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TECHNICAL REPORT

D3.3: Report on solutions to mitigate heat stress for workers of the manufacturing sector

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Summary

In this report, strategies and technologies are screened for their potential to predict heat issues and mitigate the negative effects of occupational heat stress during heat waves, thereby maintaining workers' health and well-being, and productivity. The present paper focus specifically on heat stress in the manufacturing sector while we refer to the parallel papers for industry specific issues in agriculture, tourism, transport and construction.

Considering that workers in the manufacturing industry mainly work indoors (and in settings where industrial heat may interfere with the environmental factors of importance) a first step in providing timely alert (and associated advice systems) was developing a model that would allow for prediction of the actual indoor heat stress based on weather forecasts.

The thermal conditions may vary a lot across workstations (even within one manufacturing plant) and for assessment of the individual heat load, it is suggested that a network of temperature and relative humidity sensors are installed in critical regions of the manufacturing process. The effect of the external environment on the internal/individual work conditions can then be analysed and used to train a neural network model to accurately predict heat stress, based on short-range weather forecasts. Such a tool can serve as an early warning system capable of predicting the effect of impending heat waves on the health and well-being of workers, and ability to perform work.

Another approach is assessment of the effect of the internal factory conditions on the mood and well-being of the workers, particularly during heat wave episodes. This may be obtained via feedback-systems e.g. touch sensitive screens can be placed at strategic locations in the factory, allowing the workers to provide ratings of their perception of temperature, humidity, thermal comfort and fatigue. This information provides instantaneous information regarding workers' heat strain, and can also be used for advanced analyses (utilizing the neural network) and provide predictions of thermal comfort and heat strain during heat waves.

The thermal stress and comfort of a larger population of workers can also be represented by a humanoid thermal robot/manikin. Its humanoid structure ensures that the heat exchange between the environment and the robot/manikin will simulate that between a human body and the ambient air. Its core and shell is embedded with thermal sensors, mimicking the manner in which the body perceives its thermal status. The essential component is the mathematical model of thermal comfort based on the neurophysiology of temperature perception. The model receives temperature information from the core and shell regions and provides a rating of thermal comfort.

During the course of the Heat Shield project, we implemented several heat stress mitigating strategies within a manufacturing plant producing automobile rear lights as well as tested selected interventions in an aluminium extrusion company. Combining these experiences with a systematic evaluation of methods and considering their feasibility (for industry specific settings) the following strategies are recommended:

• <u>Increased air flow – either at local workstations or via general ventilation of the production hall</u>: A system of ducts can be installed within a production hall establishing an acceptable air flow in the plant (that may be individually adjusted at the local work stations – alternatively individual workers may use an electrical fan in proximity to their work station). This will enhance/benefit evaporative heat loss and convective (as long as the air temperature is below ~35 °C).

• <u>Optimize hydration strategies</u>: The prevalence of dehydrated workers is in general high (also in the manufacturing industry) – securing easy access to unlimited amounts of cooled water and reminders to rehydrate following work is of utmost importance.

• <u>Breaks and pacing</u>: Workers will eventually slow down or take more infrequent breaks, if the heat load is too high - including brief planned breaks (preferably in cool areas of the plant) or allowing a small lowering of the pace (especially at the onset of a heat wave) may prevent excessive loss of working time later in the day or "post heat wave fatigue" (observed to be as big an issue as the effect during the actual heat wave).

• <u>After work – day to day recovery</u>: During heat waves workers should be encouraged to rehydrate (considering both replacement of water and salt deficits) and spend time in cool environments to allow/contribute to the recovery from the heat stress experienced at work.

• <u>Clothing</u>: Workers should be provided with and/or encouraged to wear clothing with low thermal and evaporative resistance. Many settings require that workers wear protective clothing (which may increase the individual heat strain), but it is possible to implement solutions (ventilation mesh or use more breathable materials for certain parts) without compromising safety (the protective requirements and effects of the

clothing). For critical (hot) areas of the manufacturing process, workers may be provided with ventilated/evaporated vests for enhanced evaporative heat loss. In the event that the company is providing workers with any component of their clothing ensemble, then it would be prudent for the company to have these garment components tested with appropriate thermal manikins, thus ensuring that they are issuing workers with appropriate garment components. In a hot environment, the garments should have low thermal resistance (ie. low insulation), and allow optimal evaporation of sweat from the skin. Clothing design should also allow efficient exchange of the air within the clothing microenvironment.

1. Background

1.1 It is quite clear that occupational heat stress can negatively affect workers' health and their capacity to perform work. This may cause a decrease in productivity, and as a consequence, a reduction in income for the individual and/or company. This decreased income can be directly related to losses of working efficiency or indirectly to illness. The present report is part of a series of five industry specific reports, each one dealing with a key European industrial sector (manufacturing, construction, transportation, tourism and agriculture). Overall the reports focus 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.

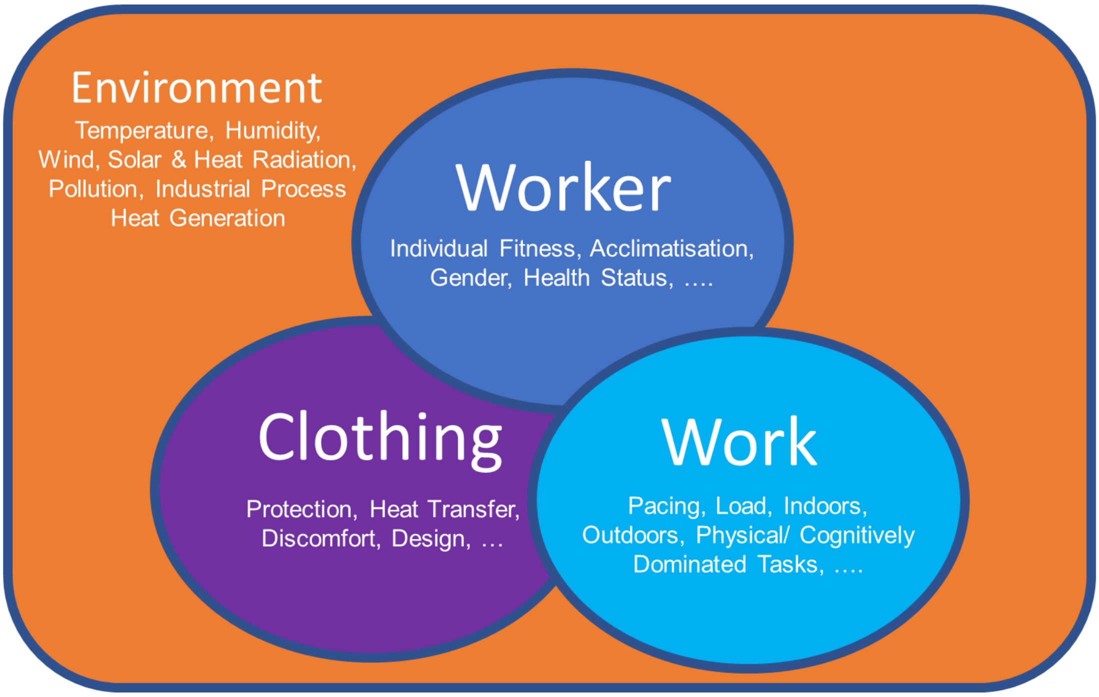

Figure 1: Overview of occupational aspects of human heat balance

Optimal 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 released will increase in proportion to the work intensity and hence increased heat production in the body. Impairment of heat loss from the body will result in an increased storage of heat within the body tissues, resulting in increased body temperature, and concomitant heat strain, and impairment of both physical and cognitive function. Excessive heat strain may provoke fatal overheating. To keep workers safe and maintain their work capacity, the produced heat must be balanced by heat lost from the body (skin) to the environment. This heat loss can be achieved by dry heat loss (primarily air convection and radiation) and/or by the evaporation of sweat from the skin surface. In occupational settings, in addition to climatic factors (air temperature, solar radiation, humidity and wind speed), the environment surrounding a specific work place may also be highly influenced by the industrial settings. In such conditions, heat balance of the worker will depend on a multitude of thermal and nonthermal factors (see Fig. 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.

When considering solutions to lower heat stress, any practice that may either lower workers internal heat production (e.g. optimizing the work procedures), 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 will consider the specific solutions screened and identified as both effective and feasible to implement for workers in the industrial sector.

1.2 This report on solutions for the manufacturing sector focuses on the industry specific issues, needs and exposure characteristics of workers from the manufacturing sector in order to identify ways to mitigate the corresponding heat stress. The focus is in suggesting tools that allow adaptation measures, including the development of a neural network for predicting environmental heat stress and heat strain of the workers, based on forecasted weather conditions. While assessing the capacity and potential of these measures to mitigate workers' heat stress, the report will also focus special attention on determining the specific requirements of the proposed solutions, and their compatibility with the intended application environment.

2. Industry specific issues for manufacturing workers- Identification of the problem

2.1 The aim of task 3: To identify ways of mitigating the heat wave-induced heat stress in the manufacturing sector. In order to accomplish this, several approaches were considered. We focused on predicting the anticipated effect of forecasted local weather conditions on the heat stress, and providing management and workers with an early warning system, which would allow timely implementation of interventions that would be suitable for a specific manufacturing plant (see Appendix 1). In addition, we investigated several specific interventions that could be implemented in the manufacturing sector, such as ventilated vests and heat acclimatization.

2.2 Local weather conditions: National meteorological services establish a weather forecast system based to a large degree on a network of meteorological stations. These stations are not necessarily in close proximity of industrial plants, and the local weather conditions might be different from the prevailing regional weather conditions (left side of Fig. 2). <u>It is necessary to establish a weather station in the vicinity of the industrial plant, and to develop an algorithm that bridges the gap between the closest meteorological station and the local conditions at the industrial plant (section 3).</u>

2.3 Factory conditions: The conditions within a factory may be affected by the external environmental conditions. <u>It is necessary to quantify the effect of external temperature on the conditions within the factory, and to assess how they affect workers' well-being and productivity (section 4).</u>

2.4 Heat strain and thermal discomfort of the workers: Ambient conditions within a factory will contribute to heat strain and thermal discomfort, both influencing the health and well-being of the workers, and ultimately their productivity. <u>To determine the effect of factory conditions on heat strain, it is necessary to establish a monitoring system, that will establish the relation between ambient conditions and heat strain in a given manufacturing setting.</u>

2.5 Productivity: The manner in which productivity is quantified differs among industries. In the manufacturing industry, such as odelo d.o.o., calculations of productivity are made for each shift, and are based on an algorithm, that takes into consideration multiple factors. <u>The quantification of productivity is essential to be able to assess the benefit of any heat stress mitigation strategy on productivity.</u>

2.6 Humanoid robot/manikin: The workforce in any manufacturing industry will comprise workers of both genders, and ranging in age. They may also have a range of health conditions. Prediction of heat strain among such a workforce must consider both thermal and nonthermal factors influencing the development of heat strain. For this purpose a neurophysiological model of thermal comfort was developed and embedded in a humanoid robot/manikin. <u>A humanoid thermal robot/manikin embedded with such a thermal comfort model can provide predictions of thermal (dis)comfort based on the prevailing conditions, and alert workers and management of the presence of excessive heat strain.</u>

2.7 Neural network: For a given factory situation, a neural network can be trained to predict workers' (dis)comfort based on the weather forecast. <u>Information of external and internal (within a factory) temperature and humidity, and productivity can be used to train a neural network model to predict occupational heat stress based on weather forecasts.</u>

2.8 Heat strain mitigating interventions: Appendix 1 provides a list of strategies that have been considered to prevent heat strain. <u>In critical areas of a manufacturing process, ventilated/evaporative vests</u>

can enhance evaporative heat loss, assuming that the ambient conditions are such that sweating is initiated.

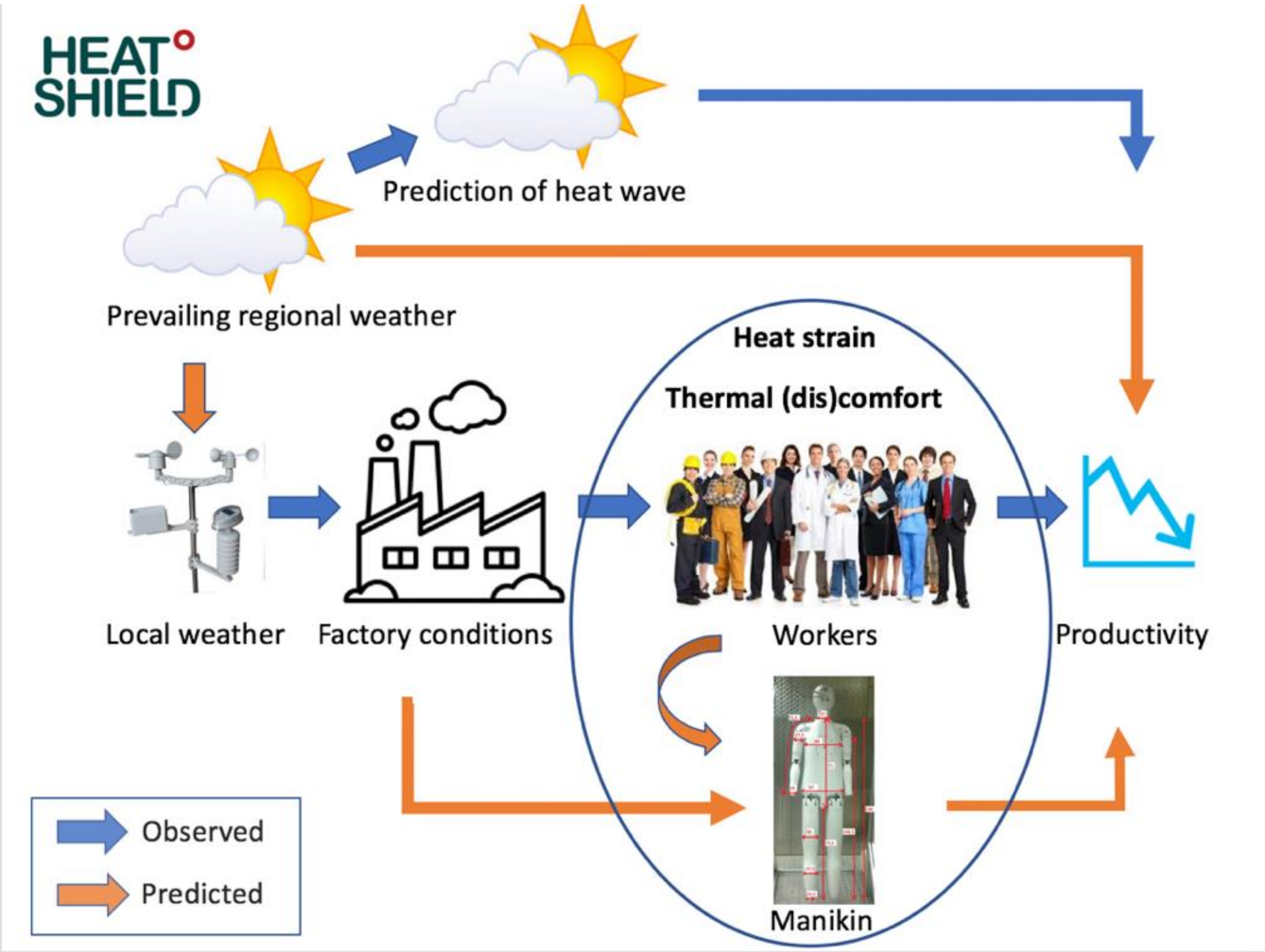

Figure 2: Research approach in developing the Heat Shield worker heat stress monitoring system capable of predicting the effect of forecasted heat waves on productivity. See text for detailed information.

3. Climate change affects summer hot days and occupational heat stress in the manufacturing industry: implications for workers' well-being

Aim

3.1 We assessed present climate conditions and examined future climate change projections in Slovenia, focussing on the local climate conditions in the region of the odelo d.o.o. manufacturing plant (Prebold, Slovenia). The study also surveyed the workers in the odelo d.o.o. manufacturing plant regarding their perception of the summer heat waves, particularly on how they were affected by summer 2016 heat waves.

