual differences in work time lost among workers, using the associated 95% confidence intervals for each ambient temperature and WBGT degree. Upper and lower bounds were developed to make predictions for workers who are either more (upper) susceptible (e.g., unfit, obese, old, using protective clothing, performing more intense tasks) or less (lower) susceptible (e.g., fit, young, performing low-intensity tasks) to occupational heat stress. The level of statistical significance was set at $p < 0.05$.

Results

Through task analysis, we identified more than 50 different types of activities occurring with varying frequency throughout the work shift of the monitored workers. The majority of these activities were directly related to work, one activity involved a timed lunch break (on average ~40 minutes) administered by management (excluded from our analysis), and three activities involved unplanned breaks that were considered as lost work time (unplanned breaks: standing, sitting, and walking). It is important to note that the duration of the administered lunch break was not adjusted based on workplace temperature and was consistent throughout the year for each monitored worksite. Based on the task analysis performed, the average metabolic rate of the monitored workers was 153.3 ± 52.6 W/m^2 (289.9 ± 106.7 W; excluding the planned lunch break provided by the management), corresponding to moderate intensity work (22).

Data collection in the field studies occurred in environments between 0 and 36 °C WBGT (agriculture: 0 to 36 °C, construction: 19 to 36 °C, and tourism: 19 to 33 °C) or 0 and 44 °C ambient temperature (agriculture: 0 to 41 °C, construction: 21 to 44 °C, and tourism: 20 to 44 °C). The WELL functions for WBGT and ambient temperature are illustrated in Figures 1 and 2, respectively. They both reveal a U-shaped relationship whereby the least work time loss is observed at 16 °C WBGT or 18 °C ambient temperature. In these conditions, the average person works for 7.4 hours in an 8-hour shift (0.6 hours lost). However, this drops to only 4.0 hours (half of the shift lost) if the work shift is performed in a hot workplace (36 °C WBGT or 40 °C ambient temperature), or to 6.0 hours (2.0 hours lost) if the work is performed in a cold workplace (2 °C WBGT or 5 °C ambient temperature).

It is important to note that since the present study was conducted in real-life occupational settings, a certain amount of work time is always lost due to unplanned breaks for reasons other than temperature (Figure 1-2, right vertical axes). Therefore, to predict the true work time loss due to thermal conditions, the lowest point in each model is suggested to be subtracted from the estimate (Figure 1-2, left vertical axes). For the examples given in the previous paragraph, the 0.6 hours lost at 16 °C WBGT or 18 °C ambient temperature should be subtracted from the 4.0 hours lost at 40 °C ambient temperature or 36 °C WBGT, resulting in 3.4 hours lost due to hot workplace conditions. The six models developed (mean as well as upper and lower bounds, for WBGT and ambient temperature) explain 72 to 86% of the variance in the work time loss due to workplace heat and cold, all $p < 0.0001$. Further metrics regarding the robustness of the models are presented in the following subsections.

Wet-Bulb Globe Temperature (WBGT)

R^2 (Upper bound: 0.84; Mean: 0.86; Lower bound: 0.75, all $p < 0.0001$; mean absolute error (Upper bound: 5.2%; Mean: 4.6%; Lower bound: 4.0%); Mean bias error < 0.0001, for all models; Lowest point in each model (Upper bound: 18.2 °C, 9.4%; Mean: 15.6 °C, 8.0%; Lower bound: 4.4 °C, 0.3%):

Temperature-induced work time loss

$$\boldsymbol{Upper\ bound} = (57.166071 - 4.752305 \times \mathrm{WBGT} + 0.091365 \times WBGT^2 + 0.001403 \times WBGT^3) - 9.4 \quad (2a)$$

$$\boldsymbol{Mean} = (29.147402 - 2.584945 \times \mathrm{WBGT} + 0.072177 \times WBGT^2 + 0.000434 \times WBGT^3) - 8.0 \quad (2b)$$

$$\textbf{Lower bound} = (1.128733 - 0.417585 \times \text{WBGT} + 0.052989 \times WBGT^2 - 0.000535 \times WBGT^3) - 0.3 \quad (2c)$$

