Chapter 6

Effect of warm-up and precooling on pacing during a 15-km cycling time trial in the heat

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ABSTRACT

Purpose
It is still unclear whether precooling or warm-up should be preferred for endurance exercise in the heat. Therefore, we analyzed the effect of different preparation regimes on pacing during a 15-km cycling time trial in the heat.

Methods
Ten male subjects completed four 15-km time trials (30°C), preceded by different preparation regimes: 10 min cycling (WARM-UP), 30 min scalp cooling of which 10 min cycling (SC+WARM-UP), ice slurry ingestion (ICE) and ice slurry ingestion + 30 min scalp cooling (SC+ICE).

Results
No differences were observed in finish time and mean power output, although power output was lower for WARM-UP than for SC+ICE during km 13-14 (17 ± 16 and 19 ± 14 W, respectively) and than for ICE during km 13 (16 ± 16 W). Rectal temperature at the start of the time trial was lower for both ICE (≈36.7°C) than both WARM-UP (≈37.1°C) conditions and remained lower during the first part of the trial. Skin temperature and thermal sensation were lower at the start for SC+ICE.

Conclusion
In conclusion, the preparation regime providing the lowest body heat content and sensation of coolness at the start (SC+ICE) was most beneficial for pacing during the latter stages of the time trial, although overall performance did not differ.
INTRODUCTION

Generally, athletes will perform an active warm-up consisting of muscular exercise similar to the competitive performance to prepare for the upcoming exercise. Most beneficial physiological responses of a warm-up are associated with increased core and muscle temperature and include: accelerated VO$_2$ kinetics (1), increased nerve conduction rate (2) and decreased muscle stiffness (3). Warming-up has proved to be beneficial for performance during exercises up to 5 min (4), but for longer durations the effects remain equivocal (5).

Although warming-up before exercise can have beneficial physiological effects, performing a warm-up will also elevate core body temperature. This is a major factor causing fatigue and reduced performance during endurance exercise in the heat (6; 7). One method to attenuate the detrimental effect of an elevated core temperature is precooling (8; 9). Precooling increases the heat storage capacity of the body and as a result, it reduces thermal strain and increases performance in endurance and intermittent sprint exercise (10; 11). Therefore, precooling can possibly prevent or delay the reduction in power output that is generally observed during prolonged aerobic exercise in the heat (9) and is suggested to be more beneficial for performance than a warm-up (7).

Several methods have been shown to be successful in cooling the body core and improving endurance exercise performance (10; 12), but few of these are suited for practical use. One method that does appear to be both effective and practically usable is ice slurry ingestion (11; 13; 14). It is effective in reducing core temperature, as the phase change of ice to water retracts extra heat from the body (15). Compared to liquid water ingestion, this leads to a more pronounced decrease in body core temperature, and therefore a greater increase in heat storage capacity (16). The lower core temperature associated with ice slurry ingestion can prevent or delay the reduction in central neural drive that is a major factor causing performance decrements in the heat (17).

Not only the lowering of the core temperature, but also a lower skin temperature and the perception of coolness could increase performance (13; 18). Recently, Schlader et al. (18) stated that thermal perception appears to be an important signal for the selection
and modulation of exercise intensity, possibly by affecting the motivation to continue exercise in the heat (19) and reducing the rating of perceived exertion (RPE). This RPE is generally accepted as an integrator of several physiological, psychological, and environmental signals and is important for the selection and modulation of work rate during self-paced exercise (20). A part of the body that is potentially suited for precooling the skin and increasing the sensation of coolness is the scalp. Although it has a limited surface area (combined with the neck ~8% of total body surface area), it is close to the thermosensitive region of the face and is easily accessible for cooling (21). Moreover, previous studies have showed that cooling of the head improves endurance cycling performance in the heat, which may be explained by a reduction of cardiovascular and thermoregulatory demands and an increased central motor drive (22). Recently, a new convective cooling method for reducing chemotherapy-induced hair loss has become available for clinical use. This method uses glycol-perfused caps to cool the skin of the scalp. By lowering the scalp skin temperature, these caps create a strong sensation of coolness. Also, cooling of the scalp might provide selective brain cooling (23) leading to maintenance of central neural drive during exercise in the heat (22). Both the sensation of coolness and possible selective brain cooling might translate into an RPE-mediated improvement in self-paced exercise performance, even when core temperatures are well below critical values associated with fatigue (24).