Methods

3.2 Mean and extreme heat conditions were analysed from daily mean (Tmean) and maximum (Tmax) temperatures available from the Slovene Environmental Agency. Data from 60 weather stations were used to build a gridded map based on the homogenized time series of daily means and maxima to account for past heat conditions. The horizontal resolution of the grid was 1x1 km, which accounted for 20916 points over the entire region of Slovenia. A set of 16 point stations well-distributed across Slovenia were considered for the climate change projections, with special focus on six locations (Fig.1c): Bilje (55 m above sea level (a.s.l.), Ljubljana (299 m a.s.l.), Celje (244 m a.s.l.), Murska Sobota (188 m a.s.l.), Novo mesto (220 m a.s.l.), and Postojna (533 m a.s.l.). For more details on the climate projections, the reader is referred to Heat Shield deliverable D.1.2.

3.3 Summer temperature conditions in Slovenia can be described with distribution maps of different summer temperature indices. Mean summer (June-August: TmeanJJA) temperature, monthly mean of the daily maximum temperature of the hottest month (July: TmaxJUL), and long-term trends of both previous variables were the key variables chosen for this purpose (Kozjek et al. 2017a; Kozjek et al. 2017b). Additionally, we also used the number of hot days (HD), defined as the number of summer days with daily maximum temperatures above 30°C, in accordance with climatological practice (e.g. Kysely 2010). The 30-yr (1981–2010) averages of TmeanJJA, TmaxJUL and HD were considered as the final indices, whereas their trends trTmeanJJA, trTmaxJUL, and trHD were obtained from the 51-year period 1961-2011 using the Theil-Sen method (Theil 1950; Sen 1968). This non-standard 51-year time period was used since it was assigned in the project “Climate variability of Slovenia” (Vertačnik et al. 2015).

Results

3.4 Climate change projections of temperature and heat stress indices were produced for the Slovene locations, obtaining the climate change signal as the difference between the projections for the period 2070–2099 with respect to 1981–2010. An ensemble of state-of-the-art regional climate models was used to produce the projections, spanning three different emission scenarios (see the Heat Shield deliverable 1.2. and references therein). All indices are projected to increase in Slovenia by the end of the 21st century and the increments vary nonlinearly with the forcing scenario (Fig.3). For instance, changes in summer mean (TmeanJJA) and July daily maximum (TmaxJUL) range from 1°C for the lower emission scenario (RCP 2.6) to 4.5°C for the highest emission scenario (RCP 8.5) in all Slovene stations. The number of hot days (HD) might increase on average 2-10 summer days under RCP 2.6 and up to 35 days under the highest emission scenario. HD changes present a larger spatial variability than the other temperature indices; they are larger in the stations with the highest TmaxJUL in present climate.

3.5 Similarly to temperature extremes, summer mean and maximum heat stress (quantified by the wet bulb globe temperature, WBGT, see the Heat-Shield deliverable D.1.1 and references therein) are projected to increase from 1 to 3.5°C depending on the emission scenario in all Slovene stations. The frequency of extreme heat stress (number of days with WBGT above 27°C, WBGTg27) will be accentuated in the locations where the frequency of HD largely increases, increasing up to 20 days in the stations in the center of the country and more than 30 days in Bilje under the strongest emission scenario. Despite the model uncertainty in the climate change signal, there is overall good agreement in the mentioned changes. Model uncertainty is quite similar across all stations for summer mean temperature and heat stress. In Bilje the uncertainty in the number of days with extreme heat stress (WBGTg27) is especially large, ranging from 10 to 50 days for RCP 8.5. It is interesting to see that, even under the low (RCP2.6) and moderate (RCP4.5) emission scenarios, important increases may occur in the number of hot days and high heat stress risk due to the warmer and humid conditions in the Sub-Mediterranean climate region.

3.6 Concomitant with the analysis of the conditions in the factory during the summer of 2016, we also surveyed the workers regarding their perception of the temperature at the workplace during heat waves. Temperature conditions were suitable for less than 4% of those completing the survey. For the majority, it was warm, hot or very hot. There was a statistically significant difference ($p < 0.001$) in the number of women compared to men, that perceived the working conditions as 'very hot', suggesting that females had a higher sensitivity to the hot conditions. Working clothes were very comfortable for less than 10% of employees, with the majority of workers reporting clothing comfort between comfortable and uncomfortable. There was no significant difference between the males and females. For about 20% of the workers, the clothes were not comfortable at all.

3.7 All acknowledged that heat stress can cause heat strain symptoms leading to heat-induced illness if the problem is not resolved, which may ultimately have fatal consequences. Since becoming operational in 2005, there has only been one incident of heat stroke in odelo d.o.o., and 13 incidences of heat-induced health problems that required hospitalisation. Thirst and excessive sweating are the first signs of hot ambient conditions, reported by men (> 70%) and women (> 80%) in the factory (differences between males and females was not significant). Tiredness ($p < 0.001$), confusion ($p < 0.001$), and dizziness ($p < 0.05$) are more commonly perceived by women (81, 19, and 39%, respectively) than men (56, 12, and 9%, respectively). Enhanced stress due to heat is experienced by 28% of men and 29% of women.

3.8 Gender differences are also evident among the reported heat-induced health problems; 39% of the male workers did not report any health problems, whereas 37% were affected by a headache and 47% by exhaustion. These percentages were much higher for female workers, with 73% ($p < 0.001$) and 64% ($p < 0.01$), respectively. Furthermore, 33% of the women experienced nausea or vomiting ($p < 0.001$) and 16% prickly heat ($p < 0.01$), while only 6% of the male group reported the occurrence of these symptoms. There were also cases of muscle cramps and fainting in both gender groups and also cases of heat cramps and heat stroke in the female group.

Discussion

3.9 There has been no 30-yr period on record with mean average European Summer temperatures as high as observed in the last 3 decades (Luterbacher et al., 2016), and Slovenia is not an exception. According to Kysely (Kyselý, 2010), the probability of occurrence of very long heat waves has risen by an order of magnitude over the recent 25 years and is likely to increase by another order of magnitude by around 2040 assuming the moderate scenario (RCP4.5) summer warming rate. As for middle and southern Europe (Thorsson et al., 2017), heat-stress related problems among the population are expected to increase as a result of climate change. Thus, the mitigation and adaptation to extreme temperature events and heat stress are of vital importance for humans during their daily activities (Basarin, Lukić, & Matzarakis, 2016).

3.10 More sophisticated climate prediction models are required to be able to translate the anticipated external conditions to the conditions within a factory. Unfortunately, this is not straightforward (Gao, Kuklane, Östergren, & Kjellstrom, 2018). Undoubtedly, external meteorological parameters impact on the conditions within a workplace, but it will depend on the heat being generated by the production process within the factory, and the efficacy of any cooling or ventilation system installed within the factory. As a result, it is recommended to use the WBGT index or monitor air temperature and humidity at workplaces. It is well established that work capacity substantially diminishes once WBGT exceeds 26°C (Kjellstrom, Holmer, & Lemke, 2009). Thus, the WBGT index allows the determination of the work/rest cycle based on the ambient conditions within the factory. Spector and Sheffield (Spector & Sheffield, 2014) describe the WBGT index as a relatively straightforward and acceptable heat stress index, which should be considered as the foundation for the development of any future heat stress assessments (ISO, 2017). Unfortunately, the WBGT index does not account for the level of an individual's activity and the clothing worn, since it is based solely on meteorological parameters (e.g. temperature, humidity, wind, and radiation). However, it can be adjusted to include factors that play an important role in heat stress (Budd, 2008; ISO, 2017). Fischer and Knutti (Fischer & Knutti, 2015) found that the probability of a hot extreme at 2°C warming is almost double than at 1.5°C in a climate change context and more than five times higher than present-day climate. The increases of WBGT projected for Europe as a result of climate change are expected in many other regions of the world (USA, Australia, India, Carribean) and are more predictable than increases in temperature at least in mid-latitude regions owing to the compensating effects of humidity (Casanueva et al., 2018; Sherwood & Huber, 2010).

3.11 The survey conducted at odelo d.o.o. demonstrates that basic symptoms of heat stress are very common during summer and gradually progress to more serious forms, such as confusion, dizziness, enhanced stress. These can cause accidents at work, but attention should also be focused on heat-induced health problems. Our survey at the odelo factory revealed that 56% of the workers experienced headache and exhaustion, which is already a bad prognosis for future and warmer conditions. The incidences of nausea, prickly heat, muscle and heat cramps, fainting and even heat stroke can be reduced or prevented by implementing different solutions, appropriate for the company and their working environment. In order to protect the workers from the effects of heat, some general guidelines should be followed (OSHA, 2017). They include: scheduling activities during cooler times of the day; providing air-conditioning areas close to the work area; train workers about the hazards leading to heat stress and ways to prevent them; allow workers to get used to hot environments by gradually increasing exposure over a 5-day work period; provide workers with plenty of cool water in convenient, visible locations close to the work area; remind workers to frequently drink small amounts of water before they become thirsty to maintain good hydration, but also inform them it is harmful to drink extreme amounts of water; reduce the physical demands of the job (excessive lifting, climbing, digging); monitor weather reports daily; schedule frequent rest periods with water breaks in air-conditioned areas; be aware that workers wearing personal protective equipment are at greater risk from heat stress. These guidelines, however, need further evaluation and case-specific assessment.

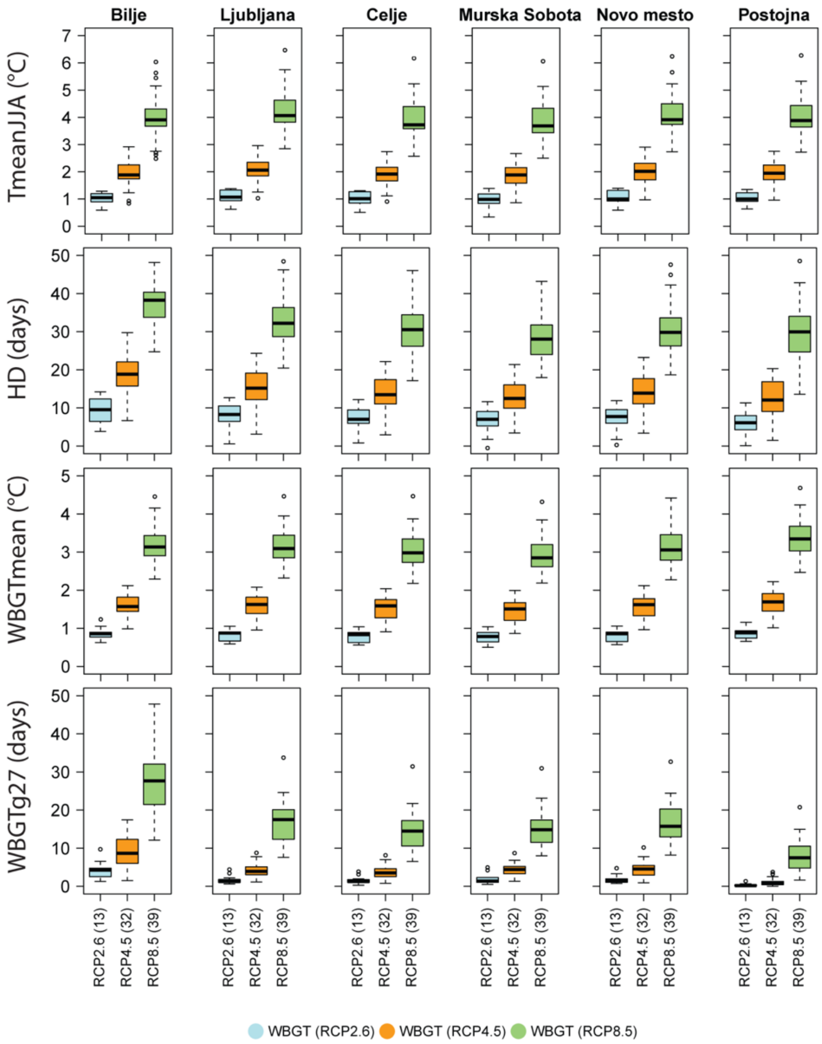

Figure 3: Climate change signal for some temperature- and WBGT-derived indices (rows) for six Slovene stations (columns). The boxes show the full uncertainty range across models for each emission scenario (RCP). The number of RCM simulations contributing to the model ensemble is depicted in brackets.

4. Hot days affect manufacturing productivity (Overall Equipment Effectiveness) in an automobile-parts plant

4.1 Cachon et al. (Cachon, Gallino, & Olivares, 2012) assessed the automobile assembly productivity during severe weather conditions over a 10-year period, including 64 U.S. vehicle assembly plants. They concluded that high temperatures, among other severe weather conditions, reduce production and that in such conditions the existing cooling systems cannot maintain the indoor temperatures below 25°C. In such conditions, the production is not likely to recover in one week, but most likely at some later date. Similarly, Sudarshan and Tewary (2014) observed decreases in manufacturing output at high temperatures (1-3% drop per one degree Celsius), which were significant and exhibited a nonlinear relation to temperature.

Aim

4.2 The aim of the present study was to evaluate the impact of the indoor and outdoor temperatures on productivity in local Slovene company producing automobile rear lights during the summer of 2017. Specifically, how the temperature during documented heat waves would correlate with productivity in workers, performing moderate intensity work in warm to hot, but not extreme ambient conditions, wearing normal clothing (T-shirt and trousers).

Methods

4.3 We conducted the study at the odelo d.o.o. manufacturing plant, and a heat wave was defined as a spell of at least three consecutive days with average daily air temperature equal to or exceeding 24°C (Slovene Meteorological Society). This definition, considered for continental climate, is used for central, northeast and southeast part of Slovenia. For the purpose of the present study it was used to determine a heat wave in the analysis and interpretation of the indoor and outdoor temperature measurements. Data regarding productivity was provided by the company and is expressed as percentage with the average value for each shift (morning, afternoon and evening) throughout the day. This will allow to observe any potential productivity differences between the work shifts.

4.3 Indoor and outdoor temperatures were monitored within the manufacturing plant during the summer 2017 with four documented heat waves, defined as spells of at least three consecutive days with average daily air temperature equal to or exceeding 24°C:

- HW1: from 20th to 24th of June
- HW2: from 6th to 11th of July
- HW3: from 20th to 23th of July
- HW4: from 31th of July to 5th of August

The beginning of the Spring season in early May was considered a baseline period of measurements for indoor and outdoor temperatures. The company provided data regarding productivity for these periods, separately for each of the three shifts – morning, afternoon and night shift.

4.4 Outdoor temperatures (°C)
Outdoor average daily temperatures were lower in May (14.3±2.8°C), compared to the summer months (22.8±4.9°C, p<0.001). During all HWs the measured temperatures were higher, compared to those measured before and after each HW (Table 1). In the 3rd and 4th HWs the differences were also reported between the pre- and post-HW temperatures, with higher temperatures measured before and lower after the HW. The analysis indicated that lower outdoor temperatures were measured during the 2nd HW (24.8±4.5°C), compared to the 4th HW (26.6±4.7°C, p=0.005). Outdoor mean temperatures differed between all three shifts, with the lowest temperatures measured during night and the highest in the afternoon (morning shift: 23.4±3.7°C, afternoon shift: 26.0±4.5°C, night shift: 17.6±3.5°C, p<0.001).

4.5 Indoor temperatures (°C)
Comparison between the Spring (29.0±0.8°C) and Summer (31.5±1.9°C) seasons indicated no difference in measured temperature within the factory (p=0.07). Indoor temperatures were higher during all HWs, compared to the temperatures measured before and after HWs (Table 1). During the 3rd HW, pre-HW temperatures were higher (30.7±1.2°C), compared to those measured post-HW (29.4±0.8°C, p=0.004). The indoor temperatures were lower during the 3rd HW (32.3±1.3°C), compared to the 1st (33.0±1.4°C, p=0.021) and 4th HW (33.1±1.6°C, p=0.019). They were lower during night shift (29.9±1.5°C, p<0.001) when compared to temperatures measured during the morning (31.8±1.6°C) and afternoon shift (32.2±1.9°C).