Total work time loss

$$\textbf{Upper bound} = 57.166071 - 4.752305 \times \text{WBGT} + 0.091365 \times WBGT^2 + 0.001403 \times WBGT^3 \quad (2d)$$

$$\textbf{Mean} = 29.147402 - 2.584945 \times \text{WBGT} + 0.072177 \times WBGT^2 + 0.000434 \times WBGT^3 \quad (2e)$$

$$\textbf{Lower bound} = 1.128733 - 0.417585 \times \text{WBGT} + 0.052989 \times WBGT^2 - 0.000535 \times WBGT^3 \quad (2f)$$

Ambient temperature (T_{air})

R^2 (Upper bound: 0.73; Mean: 0.82; Lower bound: 0.73, all $p < 0.0001$); Mean absolute error (Upper bound: 7.2%; Mean: 5.3%; Lower bound: 6.0%); Mean bias error < 0.0001, for all models; Lowest point in each model (Upper bound: 20.0 °C, 9.4%; Mean: 17.8 °C, 7.1%; Lower bound: 13.3 °C, 2.6%):

Temperature-induced work time loss

$$\textbf{Upper bound} = (68.127638 - 6.020764 \times \text{Tair} + 0.161794 \times \text{Tair}^2 - 0.000382 \times \text{Tair}^3) - 9.4 \quad (1a)$$

$$\textbf{Mean} = (42.385043 - 4.134546 \times \text{Tair} + 0.130371 \times \text{Tair}^2 - 0.000531 \times \text{Tair}^3) - 7.1 \quad (1b)$$

$$\textbf{\textit{Lower bound}} = (16.642447 - 2.248328 \times \text{Tair} + 0.098947 \times \text{Tair}^2 - 0.000679 \times \text{Tair}^3) - 2.6 \quad (1c)$$

<u>*Total work time loss*</u>

$$\textbf{\textit{Upper bound}} = 68.127638 - 6.020764 \times \text{Tair} + 0.161794 \times \text{Tair}^2 - 0.000382 \times \text{Tair}^3 \quad (1d)$$

$$\textbf{Mean} = 42.385043 - 4.134546 \times \text{Tair} + 0.130371 \times \text{Tair}^2 - 0.000531 \times \text{Tair}^3 \quad (1e)$$

$$\textbf{\textit{Lower bound}} = 16.642447 - 2.248328 \times \text{Tair} + 0.098947 \times \text{Tair}^2 - 0.000679 \times \text{Tair}^3 \quad (1f)$$

Discussion

A previous small-scale study showed that workplace temperature causes re-allocation of time during a work shift, whereby workers spend less time on work and more time on non-work-related activities, or vice versa (1). These initial results encouraged us to investigate the impact of workplace heat and cold on work time loss in different countries and occupational settings. We collected data across a wide range of thermal conditions (0-36 °C WBGT; 0-44 °C ambient temperature). The WELL functions for WBGT and ambient temperature provided a robust description of the impact of workplace heat and cold on work time loss. Also, they revealed a U-shaped relationship whereby the least work time loss is observed at 16 °C WBGT or 18 °C ambient temperature, and geometrically increases for every degree Celsius above or below this optimal point.

The method to assess the impact of workplace environmental conditions on work varies across industrial sectors (14, 23). Previous studies adopted metrics of productivity reflecting the total volume of output (e.g., goods produced) of multiple workers grouped together over an extended period of time (24, 25). But this approach to assessing productivity does not always address the way heat and cold affect working people. For example, measuring the total volume of output produced by workers does not provide the precision required to untangle the impacts of workplace heat and cold on labor, since this metric may be subject to factors other than temperature (1). It is a thought-provoking paradox and dangerous oversimplification to assume that a fisherman who ekes out a living by catching fish was not productive because he returned home empty-handed, although he spent the entire day working on a fishing boat. Drawing on this analogy, it is beyond any doubt that factors other than heat and cold, such as the availability of goods, usually play the most important role in the volume of goods produced and neglecting those factors may lead to erroneous conclusions.