Although both a warm-up and precooling have proved to be beneficial for endurance exercise performance, it remains unclear which preparation regime should be preferred for relatively short self-paced endurance exercise in the heat. Furthermore, the additive effect of scalp cooling when the core body temperature is already increased by a warm-up remains unclear. Therefore, the main goal of this study is to investigate the effect of different preparation regimes (involving warm-up, ice slurry ingestion and scalp cooling) on pacing and performance during a 15-km cycling time trial in the heat. In view of the anticipatory regulation of exercise intensity, we expect 15 km to be sufficient to observe changes in pacing pattern as a result of the different preparation regimes (25). We hypothesize that a lower body heat content and sensation of coolness at the start will result in a more beneficial time trial pacing and performance.
MATERIALS AND METHODS

Subjects

Ten healthy and physically active male subjects with an age of 24 ± 5 years, height of 187 ± 7 cm and a weight of 77 ± 6 kg participated in this study. The subjects were recreational cyclists, familiar with cycle ergometer testing and trained 7 ± 3 hrs per week at the time of the study. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate in all testing procedures. Subjects were requested to follow their usual diet and physical activities the last day before each trial. The study was approved by the Research and Ethics Committee of TNO, The Netherlands.

Overview

Subjects visited the lab five times. In the first meeting they were familiarized with the experimental set-up and distance (15 km) of the cycling time trial. During the familiarization session, in which the same protocol was used as in the experimental trials, no physiological parameters were measured. The four following sessions involved the 15-km cycling time trial in the heat (30°C, 50% RH) preceded by one of the different preparation regimes in a moderate climate (22°C): active warm-up by 10-min cycling (WARM-UP), scalp cooling + active warm-up by 10-min cycling (SC+WARM-UP), ice slurry ingestion (ICE), or scalp cooling + ice slurry ingestion (SC+ICE).

Interventions

In the precooling trials (ICE and SC+ICE), a decrease in body core temperature was created by ingestion of ice slurry with added syrup (containing approximately 6 g carbohydrates) for flavour. Subjects were instructed to ingest a total amount of 2 g ice slurry per kg body mass (BM) in 5 min to ensure a standardized ingestion rate. Pilot testing revealed that ingestion of this amount of ice slurry resulted in a $T_{re}$ decrease of $\sim$0.5°C and was well tolerated by the subjects. The ice slurry ingestion period was followed by 15 min of rest, allowing the ice slurry to adequately cool the body. Within the pre-warming trials (WARM-UP and SC+WARM-UP), the subjects cycled at a moderate power of 2 W/kg BM for 10 min. This intensity and duration was chosen to induce beneficial physiological responses associated with a common warm-up without creating
substantial fatigue that could limit subsequent time trial performance. Scalp cooling (SC) was accomplished by wearing a neoprene-covered silicone cooling cap (Paxman, Huddersfield, UK) for 30 min. After this period, stable scalp skin temperatures can be expected (26). When the ears of the subject were inside the cap or when a subject was bald, direct contact with the cooling cap was avoided using gauze swabs. The cap was connected to a cooling machine (Paxman cooler PScalpC-1, Paxman, Huddersfield, UK), which was turned on at least half an hour prior to the experiment to achieve a temperature of the coolant between -9°C and -10°C. All the interventions were carried out in a climatic chamber set at 22°C, after which subjects were transferred to the warm climatic chamber.

Protocol

Each session consisted of a 20-min habituation period in a 22°C climatic chamber (Weiss Enet, Tiel, The Netherlands) after which baseline body temperatures were determined. Then the intervention period started, which lasted 10, 20, or 30 min depending on the experimental condition (Figure 6.1). Subsequently, during a 5-min break, subjects were transferred to an adjacent 30°C, 50% relative humidity (RH) climatic chamber (Weiss Enet, Tiel, The Netherlands). This was followed by a short final preparation period of 3-min cycling at 120 W.

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<tr>
<th>Time (min)</th>
<th>Start SC</th>
<th>Ingestion ice slurry</th>
<th>Start cycling</th>
<th>End cycling and SC</th>
<th>Start warm-up in 30°C</th>
<th>Start time trial</th>
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<tr>
<td>WARM-UP</td>
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Figure 6.1. Timescale for the four interventions. Black dots indicate the applied interventions.
After the final preparation, subjects performed a 15-km self-paced time trial on a cycle ergometer (Lode, Groningen, The Netherlands). During the trial the subjects where blind to performance measures (power, cadence and heart rate), but were informed of completed distance each kilometre. The four time trials were allocated in a balanced order and all experimental sessions of one subject were performed on the same time of the day, separated by at least two days of recovery.