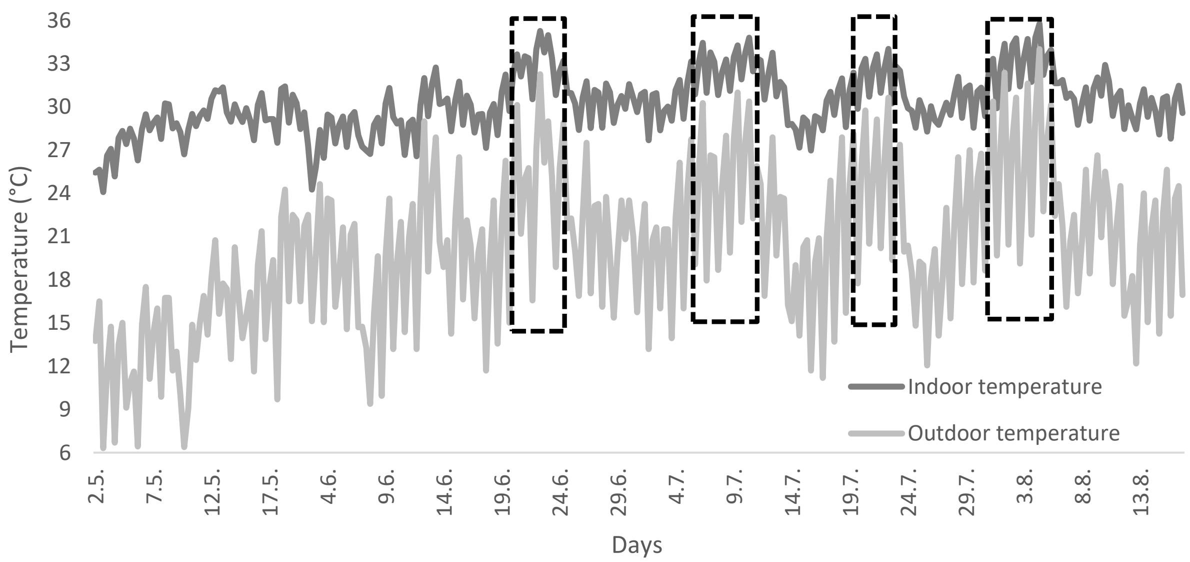

Figure 4. Average indoor and outdoor temperatures per shift (8-hr) during spring and summer 2017, with four documented heat waves (indicated by interrupted line)

4.6 Productivity

Irrespective of the outdoor temperature differences between the Spring and Summer months, the productivity was not affected by seasons, with similar productivity measured during spring and summer (Table 1). The only exception was the productivity measured after the 4th HW (69±9%), which was significantly lower to the one measured in May (82±6%, p=0.031). Productivity was also maintained during each of the four documented HWs, but dropped significantly after the 2nd and the 4th HWs were completed. The drop in productivity was therefore observed after the HW. During the 2nd HW (84±7%) productivity was significantly better compared to productivity measured during the 3rd (81±7%) and the 4th HW (79±8%). Irrespective of the indoor and outdoor temperature differences between the three shifts (morning, afternoon, night) no difference in productivity between the shifts was reported throughout the summer (morning shift: 78±8%, afternoon shift: 80±9%, night shift: 79±9%, p>0.05).

Table 1. Indoor and outdoor temperature (°C) and productivity (%)

	Indoor temperature	SD	Outdoor temperature	SD	Productivity*	SD
May	29,0	0,8	14,3	2,8	81,5	6,3
Pre HW1	29,7	1,5	19,2	4,9	70,2	11,7
HW1	33,0	1,4	25,2	4,2	85,1	9,0
Post HW1	30,1	1,3	21,0	3,8	78,8	9,2
Pre HW2	30,7	1,4	21,4	4,5	78,1	6,0
HW2	32,8	1,3	24,8	4,5	84,0	7,5
Post HW2	30,3	2,2	20,2	4,6	77,7	3,7
Pre HW3	30,7	1,2	21,9	5,2	76,2	3,2
HW3	32,3	1,3	25,1	4,1	80,5	7,4
Post HW3	29,4	0,8	17,4	3,0	80,3	7,7
Pre HW4	30,6	1,2	22,7	3,9	76,4	8,6
HW4	33,1	1,6	26,6	4,7	78,6	8,0
Post HW4	30,6	1,1	20,8	3,2	68,7	9,4

HW: heat wave; Pre: three days before heat wave, Post: three days after heat wave
*Productivity is expressed in %, with the company aiming at 82% productivity

Discussion

4.7 The main finding of the present study is that that the varying outdoor and indoor temperatures did not affect the productivity between the shifts (morning, afternoon and night shift). Two out of four documented HWs in the Summer of 2017 indicated a drop in productivity after the HW was completed, whereas during the actual HW the productivity did not change significantly.

4.8 Due to a constant exposure to warm ambient temperature (31.5±1.9°C) at work, with minor temperature fluctuations, workers seem to be well adapted to the ambient temperatures, reflected in the stable productivity values with no differences between different shifts. As long as the workers are able to recover after work by being exposed to normal ambient temperatures at home, productivity does not seem to be affected. The productivity however can be affected after a longer period of heat exposure, when workers cannot recover properly after leaving work. Prolonged exposure to high ambient temperatures may result in cumulative effect and consequent fatigue, resulting in a drop of productivity after a certain period. The cumulative effect of heat waves is usually associated with mortality as the most extreme indicator (Rocklov, Barnett, & Woodward, 2012; Urban, Hanzlíková, Kyselý, & Plavcová, 2017), whereas their effect on fatigue and further on reduced productivity in industrial settings does not seem to be generally well recognized.

4.9 High ambient temperatures at home with no possibility of temperature regulation with air-conditioning, can contribute to a poor sleep quality (Obradovich, Migliorini, Mednick, & Fowler, 2017; Okamoto-Mizuno & Mizuno, 2012) and consequently reduced physical and mental performance (Ahrberg, Dresler, Niedermaier, Steiger, & Genzel, 2012; Andrade, Bevilacqua, Coimbra, Pereira, & Brandt, 2016). An important issue that needs to be considered is the socio-economic status of people. Workers with social disadvantages can greatly be affected by temperature extremes, particularly if there are financial impediments in maintaining thermal comfort (Hansen, Bi, Saniotis, & Nitschke, 2013).

4.10 We have recently reported (Pogačar et al., 2018) that a greater portion of females perceived heat related symptoms compared to males. We concluded that this is most likely due to traditional gender roles with greater contribution of women to domestic work and therefore reduced recovery from heat strain, compared to men. Considering cumulative effect of heat waves, socio-economic status and traditional gender roles, solutions mitigating heat strain of workers must therefore also include an analysis of their conditions at home and during their travel to, and from work.

5. Cumulative effect of summer heat waves on the manufacturing productivity in an automobile-parts plant

5.1 The observed no significant change in the temperature in the manufacturing hall during a heat wave as reported in section 4 above, but a significant drop in productivity upon termination of the heat waves, would suggest a potential cumulative effect of heat. This cumulative effect may be due to the inability of the workers to recover from the thermal strain experienced at work. Namely, under normal weather conditions, the temperature external to the factory is less than the internal temperature, whereas during a heat wave the conditions external to the factory are the same as internal conditions. This may result in reduced sleep quality and increased fatigue, cumulating after a few days of constant exposure, and affecting productivity.

Aim

5.2 The aim was to monitor the mood, fatigue and thermal perception of workers throughout the day (including before and after work) in different seasons of the year, and compared these with observations pre-, per- and post heat waves.

Methods

5.3 A total of 15 workers employed in the manufacturing process volunteered to participate in the study. During each season, they were provided with 5-day questionnaires. The sleep quality questionnaire was completed after waking, whereas the mood, fatigue and thermal perception questionnaires were completed before, during and after work. During the summer, the workers were asked to complete these questionnaires during each heat wave and also a few days after each heat wave, to observe any cumulative effects.

Results

5.4 Outdoor temperatures were higher during heatwaves (25±1°C), compared to baseline (18±1°C, $p<0.001$) and post-heatwave (23±4°C, $p=0.031$) temperatures Fig. 5). Indoor temperature were however similar during baseline and during heatwaves (29±1°C), but lower once the heatwaves were terminated (27±1°C, $p<0.05$).

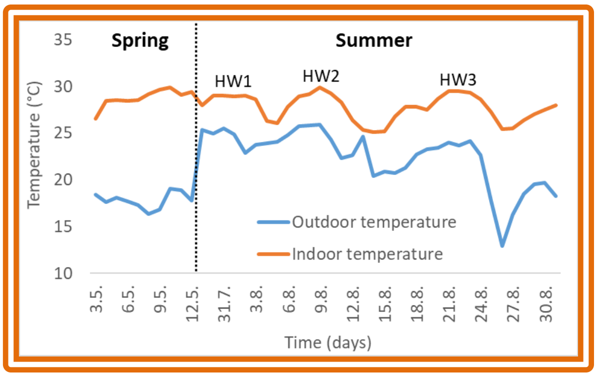

Figure 5: Indoor and outdoor measured temperature during Spring and Summer 2018. Representative work station at the odelo d.o.o. plant is shown in the right photograph.

5.5 During HWs productivity was reduced, when compared to post-HW productivity at the injection moulding work stations (HW: 83±9%, post-HW: 91±6%, $p=0.021$), and when compared to the baseline (Spring) productivity (baseline: 83±12%, HW: 79±5%, $p=0.025$) at the assembly work stations (Fig. 6).

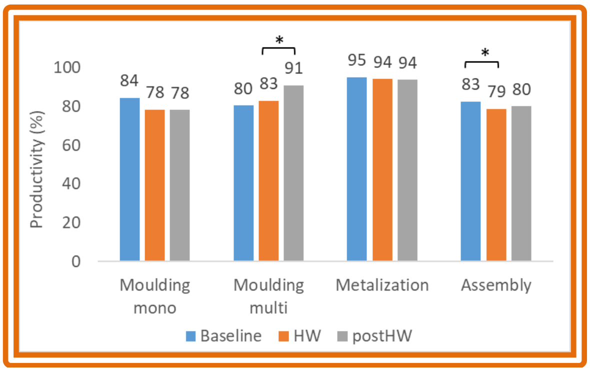

*Figure 6: Productivity at different work stations. *p<0.05*

5.6 During heatwaves, workers felt less comfortable and warmer, and perceived greater skin wettedness and exertion (p<0.05). Based on the OSA sleep inventory score, sleep maintenance was attenuated during and after heatwaves (p=0.002), compared to baseline period (Fig. 7).

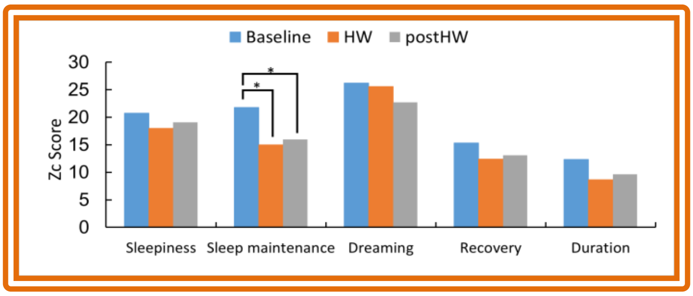

*Figure 7: OSA sleep inventory score. *p<0.05*

Discussion

5.7 Higher indoor and outdoor temperatures, documented during HWs, impaired workers` thermal comfort and sleep quality, and increased perceived exertion, which resulted in a drop in productivity at the moulding and assembly work stations. Despite a decrease in productivity, a recovery was observed in the days following the heatwaves. The participating company (odelo d.o.o.) implemented several strategies for mitigating heat stress, recommended by partners in the European Commission H2020 project Heat Shield (see section 11). As a consequence productivity was not affected in some of the workstations, and more importantly there was improvement in workers' well-being (ie. improved thermal status, and recovery).

6. Neural network predicting productivity on the basis of weather forecasts of hot days

6.1 Mitigation of the negative effects of heat waves is achieved by maintaining a thermally comfortable environment within the production halls, which would require installation of appropriate heating ventilation and air conditioning (HVAC) systems. Due to the design of most production halls (i.e. minimal insulation), this option is often unacceptable due to the cost of installing and running such installations. Other options for protecting workers against heat stress include either providing them with personal protective equipment (i.e. ventilated and/or cooling vests and helmets) during heat waves, or implementing strategies that would allow the modification of the work shift to cooler periods of the day. Both of these latter options would benefit from a warning system, which would alert the management of any impending heat stress, and thus allow for the optimal implementation of heat stress-mitigating strategies. Within Heat Shield, a web-based early warning system is under development within work package 5, consisting on short- and long-range (up to four weeks) personalized predictions of heat stress (see the Heat Shield deliverable D.1.3 for some details on the prototype).

6.2 Short-range forecasts allow to predict heat waves some days in advance. Making use of such predictions and meteorological conditions within the production hall would allow assessment of the effect of heat waves on productivity. Prediction of the effect of these heat waves on productivity would require the prediction of the effects of these heat waves on the internal environment within the production hall. The accumulation of heat in industrial production halls may be calculated based on the internal and external heat loads, accounting for the architectural design of the production halls, and the nature of the building materials used in the construction of the building. The prediction of the external weather on internal factory conditions taking into account all factors that contribute to heat transfer is complex, and would require a separate analysis for each factory.

Aim

6.3 The aim of the present study was to develop a universal method based on a neural-network, that could provide accurate predictions of heat wave-induced heat stress in a manufacturing plant, based on input from internal and external temperature and humidity sensors, and on short-range weather forecasts.

Methods

6.4 External environmental conditions were measured by a weather station installed on the grounds of the company (external to the factory), in close proximity to the production hall. For the assessment of the internal ambient conditions within the manufacturing halls, a total of 33 temperature and relative humidity sensors were installed in three halls within the manufacturing plant. These included the production hall for injection moulding, metallizing, and storage. The sensors were installed at specific workstations, such that one sensor (monitoring both temperature and relative humidity) was at approximately head height, 1.5 m from the floor, and the second sensor (monitoring only temperature) was 5 cm above the floor surface. The sensor modules streamed the data at 15 min intervals to a data cloud via the internet. Dedicated software merged the data from the outside weather station and internal sensor modules, and allowed viewing the stored data.

6.5 *Ratings of thermal and moisture comfort*

Information regarding the perception of the ambient temperature and relative humidity by the workers is essential for the prediction of well-being in any industrial environment. Ratings of thermal and moisture (dis)comfort were obtained from questionnaires displayed on touch-sensitive screens in three locations within the production halls. The questionnaires requested responses using a visual analogue scale. The display contained a radio-frequency-identification (RFID) sensor. Workers wishing to complete the questionnaire were required to log on to the software using their company-issued personal RFID. Using the company's data archives, we were able to link the ratings provide by individual workers to their gender, age and workstation in the factory. This information was only made available to the researchers, who were blinded to the names of the respondents.

6.6 Heat stress indices

Heat induced stress impacts workers' health and performance. A multitude of heat stress indices have been developed, based on a variety of environmental and physiological data. In its simplest form, an index of heat stress incorporates values of temperature and relative humidity. These indices present some advantages with respect to the meteorological variables alone, since they combine their effect and summarize it on a single value. For the purpose of this study we used three indices.

Simplified Wet bulb globe temperature (sWBGT)

WBGT was proposed as a heat stress index by Yaglou and Minard (Yaglou & Minaed, 1957). Since in the present study WBGT was determined for the indoor environment, we did not include radiation and wind speed. Based on the proposal of the Australian Bureau of Metrology (ABT) WBGT was calculated based on an air temperature and vapour pressure:

$$\text{sWBGT ABT [°C]} = 0.567\ Ta + 0.393\ \rho + 3{,}94,$$

where,

Ta = air temperature

ρ [hPa] = vapour pressure = RH/100 x 6.105exp(17.27Ta / (237.7 + Ta))

Discomfort index (DI)

In addition to the sWBGT index, we also determined the Discomfort Index (DI; (Epstein & Moran, 2006):

$$DI = 0.5\ Tw + 0.5\ Ta,$$

where,

Tw = wet-bulb temperature, and was determined from Ta and RH based on the equation proposed by Stull (2011).