Many studies report no associations between occupational heat stress and labor when defined by the volume of output produced (e.g., crops picked) (25-27). However, when researchers record the volume of crops picked by agricultural workers and simultaneously film them to examine the impacts of occupational heat stress on labor, the results often show the opposite (1). To clarify, while video recordings demonstrate that workers take multiple unplanned breaks, thus indicating significant impact of heat and cold on work time loss, these impacts are not reflected in the volume of crops harvested (1). For example, these differences often emerge when agricultural workers work in a high-yield piece of land on hot days, while choosing less fertile plots on days with environmental conditions optimal for labor. Of course, this is not always the case as often farmers work on less fertile fields during hot days, and this might exaggerate the negative impact of workplace heat on labor. At the same time, cherry-picking one or more studies that conveniently demonstrate significant impacts of heat or cold on labor, while ignoring others that do not, should not be endorsed. This is important as such practices introduce scientific bias and could potentially influence future heat-health policies (28). Measuring the total volume of output as a metric of labor is potentially ideal for studies evaluating the impacts of heat and cold on supply chain workers, particularly when products consistently pass along a conveyor belt for quality assessment. However, using the volume of output produced by a group of workers as a metric for labor in other settings may not yield reliable results. Thus, in contrast to the more traditional metric of labor which is based on the total volume of output produced over a set period of time, in the present study we adopted a metric that reflects the amount of time spent effectively doing work (1).

There are currently a few approaches to estimate the impact of workplace temperature on workability available in the literature. The approach of Bröde et al. (29), which is based on ISO 7243, suggests that labor starts being affected when WBGT rises beyond 27 °C and that almost no work can be performed above 32 °C WBGT. Similarly, the Hothaps method (30), another frequently used function to assess labor loss, was developed based on empirical data from two studies: the hourly group work output (number of rice bundles laid down by groups of workers) (24), as well as a study from the 1960s involving indigenous miners shoveling broken rock (8). The Hothaps method estimates negligible labor loss below 27 °C WBGT and rises geometrically thereafter, reaching 50% at 33.5 °C WBGT, starting to level off at 75% at 36 °C WBGT, and then reaching a plateau of 90% beyond 44 °C WBGT. Our WELL functions show that labor loss is minimum at 16 °C WBGT or 18 °C ambient temperature and increases in a U-shaped manner as heat or cold rise beyond this point. Additionally, the WELL functions show that a significant level of labor persists above 32 °C WBGT, contrasting with the ISO 7243 function which indicates no work above this level, and demonstrating significantly less impact of extreme heat on labor compared to the Hothaps approach. A potential reason for the marked differences in estimated labor loss among the ISO 7243, Hothaps, and our findings may be the original data that were used to derive the previous functions. Our study likely captures the early onset of labor loss in cooler environments because it is based on more recent data and adopted individualized second-by-second task analysis which can detect even the most negligible labor loss. In these recent data, workers had significantly more labor rights, including the right to rest, and access occupational health and safety support. This contrasts with the 1960s indigenous miners (8) that are the foundation of the previously published functions. Also, we believe the more pronounced impacts of workplace heat on labor loss estimated with the Hothaps function at high temperatures may be due to the regression model used by the authors, as the model extrapolates up to 44 °C WBGT without actual data for rice farmers above 32 °C WBGT and indigenous miners above 35 °C WBGT (30). However, it is essential to recognize that these functions were developed using the only data available at the time. They not only shed light on the effects of thermal conditions on labor but also served as the foundation for numerous international reports that helped to safeguard worker health and productivity worldwide.

Our findings are in line with a series of recent laboratory studies conducted within the framework of the HEAT-SHIELD project in Europe, showing that exponential reductions in physical work capacity (defined as *"the maximum physical work output that can be reasonably* *expected from an individual performing moderate to heavy work over an entire shift"*) emerge beyond 15 °C WBGT and increase exponentially thereafter (31, 32). Nevertheless, despite having a similar starting point for emerging impacts of temperature on labor, the findings of the present study indicate that the average worker shows less labor loss than expected based on their projected physical work capacity. For example, at 36 °C WBGT, physical work capacity is projected to drop by 65%, while the present field data show a work time loss around 42% for the average worker. Unsurprisingly, the 65% drop in physical work capacity at 36 °C WBGT observed in the aforementioned series of laboratory studies aligns closely with the 70% work time loss observed among more susceptible workers in the present study. This difference can be attributed to the fact that the physical work capacity model was developed based on non-acclimatized individuals, one of the most vulnerable groups of workers, which may have led to exaggerated estimates (32). This has significant implications for current and future labor productivity estimates, suggesting that researchers should be particularly careful when modeling climate change impacts, as different models were developed based on different populations to assess different labor metrics.