**Measurements**

During the time trials, power output was recorded (Lode Ergometry Manager, Lode, Groningen, The Netherlands) and averages per second were calculated. Knowing the amount of work per second and the total amount of work for the trial, the percentage of trial completion was determined for each second. As percentage of completion reflects distance, mean power output per kilometre could be determined.

Rectal temperature (T\text{re}) was measured using a rectal thermistor (Yellow Springs Instruments 700 series, Yellow Springs, OH, USA). The rectal thermistor was calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk, The Netherlands) using a Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). This certified combination of calibration instruments had an accuracy of ±0.03°C. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and was fixed to the lower back with tape. The sensor was attached to a custom-made data acquisition system (VU University, Amsterdam, The Netherlands), consisting of a data logger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz.

Skin temperature was measured at eight locations (forehead, right scapula, left upper chest, right arm in upper location, left arm in lower location, left hand, right anterior thigh, left calf) with a sample frequency of 0.1 Hz using iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA). A weighted average of the eight iButtons resulted in the mean skin temperature, as described by ISO 9886 (27). Mean body temperature (T\text{body}) was calculated using the following equation: \( T_{\text{body}} = a \times T_{\text{re}} + (1 - a) \times T_{\text{sk}} \) (Eq. 1), where \( a \) was set at 0.6 (\( T_{\text{sk}} < 31.5^\circ \text{C} \)), 0.7 (\( 31.5^\circ \text{C} < T_{\text{sk}} < 33^\circ \text{C} \)) or 0.8 (\( T_{\text{sk}} > 33^\circ \text{C} \)) (28). Forehead temperature (T\text{fh}), one of the eight measured skin temperatures, was also
analyzed separately to get more insight into the effect of scalp cooling on the skin temperature of the forehead.

Thermal perception and comfort were measured on a 9-point and 5-point scale, respectively (29), every 5 km during the 15-km time trial. Rating of perceived exertion (RPE) was measured every kilometre on a 20-point scale (30). Heart rate was measured using a Polar sport tester (Polar Electro, Finland) at 5-s intervals. Nude body mass of the subjects was determined on a weighing scale (Sartorius F300S, Göttingen, Germany) with resolution of one gram, directly before and after exercise.

Statistics
Statistical analysis was performed in SPSS statistical software (SPSS 17.0, SPSS Inc., Chicago, IL, USA). Experimental condition (WARM-UP, WARM+SC, ICE, SC+ICE) was the independent variable, whereas PO, T<sub>re</sub>, T<sub>sk</sub>, T<sub>body</sub>, HR, RPE, TS, and TC were the dependent variables. Significance of effects over time was determined using two-way ANOVAs for repeated measurements, with two within-subject factors (experimental condition and distance completed). Post-hoc analyses used Bonferroni correction to adjust for multiple comparisons. One-way ANOVAs were used to determine the significance of effects of the experimental conditions at separate kilometres as well as on finish times, average PO, TS and TC. Statistical significance was set at the 5% level for each analysis. For differences in finish time, we additionally drew magnitude-based inferences using a 3-level scale of magnitude (positive difference, trivial, negative difference) (31). A trivial difference was defined as the 90% confidence interval of common day to day variation in cycling time trial performance, which amounts ± 30 s (32). Values are reported as mean ± SD.

RESULTS

Effect of preparation regimes

In Figure 6.2, temperature patterns before and during the time trial are shown. In this figure, the first two data points per condition represent the temperature before the intervention (pre-intervention: PI) and at the start of the time trial (0 km). Before the start of the intervention, no significant differences in T<sub>re</sub>, T<sub>sk</sub>, T<sub>body</sub>, and T<sub>fh</sub> were observed between the experimental conditions (p<0.05).
Precooling by ice slurry ingestion resulted in a cooler core at the start of the time trial than performing an active warm-up: $T_{re}$ was significantly lower for SC+ICE (36.67 ± 0.18°C; $p<0.01$) and ICE (36.84 ± 0.31°C; $p<0.05$) than for SC+WARM-UP (37.12 ± 0.34°C) and WARM-UP (37.24 ± 0.27°C). There was a trend that $T_{re}$ was more reduced in SC+ICE than in ICE ($p=0.06$).