Universal thermal climate index (UTCI)
The Universal thermal climate index (UTCI) uses meteorological data to calculate heat induced stress.

6.7 Neural network (machine learning algorithm)
A machine learning algorithm was integrated into the software for previewing the conditions within the factory. The algorithm uses an artificial neural network with multi-layer feedforward network. Training the neural network is performed using RPROP algorithm, which is short for resilient back-propagation. RPROP was developed by Braun and Reidmiller (1992). Our software used SSN toolkit for LabVIEW (Kruczkowski, 2015). External, internal temperature and relative humidity data were used for training the artificial neural network.

The backpropagation learning works by repeating the chain rule for computing the influences of every weight in a network compared to an error function E.

$$\frac{\partial E}{\partial w_{ij}} = \frac{\partial E}{\partial s_i}\frac{\partial s_i}{\partial net_i}\frac{\partial net_i}{\partial w_{ij}}$$

where w_{ij} is the weight from neuron j to neuron i, s_i is the output, and net_i is the weighted sum of the inputs of neuron i. Once the partial derivative for each weight is known, the aim of minimizing the error function is achieved by performing a simple gradient descent:

$$\partial w_{ij}(t+1) = \partial w_{ij}(t) - \epsilon \frac{\partial E}{\partial w_{ij}}(t)$$

The pseudo code attached below displays RPROP adaption and learning process. Please note that the minimum and maximum functions return min or max of the two numbers on the bracket and that the sign returns positive 1 only if the value in the brackets is not negative.

$$if\left(\frac{\partial E}{\partial w_{ij}}(t-1) * \frac{\partial E}{\partial w_{ij}}(t) > 0\right) then$$

$$\Delta_{ij}(t) = minimum\left(\Delta_{ij}(t-1) * \eta^{+}, \Delta_{max}\right)$$

$$\Delta w_{ij}(t) = -sign\left(\frac{\partial E}{\partial w_{ij}}(t)\right) * \Delta_{i,j}(t)$$

$$w_{ij}(t+1) = w_{ij}(t) + \Delta w_{ij}(t)$$

$$else\ if\left(\frac{\partial E}{\partial w_{ij}}(t-1) * \frac{\partial E}{\partial w_{ij}}(t) < 0\right) then\ \{$$

$$\Delta_{ij}(t) = maximum\left(\Delta_{ij}(t-1) * \eta^{-}, \Delta_{min}\right)$$

$$w_{ij}(t+1) = w_{ij}(t) - \Delta w_{ij}(t-1)$$

$$\frac{\partial E}{\partial w_{ij}}(t) = 0$$

$$else\ if\left(\frac{\partial E}{\partial w_{ij}}(t-1) * \frac{\partial E}{\partial w_{ij}}(t) = 0\right) then\ \{$$

$$w_{ij}(t) = -sign\left(\frac{\partial E}{\partial w_{ij}}(t)\right) * \Delta_{i,j}(t)$$

$$w_{ij}(t+1) = w_{ij}(t) + \Delta w_{ij}(t)$$

LabVIEW development environment was used for software development. The software prepares data containers, buffers and initializes the neural network. In the second stage, sensor data are loaded into the software and into the neural network. Loaded data can be from a cloud, from a file or live data from the factory. After the data is loaded, teaching using the described RPROP algorithm is performed. When desired error value or timeout occurs, teaching is finished. After the training is completed, the neural network is ready to predict new values by making use of the short-range meteorological forecasts.

6.8 The artificial neural network was used to predict the internal conditions within the manufacturing plant based on the forecasted external meteorological conditions provided by the Slovene Meteorological Agency. To train the neural network we used meteorological data recorded in summer 2017, with multiple documented heat waves. Two thirds of recordings were used to train the artificial neural network and one third of data were used to validate the output of an artificial neural network (i.e. split-sample cross-validation). Specifically, the predicted values were compared with the observed values.

6.9 The accuracy of prediction of the neural network was evaluated by monitoring the temporal error trend during the training. The temporal error trend during the training phase is defined as the residual sum of squares.

Results

6.10 A typical example of the output of the neural network is presented in Fig. 4, where the red line represents the observed temperature measured inside the manufacturing plant, and the blue line the predicted temperature derived from the neural network. The plot represents a period of 11 days.

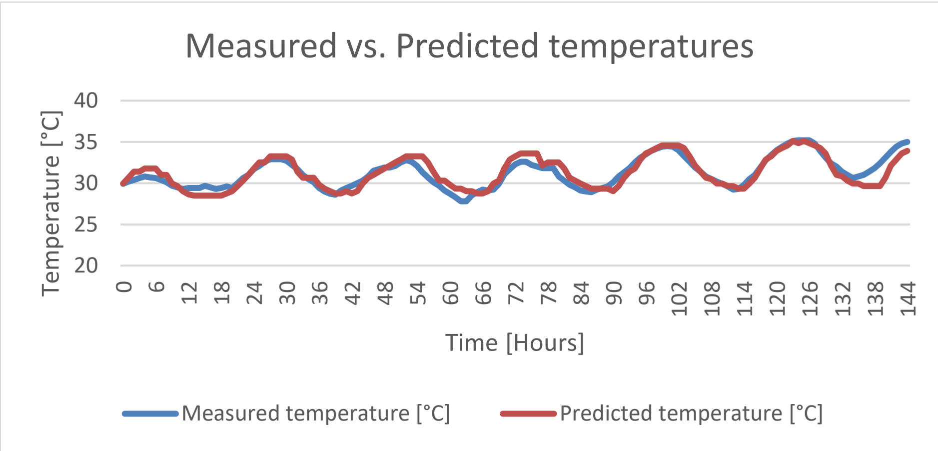

Figure 4: Comparison of the measured (blue line) and predicted (red line) temperatures within the injection molding hall of the odelo manufacturing plant for a 6 days period.

6.11 The temporal error trend drastically decreases during the first 100 iterations of teaching. Thereafter, the next few thousand teaching iterations provide only minor improvement.

6.12 The developed neural network provides accurate predictions of meteorological conditions inside a factory based on observed weather data inside and outside the factory and short-range weather forecasts. This allows the prediction of heat stress indices and resultant decrement in productivity.

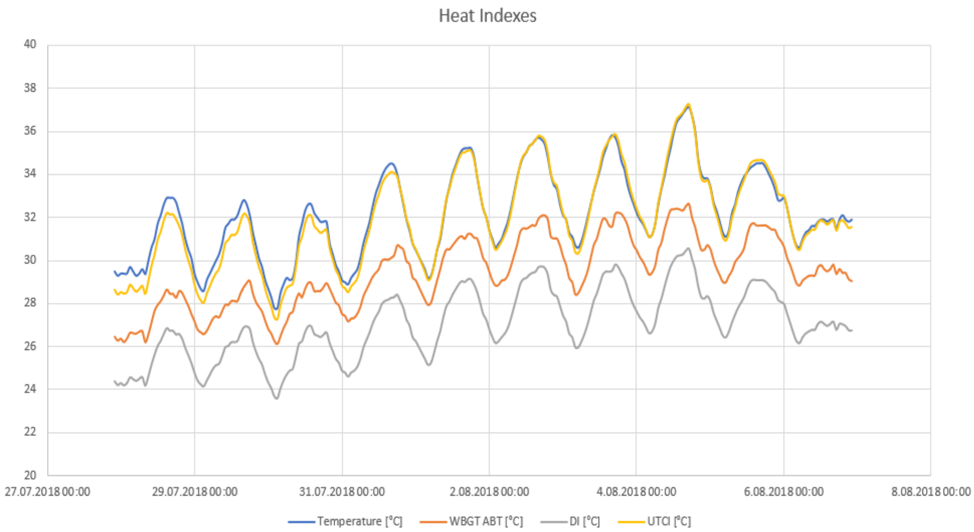

Figure 1: Comparison of the predicted heat stress indices, determined on the basis of the conditions within the factory predicted by the neural network. The plot depicts the WBGT (orange line), DI (gray line), UTCI (yellow line) and temperature (blue line).

Discussion

6.12 The developed neural network provides accurate predictions of meteorological conditions inside a factory based on observed weather data inside and outside the factory and short-range weather forecasts. This allows the prediction of heat stress indices. Inclusion of sufficient productivity data would allow training the neural network to predict productivity based on predicted meteorological conditions.

7. Perception of thermal comfort

7.1 The development of a humanoid thermal robot/manikin capable of providing ratings of thermal comfort requires the development of algorithms that can simulate human perception of thermal comfort during steady state and dynamic ambient conditions. A series of studies were conducted on human subjects to better understand the factors contributing to the perception of thermal comfort.

7.2 In the somatosensory cortex, the size of areas dedicated to the perception of physical stimuli applied to the skin, are proportional to the importance of the role of a given skin region for the organism (Anselme, Périlleux, & Richard, 1999). Skin regions therefore differ in the perception of temperature sensation and presumably in their contribution to local and overall thermal comfort (Arens, Zhang, & Huizenga, 2006; Nakamura et al., 2013; Nakamura et al., 2008; Stevens & Choo, 1998; Zhang, Huizenga, Arens, & Wang, 2004). Central integration of regional skin temperature and its rate of change (Fiala, 1998), and subsequent cortical processing of this information provides an assessment not only of the sensation of temperature, but also a rating of the thermal comfort. The derived sensation of temperature and thermal comfort are the principal factors driving our behaviour in defence of the core temperature (Schlader, Stannard, & Mundel, 2010). Thus, skin temperature has a relatively greater contribution to subjective thermal comfort than to autonomic thermoregulatory responses, and initiates behavioural thermoregulation before activation of the more metabolically demanding autonomic responses that maintain body temperature (Frank, Raja, Bulcao, & Goldstein, 1999).

7.3 The nature of human autonomic and behavioural temperature regulation has been studied predominantly with male subjects, and particularly for thermal comfort there is a paucity of data for female subjects. Gender comparisons have often focused on physiological differences, such as greater body fatness and body surface area to mass ratio in females (Tikuisis, Jacobs, Moroz, Vallerand, & Martineau, 2000), and in the contribution of the menstrual cycle (Kocjan, 2007). When matched for body mass and surface area, immersion in cold (Tikuisis et al., 2000) and tepid (Anderson, Ward, & Mekjavic, 1995) water resulted in similar responses of body core temperature and metabolic rate for both genders, whereas sudomotor sensitivity was shown to be lower in females (Gagnon, Crandall, & Kenny, 2013). It was reported that females are more sensitive to warm and cold stimuli (lower thresholds for detection of the stimulus) than men (Golja, Tipton, & Mekjavic, 2003), and display a stronger warmth sensation to a warm stimulus (Gerrett et al., 2014).

Aim

7.4 Using a new methodological approach, we tested the following hypotheses: 1) thermal comfort of different skin regions is achieved at ranges of temperatures deemed thermally comfortable, defined as the thermal comfort zone (TCZ); 2) thermal comfort zones for different skin regions will not be the same; 3) the characteristics of the regional thermal comfort zones will vary between genders.

Methods

7.6 Sixteen healthy Caucasian males (n=8) and females (n=8) participated in the study. Due to the fluctuation of body temperature during the menstrual cycle, females provided information regarding their menstruation in order to avoid the period immediately after ovulation, when higher levels of progesterone induce elevations in the internal temperature (Baker et al., 2001). They were tested for five consecutive days, starting with the first day after completing their menstruation.

7.5 During the experimental trials, subjects donned a water-perfused suit (WPS; Fig. 5) comprising five components: one covering the head and upper part of the back, one for each leg, one surrounding the torso and one for both arms and the lower back. The WPS did not cover the hands, feet, neck and face. All five components of the WPS were fed from a common manifold and consisted of identical lengths (25 meters) small-diameter (inner =4 mm, outer=5 mm) PVC tubing which were woven in the meshed lining of the suit. This ensured equal flow of water in all five segments of the suit of approximately 3.5 L/min. The total volume of water contained by the tubes in the suit was approximately 1.25 L. The WPS was designed to fit various body sizes using Velcro stripes.

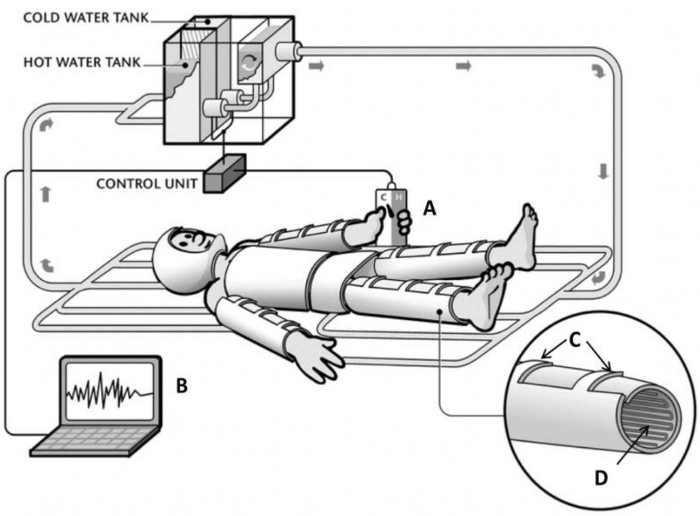

Figure 5: A schematic representation of the experimental arrangement used to assess behavioural regulation of thermal comfort. By depressing a control switch (A), the subject could invert the direction of temperature change in a water-perfused suit they were wearing when it became uncomfortably warm or cold. A computer software (B) controlled the rate and magnitude of oscillations in the temperature of the water perfusing the suit. Velcro stripes (C) embedded at the suit ensured a good fit of the water tubes (D) to the body surface.

7.6 Experimental protocol
Thermal comfort of four skin regions (arms, legs, front torso and back torso) and the whole body was evaluated with the WPS. In order to assess the temperature, perceived as thermally comfortable, subjects were requested to don a water-perfused suit (WPS) and to regulate the temperature within the WPS for the duration of a one-hour trial. A saw-tooth change in the water perfused suit temperature (Twps), potentially delivering water of temperatures between 10° and 50°C, enabled no steady state position. The rate of change of temperature during the heating and cooling phases of the saw-tooth temperature variation was similar and approximately 2.2°C.min^{-1}. For the range of temperatures applied to the skin, this was expected to provide a substantial thermal afferent stimulus. Subjects were instructed to re-adjust the water temperature whenever it was perceived as uncomfortably warm during the warming phase or uncomfortably cool during the cooling phase. Depressing a button designated with a "+" symbol, initiated an increase in the Twps. Conversely, depressing a button designated with a symbol "-" initiated a decrease in the Twps. The lower and upper peaks of the sinusoidal pattern were considered to represent the boundaries of the thermal comfort zone (TCZ) for each subject (Fig. 5).

7.7 The WPS was constructed such that subjects could regulate the temperature of individual regions (arms, legs, front torso and back torso) separately. In this manner, TCZ for individual regions could be assessed. On one occasion, subjects regulated the water temperature within the whole suit.

7.8 Upon arrival at the laboratory, subjects rested for a minimum of fifteen minutes prior to being prepared for the test. The laboratory ambient temperature (Ta) was maintained at 25.2±0.3°C, and 50% relative humidity (RH). Before entering the climatic chamber, males dressed in shorts, and females in shorts and bra. Thereafter they transferred to a climatic chamber, with ambient conditions maintained at 33°C (Ta) and 30% RH. Before donning a WPS, they were instrumented with temperature sensors. They remained in a semi-supine position for the duration of the entire trial. Each trial commenced with a 10 min baseline, with the Twps maintained at 33°C (equal to ambient temperature). The subjects were informed that in the absence of any regulation, the temperature of the suit would change in a saw tooth manner from approximately 10° to 50°C. This saw tooth temperature regulation (TR) commenced after the baseline measurements were completed. Subjects were given a remote control switch and started regulating the Twps of one region/whole body within their preferred range for the duration of one hour. When the Twps of one region was being regulated by a subject, the remaining regions within the WPS were maintained at 33°C whereas in the case of the whole body TR, the Twps of all regions was being regulated by a subject.