In a population of workers, some are more susceptible to physiological heat strain than others (14, 33). As thermal stress rises, the vulnerable workers are more likely to a face significant labor loss. In the present study, we created three levels of labor loss impacts to allow future studies to make predictions for workers who are more susceptible or less susceptible to occupational heat stress. The function calibrated based on the average worker will likely yield more accurate results for most workers, while the upper and lower bound functions will provide more accurate estimates for more or less vulnerable workers, respectively. Moreover, it is important to consider that since the WELL functions are based on experienced and acclimatized workers, it is logical to assume that projected work time loss will be higher for inexperienced and/or non-acclimatized workers. It is also important to note that the WELL functions as well as all previous labor loss functions primarily address the direct effects of workplace temperature on labor, often neglecting other extreme weather phenomena such as heatwaves. Another limitation of our study, as in all other previous field studies assessing labor metrics, is that the measurements were conducted among individuals who work consecutively for multiple days (particularly during the harvest season where fruits have to be picked quickly before they rot). This is known to have significant impacts on thermoregulatory function (34) and may potentially affect labor capacity. Additionally, increased work time loss was observed more during the hot and cold seasons across the different sectors monitored. However, it is important to note that in the tourism and construction industries, we could not monitor worksites with very cold conditions, primarily because these industries are less active during the cold seasons of the year, or workers tend to work indoors or in vehicles in the countries assessed. The reader should also consider that, in contrast to previous efforts, the WELL functions were developed using data from multiple countries and ethnicities to better describe the impacts of workplace temperature on different geographical regions and modern worksites, where people with diverse backgrounds and habits work on the same tasks. However, it is important to acknowledge that societal and cultural differences may influence the physiological strain experienced by workers in varying ways (14), as well as that multicultural worksites can affect the physiological strain experienced by different ethnic groups differently (35). In addition to the above, since no standard mandatory clothing ensemble was required at the monitored worksites, workers could adjust their clothing for optimal thermal comfort (36-38). Protective helmets, boots, and gloves were mandatory in some of the monitored worksites; however, there was still a degree of freedom in clothing choices (e.g., t-shirt to multilayered jacket) and thus it was assumed that all workers adjusted their clothing to the best of their ability to optimize thermal comfort. Nevertheless, despite the above limitations, the models provided in this study are based on real-world scenarios that account for current work practices and should, therefore, be considered representative of the present state. Of course, as technology progresses and mechanization becomes more widespread, our understanding of the relationship between thermal conditions and work time loss will need recalibration.

Concluding Remarks

We conclude that the developed WELL functions can accurately quantify the impact of workplace heat and cold on work time loss. Also, the present findings suggest a re-thinking of how workplace temperature affects work time loss. We show that work time loss due to workplace heat and cold is less extreme than what previously thought, but much more widespread, extending to thermal conditions that were previously thought to be unaffected. In other words, while it was previously believed that thermal conditions were a problem only in very hot workplaces or countries, our findings demonstrate that work time loss can occur even at temperate environments. This has significant implications for current and future climate change policies, because it suggests that billions of people are currently working in temperatures not optimal for work, but this goes unnoticed. Our findings suggest the adoption of the WELL functions for current and future modeling of workplace heat and cold on the capacity of workers to effectively carry out their job duties and tasks.