The combination of ice slurry ingestion and scalp cooling (SC+ICE) led to a lower $T_{sk}$ at the start of the time trial (32.58 ± 0.37°C) than the other conditions (ICE: 33.10 ± 0.83°C, SC+WARM-UP: 33.17 ± 0.66°C and WARM-UP: 33.57 ± 0.38°C; $p<0.05$ for all comparisons). Similarly, $T_{body}$ at the start of the time trial was significantly lower in the SC+ICE condition compared to all other conditions ($p<0.05$). In addition, $T_{body}$ was lower for ICE compared to WARM-UP ($p=0.01$).

**Figure 6.2.** Temperature patterns ($T_{re}$, $T_{sk}$, $T_{body}$, and $T_{ff}$) pre-intervention (PI), at the start of the time trial (km 0) and averaged per km of the time trial. *Significant difference between SC+WARM-UP and SC+ICE ($p<0.05$). †Significant difference between SC+WARM-UP and ICE ($p<0.05$). ‡Significant difference between SC+ICE and all the other conditions. For clarity of the figure, no error bars are displayed.
Looking at forehead temperature separately, both SC+ICE and SC+WARM-UP decreased $T_{fh}$ substantially ($p<0.05$) to $31.10 \pm 1.79{\degree}C$ and $32.20 \pm 1.79{\degree}C$ at the start of the time trial. This was significantly lower (~3.7{\degree}C and ~2.6{\degree}C, respectively; $p<0.001$) than the conditions without scalp cooling. For SC+WARM-UP, the lower $T_{fh}$ did not result in a lower average $T_{sk}$ as the active warm-up rescinded its effect on $T_{sk}$.

In line with the $T_{sk}$ results, the TS score at the start of the time trial was lower for SC+ICE (0.0 $\pm$ 0.8) than for ICE (0.7 $\pm$ 0.7; $p<0.05$), SC+WARM-UP (0.8 $\pm$ 0.6; $p<0.05$) and WARM-UP (1.4 $\pm$ 0.7; $p<0.001$). However, no significant differences were observed in TC. HR at the start of the time trial in WARM-UP (125 $\pm$ 10 bpm) was higher than for the other conditions (SC+ICE: 111 $\pm$ 11 bpm, ICE: 114 $\pm$ 10 bpm, SC+WARM-UP: 119 $\pm$ 7 bpm; $p<0.05$ for all comparisons).

**Time trial performance**

In Figure 6.3, the average PO per kilometre of the time trial is shown. There was no overall effect between conditions ($p=0.32$). However, during km 13 and 14, PO for SC+ICE (231 $\pm$ 23 and 239 $\pm$ 24 W, respectively) was significantly higher than for WARM-UP (214 $\pm$ 28; $p=0.01$ and 219 $\pm$ 27 W; $p=0.02$, respectively). In addition power output for ICE (230 $\pm$ 32 W) was higher than for WARM-UP during km 13 ($p=0.03$).

![Figure 6.3. Power output during the time trial. *Significant difference between WARM-UP and SC+ICE (p<0.05). #Significant difference between WARM-UP and ICE (p<0.05). For clarity of the figure, no error bars are displayed.](image-url)
This did not result in significant differences in finish time: SC+ICE: 29:07 ± 3:59 ICE: 29:19 ± 04:07 WARM-UP: 29:50 ± 4:07 and SC+WARM-UP: 29:58 ± 4:19 min (p=0.28). Also, when drawing magnitude based inferences (31) on the differences in finish time, the outcomes are unclear. Therefore, from the current data, no meaningful differences in finish time could be detected.

**Physiological responses**

In Figure 6.2, the temperature patterns during the time trial are shown. Regarding T_re, there was a significant overall difference between SC+WARM-UP and ICE (p<0.05) and between SC+WARM-UP and SC+ICE (p<0.05). Analyzed per kilometre, significant differences in T_re between the ice slurry and warming-up conditions were observed during the first half of the trial: SC+ICE and WARM-UP were different during km 1-9, SC+ICE and SC+WARM-UP during km 1-7, ICE and WARM-UP during km 1-6 and ICE and SC+WARM-UP during km 1-4.