For each subject, the trials were carried out at the same time of the day to avoid the effects of circadian rhythm, with the order of the trials counterbalanced between subjects.

Results

7.9 Thermal comfort zone (TCZ, °C)
The regulation of temperature (TR) within different skin regions and overall body indicated no difference in the lower and upper limits and magnitude of the TCZ between males and females (Table 2). Whole body TR however, exhibited higher regulated temperature ($p<0.05$) when compared to other regions, irrespective of gender. No difference in the number of changes in the direction of the Twps initiated by the subjects was observed between males and females. The median (range) number of changes in the direction of the Twps was 12 (29) for the arms, 15 (43) for the legs, 11 (13) for the front torso, 14 (21) for the back torso, and 18 (32) for the whole body, irrespective of gender. Whole body TR however resulted in a greater number of changes in the Twps, compared to arms TR ($p<0.05$), front torso TR ($p<0.01$) and back torso TR ($p<0.05$). No difference between different skin regions was noted.

7.10 Subjective ratings of thermal comfort and thermal sensation
No within or between gender differences were observed with ratings indicating thermal comfort. Thermal sensation was also not influenced by gender or experimental condition, with subjects perceiving the temperatures between neutral and warm. There was no effect of gender on the correlation between subjective ratings and skin temperature.

Table 2: Median (range) lower limit, upper limit and the width of the thermal comfort zone (TCZ) for males and females during the temperature regulation (TR) of the arms, legs, front torso, back torso and whole body. The p values are reported for the gender differences.

Condition	Lower limit of the TCZ				Upper limit of the TCZ				Width of the TCZ			
	Males	Females	Both	P	Males	Females	Both	P	Males	Females	Both	P
Arms TR	19.7 (12.2)	21.9 (14.2)	21.7 (14.2)*	0.64	24.4 (22.6)	29.5 (23.1)	28.1 (29.0)*	0.40	5.9 (10.7)	8.9 (13.6)	6.8 (15.5)	0.25
Legs TR	20.2 (17.0)	23.2 (14.0)	22.7 (17.0)*	0.64	27.1 (22.9)	33.3 (12.3)	31.9 (22.9)	0.21	7.0 (8.0)	10.4 (19.2)	8.9 (19.2)	0.06
Front torso TR	16.8 (15.5)	18.6 (13.9)	17.4 (15.5)*	0.43	24.0 (21.9)	30.0 (16.9)	26.8 (25.1)	0.14	5.4 (17.5)	10.9 (14.7)	9.1 (18.0)	0.14
Back torso TR	17.5 (17.8)	20.7 (18.0)	18.9 (18.7)*	0.79	26.4 (24.7)	31.7 (20.3)	29.6 (26.2)	0.40	5.1 (19.6)	8.2 (20.9)	6.9 (22.3)	0.10
Whole body TR	22.3 (11.1)	27.0 (8.4)	25.4 (13.1)	0.12	30.8 (9.6)	33.2 (7.0)	31.7 (10.4)	0.10	5.4 (12.9)	5.6 (8.9)	5.6 (13.8)	1.00

* Significant regional difference compared to whole body TR.

Discussion

7.11 Based on the known differences in regional cutaneous temperature sensitivity (Frank et al., 1999; Nakamura et al., 2013), the finding that such differences are not observed in the regional thermal comfort zones might be considered somewhat surprising. However, it underscores the fact that the temperature sensitivity of a region does not necessarily affect the perception of the temperature of that region. The greater receptor density of a skin region and perhaps a greater influence of that region centrally, apparently do not affect the range of temperatures considered comfortable. The daily variations in skin temperature of the regions investigated were not of a magnitude, which would suggest differences in regional temperature habituation. In contrast to previous studies (Cotter & Taylor, 2005; Nakamura et al., 2013; Nakamura et al., 2008), which investigated regional differences in skin thermosensitivity, our study assessed the range of temperatures considered thermally comfortable at different skin regions. It should be emphasised however, that in the present study subjects' decision to change the direction of the temperature change of the water within the WPS was driven by achieving a level of discomfort. The upper and lower temperature limits of the TCZ thus represent temperatures that were considered thermally uncomfortable. Although behavioural thermoregulation is driven by thermal discomfort (Schlader et al., 2010), this does not alter the concept of the thermal comfort zone as defined in the present study.

8. Neurophysiological correlate of thermal (dis)comfort

8.1 Common to most studies investigating subjective ratings of the perception of temperature and thermal comfort is the assumption that such perceptions are dependent on the combination of skin and core temperatures, disregarding the possibility that the direction of the change in temperature may also exert an effect on these perceptions. Animal studies (Duclaux & Kenshalo, 1980; Kenshalo & Duclaux, 1977) have demonstrated that the response of a temperature sensor to a step change in temperature is a dynamic overshoot or undershoot in activity, which subsides to a steady state level of tonic activity, corresponding to the adaptation temperature. Cooling will increase the dynamic activity of the cold and decrease dynamic activity of the warm sensors. Conversely, warming will increase and decrease the dynamic activity of the warm and cold sensors, respectively.

Aim

8.2 Since the central perception of temperature is dependent on the thermoafferent information from the peripheral sensors, which in turn is dependent on the magnitude of the thermal stimulus, its rate of change and direction (i.e. heating or cooling), the present study tested the hypothesis that the direction of the temperature change will influence the perception of temperature and thermal comfort. It further tested the hypothesis that the perception of thermal discomfort is correlated with behavioural actions to counteract the discomforting thermal stimulus. The test of this latter hypothesis is fundamental to all studies using visual analog scales of thermal discomfort, as an index of behavioural temperature regulation. Namely, should behavioural modifications to minimise thermal discomfort not match the ratings reported by subjects, then this would invalidate visual analog scales as an index reflecting behavioural temperature regulation.

Methods

8.3 Experimental Protocol

Subjects participated in two experimental trials. In both, the subjects donned a water-perfused suit (WPS) with a control unit designed to allow either the subject, or the experimenter, control over the temperature of the water perfusing the WPS (Fig. 5). Specifically, by depressing a control switch, the subject (or experimenter) could change the direction of the temperature change of the water perfusing the WPS. The temperature control unit had no steady-state position, thus, the temperature of the WPS alternated between a cooling and heating mode according to the subject's, or experimentor's control. Using this experimental arrangement, two separate studies were conducted. In both, the experimental session commenced with a 30-min acclimation to room conditions (Ta=25°C, RH=30%) and familiarization with the equipment and study protocol. Then, subjects were instrumented with skin sensors, donned a WPS and assumed a supine position on a gurney. Male subjects were dressed in shorts, and females in shorts and a bikini top.

8.4 Perception of thermal comfort

The temperature of the water perfusing the WPS (T_{wps}) was initially regulated at a slightly cool baseline temperature (T_{wps}=27°C) for 10 minutes. Thereafter, subjects were exposed to a heating and cooling protocol that was repeated thrice, during which T_{wps} varied from 27°C to 42°C and back, at a rate of 1.2°C.min^{-1}. At each 3°C change in temperature subjects were requested to rate their thermal perception on a 7-point scale (-3: very cold; -2: cold; -1: slightly cold; 0: neutral; +1: slightly warm; +2: warm; +3: very warm) and thermal discomfort on a 4-point scale (0: comfortable; 1: slightly uncomfortable; 2: uncomfortable; 3: very uncomfortable). Furthermore, they were asked to report when they perceived the temperature change from a comfortable to and uncomfortable level and vice versa, thus indicating the boundaries (T_{low} and T_{high}) of their thermal comfort zone (TCZ) during heating and cooling.

8.5 Regulation of thermal comfort

As in the previous trials (Perception of thermal comfort), T_{wps} was regulated by the control unit to vary between 27°C and 42°C, at a rate of 1°C.min^{-1}. In contrast to the Perception of thermal comfort trials, in these trials subjects were instructed that they could initiate a change in the direction of the temperature of the water perfusing the WPS once it became either uncomfortably warm during heating, or uncomfortably cool during cooling, by depressing a button on a manual control switch. Subjects were instructed to maintain T_{wps} within a preferred range for a total of one hour. These trials provided a characteristic saw-tooth T_{wps} pattern indicating the lower (T_{low}) and upper (T_{high}) temperature boundaries, and thus also the range, of the thermal comfort zone (TCZ) during heating and cooling. In all trials, subjects were naïve regarding the absolute temperature of the water perfusing the WPS. They could only assess their thermal (dis)comfort (self-reporting, ranking on a scale, depressing a switch) according to their subjective assessment of the temperature change.

Results

8.6 Thermal comfort perception and temperature sensation

Subjects were requested to rate their perception of the temperature and thermal (dis)comfort using Visual Analog Scales at each 3°C change in the T_{out} during heating and cooling of the WPS in the range 27°C to 42°C. There were no significant differences between the median votes over the given range of temperatures. During the heating process, the lowest ratings of discomfort were reported at T_{wps} = 30°C and 33°C (Fig. 6). These values were perceived as "neutral" and "slightly warm" (Fig. 6), respectively. Similarly, during cooling subjects felt least uncomfortable at T_{wps}= 36°C and 39°C (Fig. 3A), which also corresponded with perceptions of "neutral" and "slightly warm" (Fig. 6), respectively.

8.7 In addition to providing ratings of thermal comfort and temperature perception, subjects were also requested to indicate transitions between thermal comfort and discomfort. In the three trials, subjects reported the boundaries of their TCZ reproducibly. There were no significant differences (P>0.05) between T_{low}, T_{high} and the width of TCZ as derived in three repeat trials, confirming the repeatability of the test. The boundaries of TCZ (mean±SD) during warming were 30.0±1.5°C (T_{low}) and 35.1±2.9°C (T_{high}), and during cooling 35.4±1.9°C (T_{low}) and 38.7±2.3°C (T_{high}). The coefficient of variation, reflecting the measure of accuracy of the T_{wps} eliciting discomfort, was 2.32% for cold discomfort (T_{low} during cooling), and 5.5% for warm discomfort (T_{high} during heating).

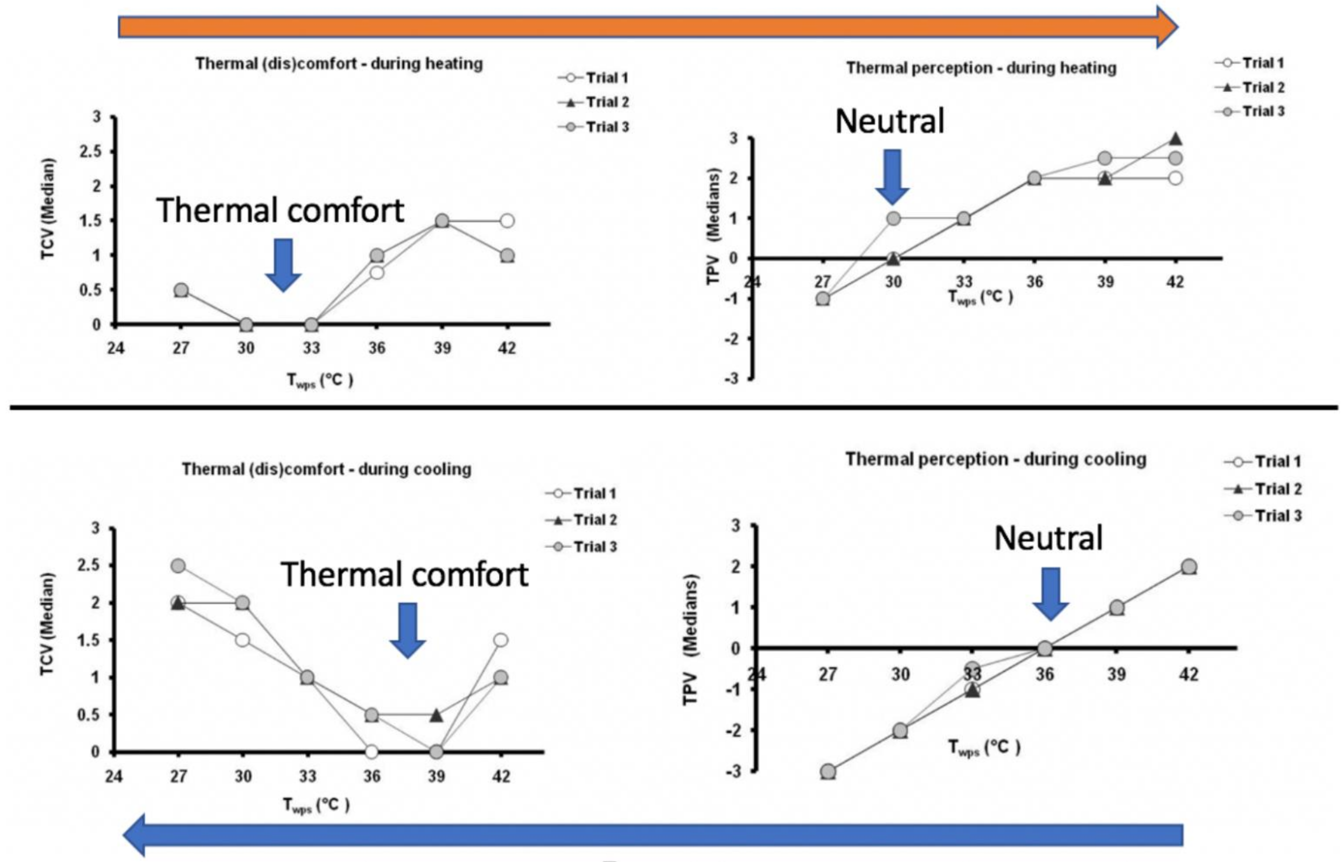

Figure 6: Thermal comfort perception during heating (upper panel) and cooling (lower panel) of subjects. Thermal comfort (left panel) and the perception of thermal neutrality (right panel) were observed at lower temperatures of the water perfusin the suit during heating, compared to cooling.

8.7 Thermal comfort regulation and Correlation between perceptual change and behavioural response

In the Thermal comfort regulation trial subjects were not asked to provide any ratings. There only task was to regulate Twps, by altering the direction of Twps when it was perceived as uncomfortable. In this manner, they defined the boundaries of their thermal comfort zone. There was no significant difference between the T_{wps} at which discomfort was reported (Thermal comfort perception trial) and the T_{wps} at which behavioural responses were initiated (Thermal comfort regulation trial). Fig. 7A shows the relation between the T_{wps} subjects reported as perceiving uncomfortably cool during cooling, and the T_{wps} at which they altered the direction of T_{wps} to heating. Similarly, Fig. 7B shows the relation between the T_{wps} subjects reported as perceiving uncomfortably warm during heating, and the Twps at which they altered the direction of T_{wps} to cooling. There was a strong correlation between these perceptual and behavioural T_{wps} thresholds. The Pearson correlation coefficient was 0.73 during heating (Fig. 7A) and 0.84 during cooling (Fig. 7B).

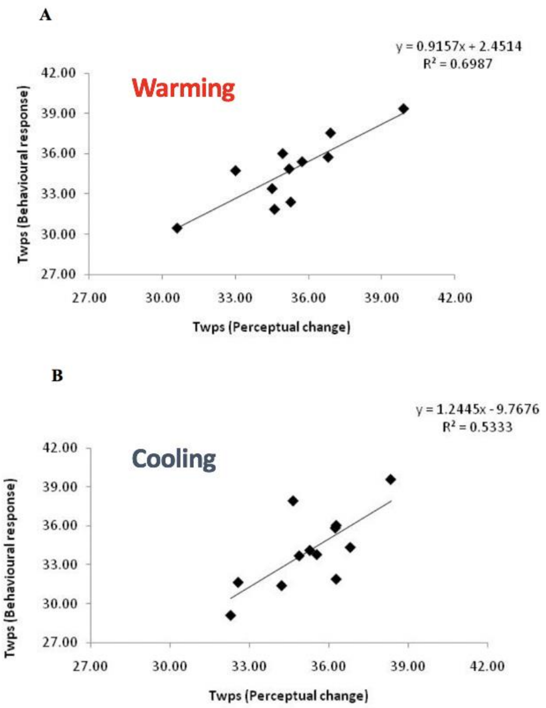

Figure 7: Correlation between the regulation of thermal comfort within the water perfused suits (Behavioural response) and the reported perception of thermal comfort (Perceptual change).