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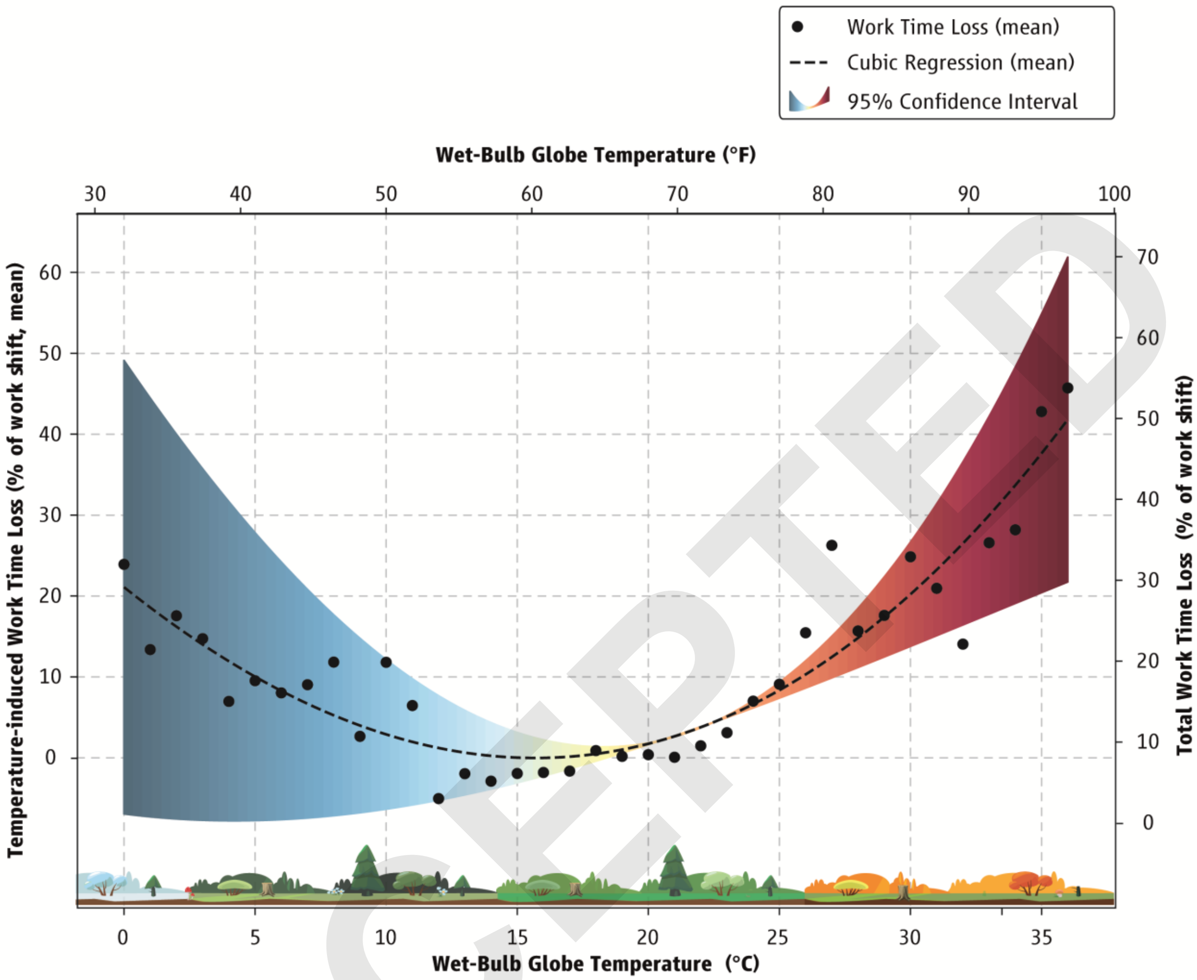
Figure Legends

Figure 1. The Workplace Environmental Labor Loss (WELL) function describing the changes in work time loss (percent of time allocated to non-work-related tasks) for every degree of workplace Wet-Bulb Globe Temperature. Circles indicate mean of work time loss for every degree in the horizontal axis. Shaded areas represent 95% confidence interval for the inter-individual (between workers) variance in recorded work time loss.