Discussion

8.8 Neurophysiological correlate of thermal comfort – a hypothesis

The effect of the direction of the temperature change on temperature perception and thermal comfort may be explained on the basis of the neurophysiology of thermoreception. Cortical integration of thermoafferent information elicits a conscious assessment of whether the thermal status of the skin is pleasant or unpleasant. We have previously reported that the range of temperatures considered thermally comfortable is centred around 35°C, which coincides with the region of overlap of the static firing characteristics of the warm and cold sensors (I. Mekjavic & Morrison, 1985), as shown in Fig. 8. According to Bazett (Bazett, 1949) and Vendrik (Vendrik, 1959), this point of overlapping activity of the cold and warm sensors could be considered as a peripheral "reference" temperature, deviations from which would activate behavioural responses. Teleologically such an arrangement would make sense, since decreases and increases in temperature of the skin would be associated with increased firing rate of the cold and warm receptors, respectively. Two perception thresholds are postulated: perception of a thermal stimulus, and perception of (dis)comfort. The stimulus perception threshold corresponds to the minimal temperature change that can be perceived by an individual. The temperature at the perception threshold may not necessarily be perceived as uncomfortable.

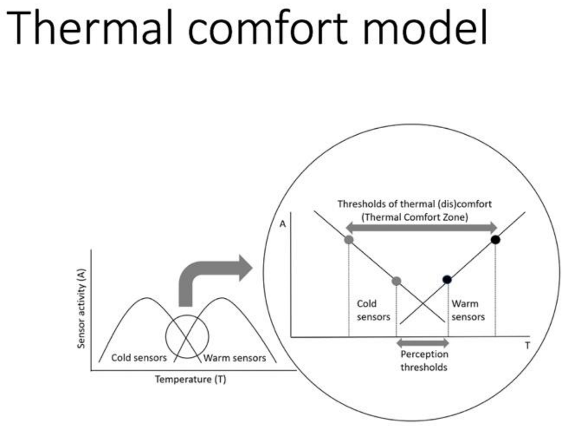

Figure 8: A theoretical neurophysiological correlate of the perception of thermal comfort.

According to the hypothesis presented in Fig. 8, the thresholds for warm and cool discomfort may require a greater thermal stimulus, i.e. they would occur as a consequence of greater temperature receptor activity. It may be that the perception of thermal discomfort formulated in the sensory cortex is related to a threshold of sensor activity, or rather to the perception of this threshold. Assuming that a same level of activity of the cutaneous cold and warm sensors is associated with a threshold perception of cold and warm thermal (dis)comfort, respectively, then this range of temperatures could provide a neurophysiological correlate of the TCZ. Assuming that the static and dynamic characteristic of the cutaneous thermoreceptors (Duclaux & Kenshalo, 1980; Kenshalo & Duclaux, 1977) similar in different regions of the skin, then this would imply that the neurophysiological correlate of the region of thermal comfort (i.e. region of equivalent firing rates) would also be the same. This line of reasoning is certainly supported by the results of the present study. As yet, the threshold level of sensor activity required for the initiation of the perception of thermal (dis)comfort remains unresolved. As suggested in Fig. 8, it is unlikely that the perception of warm and cold (dis)comfort is centred at one temperature, but that separate threshold temperatures exist for cold and warm (dis)comfort. These threshold temperatures describe the limits of the TCZ. The limits, and thus the range, of the TCZ is most likely affected by the rate of change of skin temperature, as this influences the dynamic activity of the sensors.

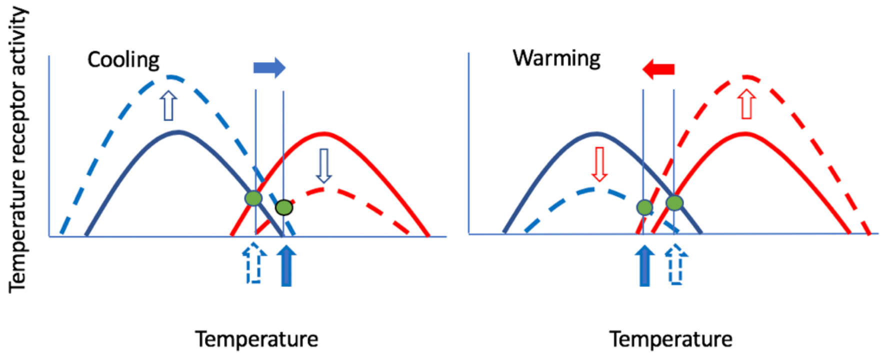

Figure 9: The hypothesized manner in which transient thermal stimuli affect the perception of thermal comfort.

8.9 To understand the shift in the boundaries of TCZ it is necessary to appreciate that the thermoreceptors have static and dynamic responses, which are centrally integrated. The effect of cooling would be to increase the firing rate of the cold and decrease the firing rate of the warm sensors (Fig. 9, left panel), whereas warming would cause an increase in firing rate of the warm sensors and a decrease in the activity of the cold sensors (Fig. 9, right panel). As shown in Fig. 9, cooling would thus result in a shift of the region of equal and overlapping activity of the cold and warm sensor to a higher temperature, whereas this region of equal and overlapping activity would be shifted towards lower temperatures. This would explain, to a degree, the differences regarding TCZ during thermal transients.

9. Prediction of thermal comfort based on the neurophysiology of thermoreception

9.1 According to the reciprocal cross-inhibition (RCI) theory (Bligh, 2006), thermoafferent information from peripheral (cutaneous) and core sensors provides the neural drive for heat production (HP; shivering) and heat loss (HL; sweating), as depicted in Fig. 9. The excitatory drive in the HP sensor-to-effector pathway also provides an inhibitory drive in the HL sensor-to-effector pathway, and vice versa. In this manner, the overlapping activity/temperature characteristics of the cold [preoptic cold (PC)] and warm [preoptic warm (PW)] sensors can establish a regulated level of Tc. Nonthermal factors can affect components in the sensor-to-effector pathway before the region of RCI (pre-RCI) or after (post-RCI).

9.2 The RCI theory was used by Mekjavic and Morrison (I. Mekjavic & Morrison, 1985) to develop a neurophysiological model simulating cold-induced heat production. This neurophysiological model was further developed to simulate the autonomic responses of sweating and vasomotor tone (Kingma, Schellen, Frijns, & van Marken Lichtenbelt, 2012).

9.3 The observations presented in section 8 of this report (see Fig. 8) would suggest that the hysteresis observed in the perception of thermal comfort and temperature during heat and cooling could be explained on the basis of the static and dynamic activity of the cutaneous warm and cold receptors, accounting for the reciprocal cross-inhibition of the cutaneous thermoafferent information.

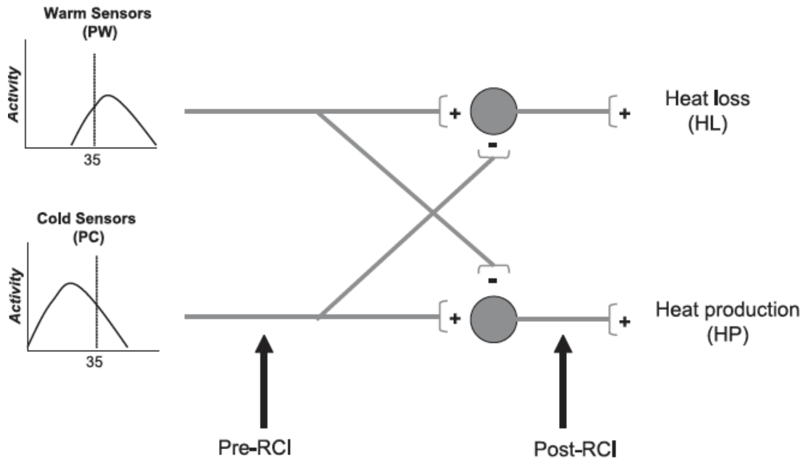

Figure 10: Diagrammatic representation of the Reciprocal Cross-Inhibition (RCI) theory, by which the thermoafferent information from the peripheral warm (PW) and cold (PC) sensors provide the stimulus for HL and HP. The cross inhibition of the thermoafferent information establishes a zone of equal neural activity, defined as the region of overlap of the activity of the cold and warm sensors. This model was used to simulate the perception of thermal comfort. Adapted from Mekjavic and Eiken (I. B. Mekjavic & Eiken, 2006).

Aim

9.4 We developed a model of thermal comfort based on the neurophysiology of thermoreception using data derived from a series of human experiments on male subjects exposed to transient ambient temperature.

Methods

9.5 Twelve healthy young males participated in the study. They were exposed to slow (0.5°C.min^{-1}) and fast (1.0°C.min^{-1}) saw-tooth change in ambient temperature as shown in Fig. 10. At regular 3-min intervals during each exposure, subjects provided a rating of thermal comfort. The duration of the test was 150 min, and a portion of the subjects commenced with ambient heating (as shown in Fig. 10), whereas the remainder commenced the trials with ambient cooling. The order of the slow and fast trials was randomised.

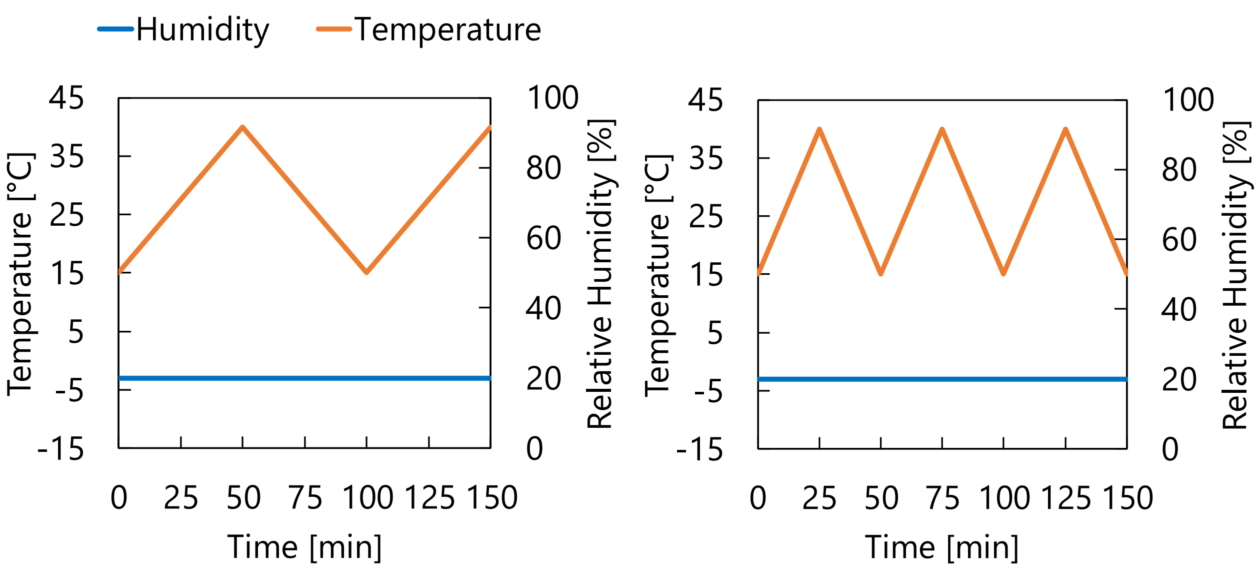

Figure 10: Experimental protocol of the study.

9.6 Essential to the development of the Mekjavic-Morrison (I. Mekjavic & Morrison, 1985) neurophysiological model for thermal comfort was the simulation of the static and dynamic firing characteristics of the warm and cold cutaneous receptors. This was done using the data reported by Zotterman (Zotterman, 1953).

Determining the static response of the cold/warm receptors:

$$F_{cold/warm} = \sum_{i=0}^{10} P_i T^i$$

Determining the dynamic response of the cold/warm receptors:

$$F_{(t)} = PA\big(\exp(-t/K_e) - \exp(-t/K_i)\big) + A_0\big(1 - \exp(-t/K)\big)$$

The total neural drive from the skin receptors is then computed by adding the neural drives from the cold and warm receptors using superposition theory, as shown in Fig. 11.

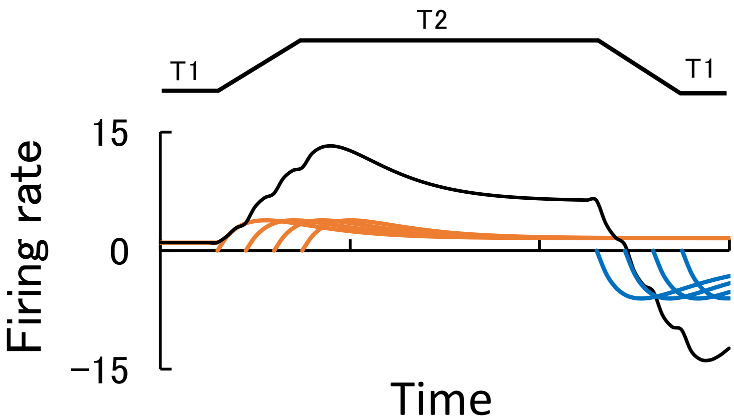

Figure 11: The developed neurophysiological model of thermal comfort derives a total neural drive from both cold and warm receptors using superposition theory. The figure depicts the computed neural drive (bottom panel) from the warm receptors during heat from T1 to T2 (top panel), and during cooling from T2 to T1.

Results

9.7 Using part of the data obtained from the human laboratory studies we developed a neurophysiological model for predicting thermal comfort, and evaluated the model using the remainder of the data. The results of the evaluation are presented in Fig. 12. The graph depicts the thermal comfort ratings during cooling and rewarming as a function of the calculated firing rate of the cutaneous cold and warm sensors.

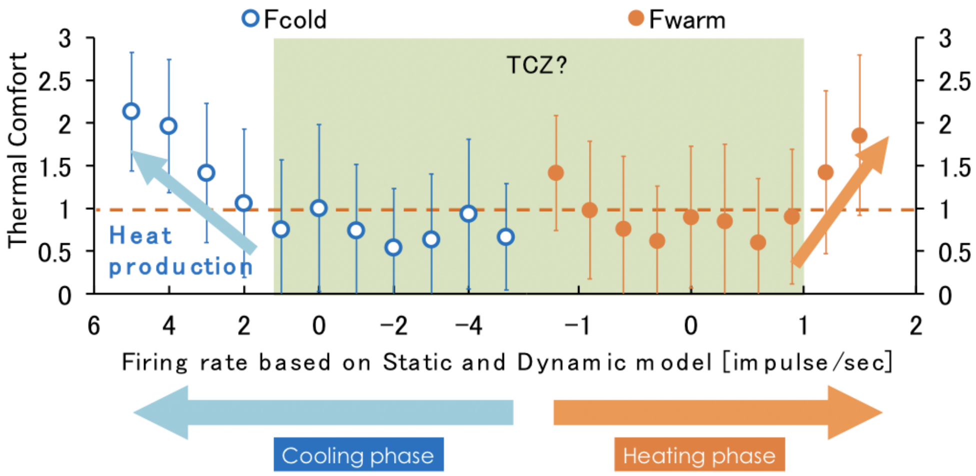

Figure 12: Observed thermal comfort during cooling and rewarming, as a function of the calculated activity of the cutaneous cold and warm sensors.

9.8 The calculated firing rate of the cold and warm sensors establishes a zone in which the thermal comfort ranges from 0.5 to 1. This zone can be defined as the thermal comfort zone.

9.9 Assuming that the overlap of the activity of the cold and warm sensors represents the zone of optimal comfort, then the ratings of thermal comfort would be the smallest (0=comfortable; 3=very uncomfortable) in the region where the firing rate of both cold and warm sensors is lowest, and which corresponds to the region of overlapping activity (see Fig. 8). Fig. 13 depicts the relation between the derived relative change in cold and warm neural drives during cooling and heating, with the ratings of thermal comfort provided in the squares. As stated earlier, the lowest ratings of thermal comfort are in the region where the relative neural drives are minimal.

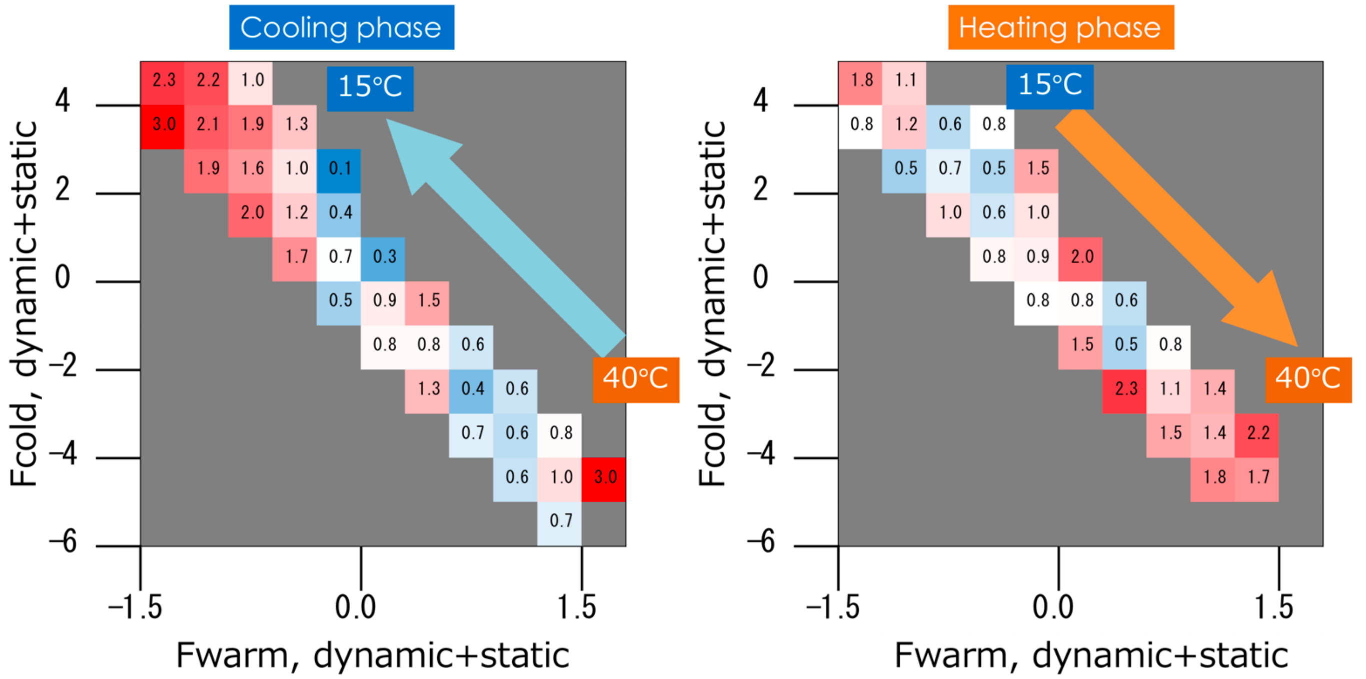

Figure 13: The relation between the relative neural drive from the cold (Fcold) and warm (Fwarm) cutaneous sensors during cooling (left panel) and heating (right panel). The boxes contain the ratings of thermal comfort.

Discussion

9.10 The developed neurophysiological model based on the Mekjavic-Morrison model (I. Mekjavic & Morrison, 1985) appropriately predicts thermal comfort during heating and cooling.

9.11 This thermal comfort model will be embedded in the control unit of the humanoid thermal robot/manikin, with the purpose of providing ratings of thermal (dis)comfort in the conditions prevailing in the manufacturing plant. This will provide managers with information regarding the workers' thermal (dis)comfort, which contributes to their well-being and productivity.

10. Identification/screened solutions

10.1 Neural network model

The developed neural network model described in section 6.0 can be implemented in any manufacturing plant. The investment required includes a meteorological weather station external to the manufacturing plant, and a network of temperature and humidity sensors installed at designated work stations in the manufacturing plant. Together with the weather forecast, the information from these sensors is provided to a neural network model running on LabView software. The output of the software is the prediction of the anticipated internal conditions within the factory as a consequence of the forecasted weather, as well as the expected heat stress. By providing the model with daily information regarding productivity, the prediction will also include the predicted productivity during the forecasted weather conditions.

10.2 Humanoid thermal robot/manikin

10.2.1 The development of a humanoid thermal robot/manikin was completed. The dimensions of the humanoid robot/manikin are provided in Fig. 14.

Figure 14: The core of the humanoid thermal robot/manikin (left panel), before application of a thermosensitive skin layer (right panel; right arm of the). The photograph depicts the skin layer on the right arm.

10.2.2 The humanoid thermal robot/manikin was exposed to the same experimental conditions as presented in section 10.3 (below). Namely, subjects were exposed to a saw-tooth change in ambient temperature ranging from approximately 15 to 40°C. During this protocol the aluminium core structure of the manikin was maintained at 37°C, and we monitored the response of the temperature of the skin layer. This response was then compared to the responses observed in the human subjects. Fig. 15 compares the responses of the human subject's skin temperature (blue line) with that of the manikin (red line), in response to the changing ambient temperature (dashed blue line-human subject trial, and dashed red line – manikin trial). For this particular subject, the skin temperature response is appropriate, differing by about 1.5°C.

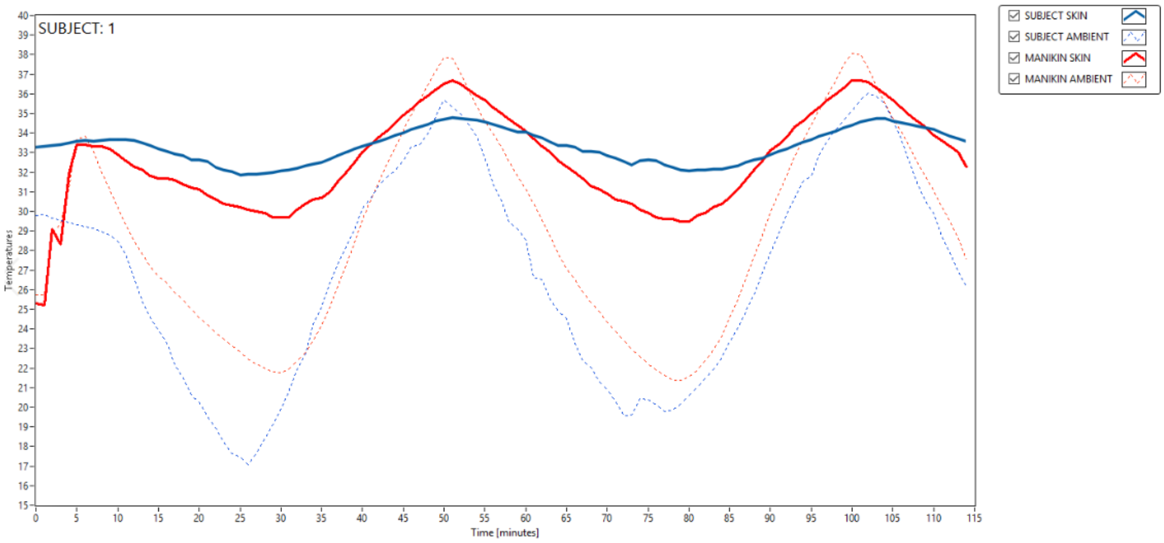

Figure 15: Comparison of the skin temperature response of a human male subject (solid blue line) and the temperature of the manikin skin layer (solid red line), during exposure to a saw-tooth change in ambient temperature (dashed blue line-human trial; dashed red line-manikin trial).

10.2.3 The temperature responses of the manikin core and shell structures were used as inputs to the neurophysiological model of thermal comfort presented in section 9. The manikin control unit was therefore embedded with a function that allows the prediction of the rating of thermal comfort using on the algorithms developed in section 9, weighted according to the observed human responses presented in section 10.3.

Preliminary results from laboratory trials demonstrate that this modelling approach is valid, but may not account for the wide range of subject variability in the responses of thermal comfort ratings for a similar exposure.

10.2.4 Further development of the humanoid thermal robot/manikin will try and incorporate the range of anticipated subject variabilities in the responses of thermal comfort, for the working population within the odelo d.o.o. factory. In addition, the manikin will be installed in the injection moulding section of the odelo d.o.o. plant and its responses of thermal comfort compared to the responses provided by the workers in close proximity to the manikin.

10.2.5 The Heat Shield Humanoid Thermal Robot/Manikin will be demonstrated at the International Conference on Environmental Ergonomics, which will be held in Amsterdam in July 2019. Prior to this date, a video will be produced and made available to the partners and European Commission.

10.3 Improving thermal comfort by establishing ambient thermal transients

10.3.1 Fanger (Fanger, 1970) developed the most widely used thermal comfort index – Predicted Mean Vote (PMV) – which predicts the thermal perception of people in a steady-state thermal environment. Within industrial settings, and particularly during periods of heat waves, thermal environments are often transient, with drifts in the indoor temperatures (R. J. de Dear et al., 2013). In such environments, PMV does not seem to be appropriate for predicting thermal sensation of occupants (Chun & Tamura, 2005; Gallardo, Palme, Lobato-Cordero, Beltrán, & Gaona, 2016; Ioannou, Itard, & Agarwal, 2018; Kumar, Mathur, Mathur, Singh, & Loftness, 2016). It has also been recognized that uniform thermal environments in fact do not ensure optimal thermal comfort (Arens et al., 2006; Karjalainen, 2007) and limit the thermal challenges the body has to cope with, potentially leading to obesity and pathologies related to obesity (Johnson, Mavrogianni, Ucci, Vidal-Puig, & Wardle, 2011). A study performed in Finland revealed that people perceive greater thermal discomfort in offices where temperatures are kept constant, by feeling colder or hotter more often than at home. It was concluded that the likely reason for this is that they have fewer opportunities to control the thermal environment at work (Karjalainen, 2007). Following these findings, the adaptive thermal comfort model has been developed to improve the accuracy of prediction of human thermal sensation in naturally conditioned buildings (R. De Dear & Brager, 1998; Nicol & Humphreys, 2010), which ensure greater control over thermal environment (Raja, Nicol, McCartney, & Humphreys, 2001; van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006).

10.3.2 We evaluated the thermal comfort of participants, exposed to triangular changes in the ambient temperature, ranging between 15 and 40°C, at two different rates of change. It was hypothesised that the rate of change of ambient temperature would affect the thresholds and magnitude of the thermal comfort zone.

10.3.3 We investigated thermal comfort and sensation of temperature of twelve male participants while exposed to continuously changing ambient temperatures (Ta), varying between 15 and 40°C, and vice versa, with ambient relative humidity maintained at 20%. Participants visited our laboratory three times, during which they conducted three experiments. Upon their arrival to the laboratory, they donned shorts and were instrumented with sensors. Before entering the climatic chamber, they rested quietly for 20-min at the Ta of ~25°C. When entering climatic chamber (chamber air flow: 0.1±0.0°C $m.s^{-1}$), they were immediately seated on a chair, placed on a weight scale for continuous recording of weight loss during the experiment. Once seated, the Ta started to increase, going from 15 to 40°C (named as "heating"), and decrease, going from 40 to 15°C (named as "cooling"), continuously. This triangular change in the Ta was done at, so called, "fast rate" (Figure 16, left panel) and "slow rate" of change (Figure 16, right panel), meaning $1°C.min^{-1}$ and $0.5°C.min^{-1}$ change in the Ta, respectively. One complete cycle included the Ta going from 15°C to 40°C and back to 15°C (one heating and one cooling phase), or going from 40°C to 15°C and back to 40°C (one cooling and one heating phase). Each cycle at both, fast and slow rate, was repeated three times for each participant to observe the variability in reported rates of thermal comfort and sensation. During the experiments, participants were given tablets (iPad, Apple, USA) and were asked to complete a dedicated questionnaire regarding their thermal comfort and sensation every 3-min or whenever they perceived a change in their perception. They were reminded to complete the questionnaire by a visual and vocal timer or by a researcher. Thermal comfort scale included ratings of: 0 = comfortable, 1 = slightly uncomfortable, 2 = uncomfortable, 3 = very uncomfortable. Thermal sensation scale included ratings of: -3 = cold, -2 = moderately cold, -1 = cool, 0 = neutral, 1 = warm, 2 = moderately hot, 3 = hot. With participants seated on a chair placed on a weight scale, weight loss was documented each 5-min. Participants were not allowed to drink during a 150-min experiment.

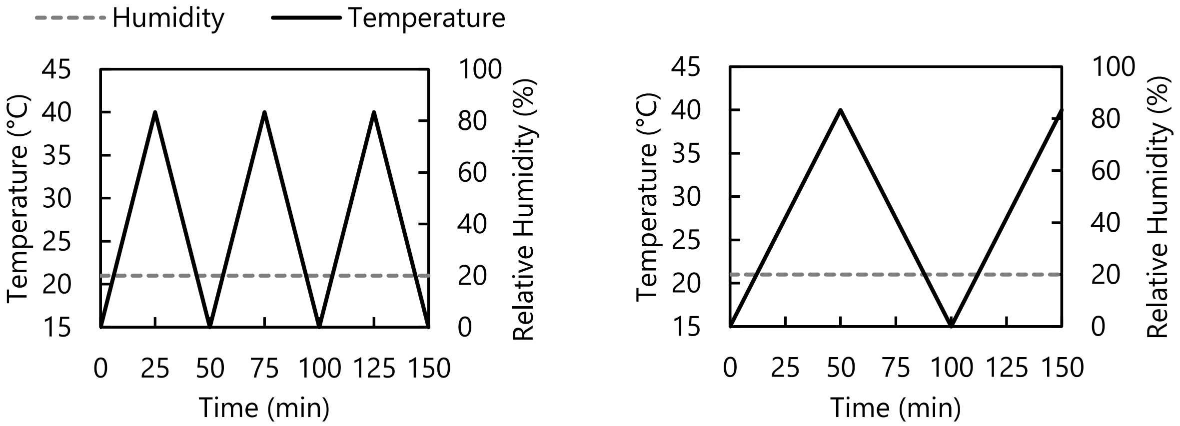

Figure 16. Experimental protocol. Fast (1°C.min^{-1}; left panel) and slow (0.5°C.min^{-1}; right panel) rate of change in the ambient temperature, starting at either 15 or 40°C.

10.3.4 The main finding of the present study is that thermal comfort is influenced by dynamics of the ambient temperature changes, including the direction and rate of change. As can be discerned from Fig. 17, thermal comfort was established at the ambient temperatures between 22–30°C and 21–33°C during fast and slow rate heating, respectively, and between 25–34°C and 23–34°C during fast and slow rate cooling. In general, it was observed that the increasing ambient temperature (heating) established the TCZ at lower ambient temperatures, compared to decreasing ambient temperature (cooling). The difference between the heating and cooling phases in preferred Ta was more evident during the fast rate changes, indicating that rate of change also contributes to the establishment of human thermal comfort.