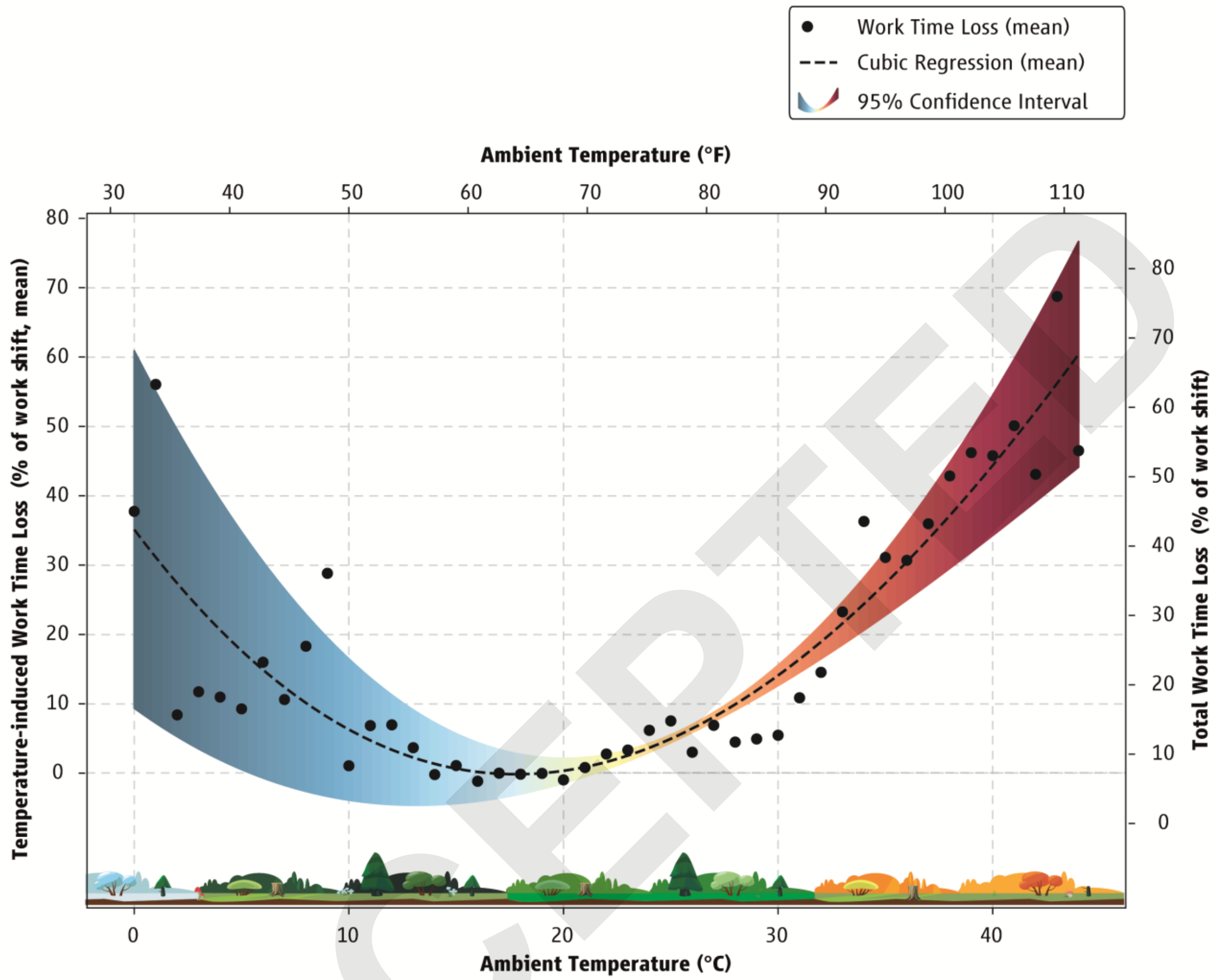
Figure 2. The Workplace Environmental Labor Loss (WELL) function describing the changes in work time loss (percent of time allocated to non-work-related tasks) for every degree of workplace ambient temperature. Circles indicate mean of work time loss lost for every degree in the horizontal axis. Shaded areas represent 95% confidence interval for the inter-individual (between workers) variance in recorded work time loss.

Figure 1



Work Time Loss (mean)
Cubic Regression (mean)
95% Confidence Interval
Wet-Bulb Globe Temperature (°F)
30
40
50
60
70
80
90
100
Temperature-induced Work Time Loss (% of work shift, mean)
60
50
40
30
20
10
0
Total Work Time Loss (% of work shift)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Wet-Bulb Globe Temperature (°C)

Figure 2



Work Time Loss (mean)
Cubic Regression (mean)
95% Confidence Interval
Ambient Temperature (°F)
30
40
50
60
70
80
90
100
110
Temperature-induced Work Time Loss (% of work shift, mean)
80
70
60
50
40
30
20
10
0
Total Work Time Loss (% of work shift)
80
70
60
50
40
30
20
10
0
0
10
20
30
40
Ambient Temperature (°C)

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	Title page; 1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	Title page; 1
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	2-3
Objectives	3	State specific objectives, including any prespecified hypotheses	2-3
Methods			
Study design	4	Present key elements of study design early in the paper	3
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	3-5
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	3-4
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	N/A
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	5-6
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	*5-6*
Bias	9	Describe any efforts to address potential sources of	5

		bias	
Study size	10	Explain how the study size was arrived at	3-4
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	N/A
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	6-7
		(*b*) Describe any methods used to examine subgroups and interactions	N/A
		(*c*) Explain how missing data were addressed	N/A
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	N/A
		(*e*) Describe any sensitivity analyses	N/A

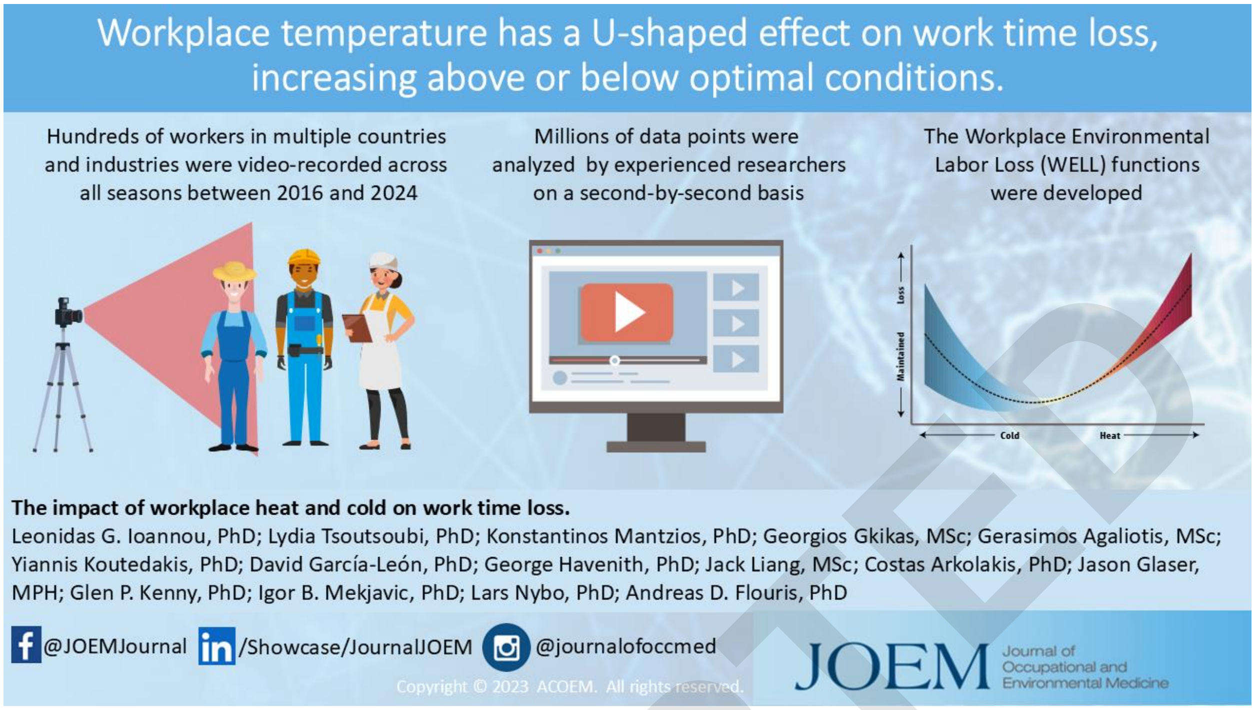
Results

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	3-4
		(b) Give reasons for non-participation at each stage	N/A
		(c) Consider use of a flow diagram	N/A
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	4
		(b) Indicate number of participants with missing data for each variable of interest	4
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	N/A
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	*N/A*
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	*N/A*
		Cross-sectional study—Report numbers of outcome events or summary measures	*4*
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	N/A
		(*b*) Report category boundaries when continuous variables were categorized	N/A

		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	N/A
Discussion			
Key results	18	Summarise key results with reference to study objectives	11-12
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	15-16
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	15-16
Generalisability	21	Discuss the generalisability (external validity) of the study results	15-16
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Title page; 1

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.



Workplace temperature has a U-shaped effect on work time loss, increasing above or below optimal conditions.
Hundreds of workers in multiple countries and industries were video-recorded across all seasons between 2016 and 2024
Millions of data points were analyzed by experienced researchers on a second-by-second basis
The Workplace Environmental Labor Loss (WELL) functions were developed
Loss
Maintained
Cold
Heat
The impact of workplace heat and cold on work time loss.
Leonidas G. Ioannou, PhD; Lydia Tsoutsoubi, PhD; Konstantinos Mantzios, PhD; Georgios Gkikas, MSc; Gerasimos Agaliotis, MSc; Yiannis Koutedakis, PhD; David García-León, PhD; George Havenith, PhD; Jack Liang, MSc; Costas Arkolakis, PhD; Jason Glaser, MPH; Glen P. Kenny, PhD; Igor B. Mekjavic, PhD; Lars Nybo, PhD; Andreas D. Flouris, PhD
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