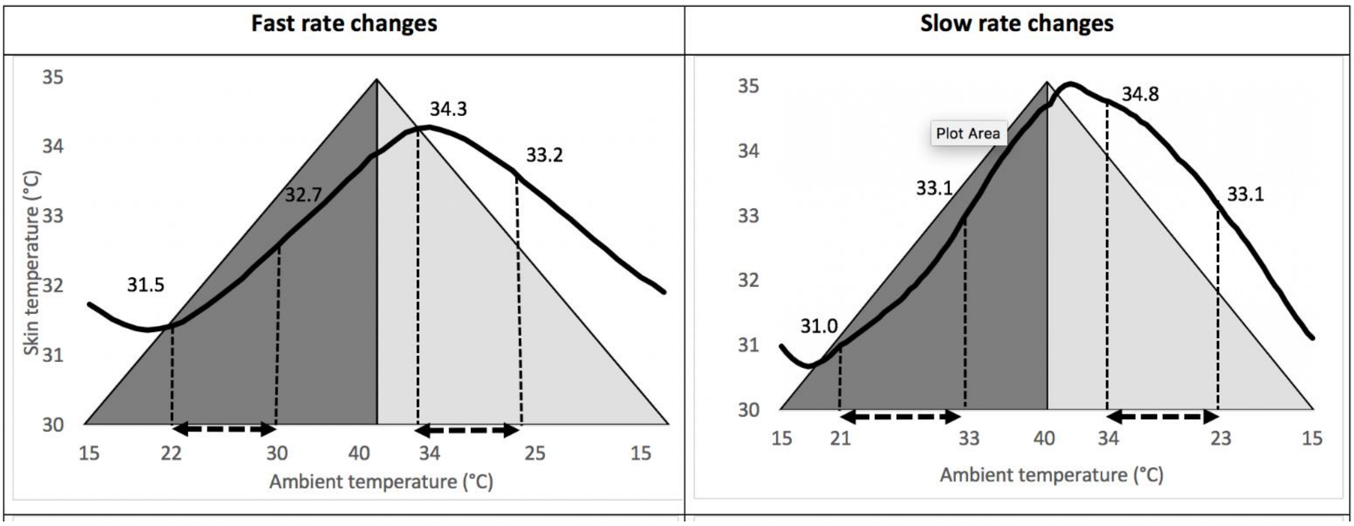

Figure 17: The cutaneous thermal comfort zone (indicated by the arrows in the x axis) during the fast (1°C, left side) and slow (0.5°C, right side) rates of ambient temperature changes. Dark grey part of the triangle in the background indicates the heating phase of the experiment, whereas the light grey part indicates the cooling phase.

10.3.5 The findings of the present study suggest that when evaluating and/or designing thermal environments, the dynamics of the ambient temperature change can significantly affect the establishment of the TCZ.

10.3.6 Several studies have reported on thermal comfort in transient temperature conditions, including cyclical (triangular or sinusoidal) temperature fluctuations, drift and ramp variations (Du et al., 2014; Hensen, 1990; Kolarik, Olesen, Toftum, & Mattarolo, 2007; Kolarik, Toftum, Olesen, & Denmark, 2015; Rohles, 1980; Schellen, van Marken Lichtenbelt, Loomans, Toftum, & De Wit, 2010), which include slow to moderate variations in the ambient temperature (0.5–5°C.h^{-1}). These studies usually simulate everyday life scenarios, with the main focus on insuring the thermal comfort in transient environments and lowering of energy consumption, required by heating, ventilation and air conditioning (HVAC) systems. The design of the present study was different, with the aim being to observe whether thermal comfort would be affected by the direction and rate of change in the Ta. To achieve this, participants were exposed to notable temperature changes within wide ranges, insuring perception and establishment of the TCZ. As observed, the TCZ was significantly affected by direction (heating vs. cooling) at both rates of change in the ambient temperature.

10.3.7 Thermal comfort may be established at a lower cost with a transient thermal environment. Compared to a steady state environment, where the heating, ventilation and air conditioning (HVAC) system needs to be active at all times, transient thermal environments would only require the HVAC system to be on intermittently. As suggested by the results of the present study and that described in section 8, thermal comfort might be achievable at a higher temperature compared to that in a steady state temperature environment. For large manufacturing halls, this avenue of research and development should be considered.

10.3.8 The results of the present and previous studies (see paragraph 10.3.6) would suggest that in order to affect the perception of thermal comfort, the rate of change of temperature has to be of sufficient magnitude to induce a significant dynamic component of the cutaneous thermosensors.

10.4 Clothing and ventilated vest

Heat stress issues in industrial/occupational settings is a combination of environmental/climatic factors (with absolute air temperature and humidity as the predominant stressors for indoor heat load), additional heat from the industrial production process (for example very high in aluminium factories), the workers' metabolic heat production and clothing limiting heat dissipation (helmets and other safety requirements). It is therefore imperative that workers are provided with protective clothing that has appropriate thermal characteristics. Thermal (Rt) and evaporative (Re) resistances may be determined quite easily with thermal manikins. Whole body manikins can evaluate Rt and Re for entire garment ensembles, whereas foot, hand, head and torso manikins can assess Rt and Re for individual components of the garment ensemble (ie. footwear, gloves, helmets, and shirts, respectively; see also Deliverable 3.4).

10.4.1 The thermal characteristics of clothing becomes an important issue, when recommending workers' clothing ensembles. During summer months in the odelo d.o.o. factory, the thermal and evaporative resistances of the clothing ensemble should be minimal. In addition, consideration may also be given to including components that may enhance heat loss. Such an addition would be a ventilated vest. Such vests incorporate a battery operated fan, providing a moderate air flow through the microenvironment between the vest and skin. Ventilated vests are often referred to as evaporative vests, implying that their main function is to enhance evaporative heat loss. Thus, the underlying assumption when using these vests is that sweating has been initiated and that the skin is wet. In a hot ambient, and in the absence of sweating, these vests will not provide any benefit.

10.4.2 A major factor influencing the efficiency of a ventilated vest is the ambient humidity. Assuming fully wetted skin, enhancement of evaporative heat loss will be influenced by the relative humidity in the surrounding air.

10.4.3 We investigated the effect of ambient relative humidity on evaporative heat loss with, and without a ventilated vest, using the humanoid thermal robot/manikin.

10.4.4 In all trials, the skin of the manikin was completely wetted. Measurements of evaporation were made with the manikin naked (blue line in Fig. 18), with the manikin wearing protective clothing with low permeability (red line in Fig. 18), and with the manikin wearing low permeability clothing and a ventilated vest.

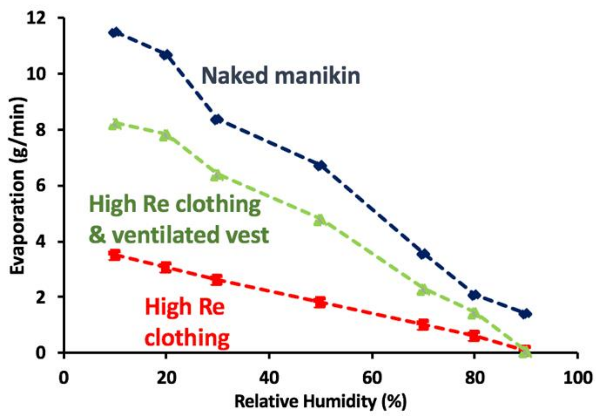

Figure 18: Evaporation from the wetted skin of the manikin over a range of ambient relative humidities in three conditions: naked manikin (blue line), manikin wearing protective clothing with low permeability (high Re clothing; red line), and with the manikin wearing low permeability clothing and a ventilated vest (green line).

10.4.5 Evaporation in the three conditions was measured during exposures to 45°C in a climatic chamber. For each condition the measurements were made for relative humidities ranging from 10% to 90%.

10.4.6 As evident from Fig. 18, for the naked manikin condition evaporation decreased with increasing relative humidity (RH), from 12 g.min^{-1} at 10% RH to 2 g.min^{-1} at 90% RH. Donning the protective clothing low permeability decreased evaporation, such that it ranged from 4 g.min^{-1} at 10% RH to 0 g.min^{-1} at 90% RH. By adding the ventilated vest, evaporation was re-instated, reaching 9 g.min^{-1} at 90% RH and decreasing linearly to 0 g.min^{-1} at 90% RH.

10.4.7 These results confirm the utility of ventilated vests in situations when the skin is wetted.

11. Recommendations

11.1 Strategies for mitigating heat strain of workers in the manufacturing sector

The mitigation of heat stress, and consequently heat strain, in the manufacturing sector may be somewhat more difficult to analyse in situations where the workers need to conduct tasks in a timed manner. In such a manufacturing process it is not possible to evaluate different solutions *in situ*. These need to be planned in advance, and be shown to be effective, before being introduced in the manufacturing process.

11.2 Successful strategies implemented in the manufacturing sector

During the course of the Heat Shield project, we implemented several heat stress mitigating strategies within a manufacturing plant producing automobile rear lights as well as tested selected interventions in an aluminium extrusion company. Combining these experiences with a systematic evaluation of methods and considering their feasibility (for industry specific settings) the following strategies are recommended:

• <u>Increased air flow – either at local workstations or via general ventilation of the production hall</u>: A system of ducts can be installed within a production hall establishing an acceptable air flow in the plant (that may be individually adjusted at the local work stations – alternatively individual workers may use an electrical fan in proximity to their work station). This will enhance/benefit evaporative heat loss and convective (as long as the air temperature is below ~35 °C).

• <u>Optimize hydration strategies</u>: The prevalence of dehydrated workers is in general high (also in the manufacturing industry) – securing easy access to unlimited amounts of cooled water and reminders to rehydrate following work is of utmost importance.

• <u>Breaks and pacing</u>: Workers will eventually slow down or take more infrequent breaks, if the heat load is too high - including brief planned breaks (preferably in cool areas of the plant) or allowing a small lowering of the pace (especially at the onset of a heat wave) may prevent excessive loss of working time later in the day or “post heat wave fatigue” (observed to be as big an issue as the effect during the actual heat wave).

• <u>After work – day to day recovery</u>: During heat waves workers should be encouraged to rehydrate (considering both replacement of water and salt deficits) and spend time in cool environments to allow/contribute to the recovery from the heat stress experienced at work.

• Clothing: Workers should be provided with and/or encouraged to wear clothing with low thermal and evaporative resistance. Many settings require that workers wear protective clothing (which may increase the individual heat strain), but it is possible to implement solutions (ventilation mesh or use more breathable materials for certain parts) without compromising safety (the protective requirements and effects of the clothing). For critical (hot) areas of the manufacturing process, workers may be provided with ventilated/evaporated vests for enhanced evaporative heat loss. In the event that the company is providing workers with any component of their clothing ensemble, then it would be prudent for the company to have these garment components tested with appropriate thermal manikins, thus ensuring that they are issuing workers with appropriate garment components. In a hot environment, the garments should have low thermal resistance (ie. low insulation), and allow optimal evaporation of sweat from the skin. Clothing design should also allow efficient exchange of the air within the clothing microenvironment.

Workers should be encouraged to wear clothing with low thermal and evaporative resistance. For critical (hot) areas of the manufacturing process, workers should be provided with ventilated vests, which will enhance evaporative heat loss.

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Appendix 1

Table 1. 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
Environmental manipulation					
Air conditioning	📄📄📄	+++	$$$	👎👎👎	🍃
Ventilation	📄📄	- to ++	$	👎	🍃🍃
Shading	📄	0 to ++	$	👍	🍃🍃🍃
External cooling					
Cold water immersion	📄📄📄	+ to ++	$$	👎👎	🍃🍃
Phase change garments	📄📄📄	+ to +++	$$	👎	🍃🍃
Cooling packs	📄📄📄	0 to ++	$$	👎	🍃🍃
Ice towels	📄📄	+++	$$	👎👎	🍃🍃
Skin wetting	📄📄	- to +++	$	👍	🍃🍃🍃
Menthol application	📄📄	0 to +++	$	👍👍	🍃🍃🍃
Vacuum glove	📄📄	0 to +	$$$	👎👎	🍃🍃
Internal cooling					
Ice slurry ingestion	📄📄📄	+ to +++	$	👎	🍃🍃
Mixed method cooling					
External and internal cooling	📄📄📄	++ to +++	$ to $$	👎👎	🍃🍃
Hydration					
Hyperhydration	📄📄📄	++	$	👍	🍃🍃🍃
Maintenance	📄📄📄	++ to +++	$	👍👍	🍃🍃🍃
Rehydration	📄📄📄	++ to +++	$	👍👍	🍃🍃🍃
Clothing					
Liquid & air-cooled	📄📄📄	+++	$$$	👎👎👎	🍃
Compression	📄📄📄	- to +	$$	👍👍👍	🍃🍃
Elevated design	📄📄	++	$$	👍👍👍	🍃🍃
Heat acclimation					
Long term	📄📄📄	+++	$ to $$$	👎👎👎	🍃🍃🍃
Medium	📄📄📄	++ to +++	*$ to $$$*	👎👎	🍃🍃🍃
Short	📄📄📄	+ to ++	*$ to $$$*	👎👎	🍃🍃🍃
Nutrition					
Carbohydrate	📄📄📄	0 to +	$	👍👍	🍃🍃🍃
Amino acids	📄📄	0 to ++	$	👍👍	🍃🍃🍃
Electrolytes	📄	++	$	👍👍	🍃🍃🍃
Pacing strategies					
Breaks	📄	0 to +++	$	👍👍 to 👎👎👎	🍃🍃🍃

Pacing		0 to +++	$	to	
Scheduling		?	$	to	

Legend: = Strength of evidence, + (positive) or – (negative) effect, $ = cost, or = feasibility, = sustainability

Appendix 2

Occupational heat stress: considerations for the manufacturing industry in general, and the Hydro-DK aluminium factory (Denmark), in particular.

In addition to the field study being conducted at the odelo d.o.o. manufacturing plant in Slovenia, a separate study was performed by partners UoC, UoT and CETRI at the Hydro-DK aluminium factory in Denmark.

Heat stress issues in industrial/occupational settings is a combination of environmental/climatic factors (with absolute air temperature and humidity as the predominant stressors for indoor heat load), additional heat from the industrial production (very high in Hydro-DK aluminium factories), the workers' metabolic heat production (hence highest heat load Hydro-workers engaged in packing/manual tasks) and clothing limiting heat dissipation (helmets and other safety requirements). Temperatures at production/work-sites may be very heterogeneously distributed, but are often higher than the outdoor (shade) temperature, as industrial machinery adds heat to the outdoor heat load. This is indeed observed in the Hydro-DK production bays, since the heat from aluminium is convective, and not radiant heat. The limited ability to get rid of industrial heat at specific production sites is a challenge that requires attention at the planning stage as well as implementation stage of manufacturing processes.

Occupational heat stress is highly dependent on individual work intensity. For HYDRO-DK, the workers engaged with packing have on average ~2 times higher endogenous heat production [~ 400 watt] than the engineers handling/supervising the machinery [~ 200 watt]) and heat-dissipation possibilities (see below for specific boundary effects provided by special clothing/helmets/safety shoes).

Hence, higher heat stress than prescribed/interpreted from climatic/environmental data is often observed among manufacturing workers. Preliminary research from HEAT-SHIELD at Hydro-DK demonstrate that workers engaged in manual tasks and required to wear protective clothing are especially affected by heat during a large part of the year (from one-third to half of the year). Fatigue, thirst, and notably high head temperatures (for those wearing safety-helmets) were the most frequent issues/symptoms reported. Many workers appear to commence work in a hypo-hydrated state or fail to maintain hydration during the work-shift and dehydration will aggravate heat-issues such as dizziness, fatigue and concentration problems.

To minimize heat-health problems as well as avoid significant loss of productivity, the following actions and precautions should be considered (with timely relevant advices for workers and supervisors) to increase awareness of preventive methods available:

• Allow workers to have scheduled (brief) breaks with "active resting" e.g. planned hydration and cooling (e.g. by one of the below mentioned methods) – overall this will benefit productivity and prevent excessive fatigue or lost work time due to illness. The ability to take breaks is already possible at Hydro-DK, but it could be more formalized.

• Ensure access to cold drinking water (during severe periods crushed ice to maximize cooling) and advise workers to drink on a regular basis – and drink before getting thirsty. Hydro-DK workers have very good access to drinks.

• Make it possible to adjust airflow at individual workstations to facilitate heat dissipation.

• When heat loads are very high, and especially for elderly workers, encourage spreading water on exposed skin to support evaporative cooling. This is not necessary for the workers in Hydro-DK, but could be relevant in very high-heat scenarios.

• Consider optimization of clothing. Although protective clothing is required in many manufacturing setting, it is possible to find (scenario-specific) solutions that allows for protection, but with breathable material that allows for airflow and evaporation. (**see pictures below**)

Effects of clothing inventions

The following is a specific example from the study conducted at DK-Hydro:
• change from traditional T-shirt and “arm-protectors” to high breathable fabricate) and helmet vs. “protective cap” (standard Hydro work-wear)