During the time trial, T_sk was significantly lower for SC+ICE (34.25 ± 0.74°C) than for WARM-UP (35.29 ± 0.38°C; p=0.02). Per kilometre, differences were found between the ice slurry and active warm-up conditions during the first part of the trial. T_sk in SC+ICE was lower than WARM-UP and SC+WARM-UP during km 1-6. T_sk in ICE was lower than WARM-UP and SC+WARM-UP during km 1-4.

For T_body, differences in T_re and T_sk add up to overall differences of SC+ICE (36.50 ± 0.35°C) vs. both WARM-UP (37.25 ± 0.36°C; p=0.001) and SC+WARM-UP (37.19 ± 0.38°C; p=0.004) and of ICE (36.68 ± 0.43°C) vs. WARM-UP (37.25 ± 0.36°C; p<0.001). The differences with SC+ICE could be observed during each separate kilometre, differences of ICE vs. WARM-UP and SC+WARM-UP during km 1-11.

HR patterns deviated most at the initial stages of the trial. Overall, HR was significantly higher for WARM-UP (170 ± 9) than for SC+WARM-UP (165 ± 10; p=0.04). HR for WARM-UP was higher than for SC+ICE during the first 3 km of the time trial and higher than for ICE during the first 2 km.
Perceptual responses

No overall effect for RPE was observed, but at separate kilometres in the final stages of the time trial, some RPE scores deviated (Figure 6.4). During km 12, SC+ICE (15.8 ± 1.8) scores were significantly lower than WARM-UP (17.3 ± 1.6; \( p=0.03 \)), while in km 14, both SC+ICE (17.3 ± 2.0) and SC+WARM-UP (17.2 ± 2.0) scores were lower than WARM-UP (18.7 ± 1.2; \( p=0.02 \) and \( p=0.04 \), respectively). No significant main effects for TS and TC were observed during the time trial (\( p=0.09 \) and \( p=0.23 \), respectively), nor were there any differences in these scores at separate measurement moments.

**Figure 6.4.** Rating of perceived exertion during the time trial. *Significant difference between WARM-UP and SC+ICE (\( p<0.05 \)). #Significant difference between WARM-UP and SC+WARM-UP (\( p<0.05 \)). For clarity of the figure, no error bars are displayed.

DISCUSSION

The aim of this study was to determine the effect of different preparation regimes on pacing and performance during a 15-km cycling time trial in the heat. The main outcome was that the lower the mean body temperature and sensation of coolness at the start of the time trial, the more beneficial it was for the pacing profile (higher power output) at the final stages. However, this did not result in a higher mean power and a faster finish time. Therefore, we largely have to reject our hypothesis.
Our results are only partly in accordance with Ihsan et al. (13) and Duffield et al. (9), who studied performance during a 40-km cycling time trial after precooling by ice slurry ingestion and cold water immersion, respectively. In line with the current data, both studies showed physiological differences in the first part of the trial and pacing adjustments at the final stages when physiological differences had largely disappeared. However, they also found an improvement in performance while we only observed a difference in power output during km 13 and 14, and no overall effect on performance. Improved performance in endurance exercise performance of >40 min after ice slurry ingestion has also been found in a study on running to exhaustion (14). The mentioned studies are difficult to compare directly with the current study due to methodological differences, but it becomes clear that exercise time is an important issue for obtaining performance benefits from precooling. Nevertheless, although we did not find performance benefits for this 15 km time trial, a higher work rate near the finish as a result of precooling may still be beneficial during tactical races.

Forehead temperature after scalp cooling was, not surprisingly, strongly reduced. This reduction decreased substantially from removal of the cooling cap and the influence on average skin temperature was small from the start of the time trial. The limited physiological effects of scalp cooling may be due to the insulative capacity of the skull. Mathematical modelling suggests that conductive heat loss through the skull surface or the upper airways is minimal (33). Furthermore, Pretorius et al. (34) showed that the head does not contribute more than the rest of the body to heat loss when surface area is taken into account. Although the physiological effects of scalp cooling are limited, this method may have beneficial effects by creating a sensation of coolness. At the start of the time trial, thermal sensation (TS) was lower for SC+ICE than for all the other conditions. Most likely, this was a result of the lower skin temperature caused by the scalp precooling and the ice slurry ingestion. This result is in line with Kato et al. (35) who showed that skin temperature is the most important signal for TS. Although TS was lower at the start of the time trial, the initial power output did not differ between conditions. The relationship between thermal perception and exercise regulation is still debated. Barwood et al. (36) found that inducing a feeling of coolness and increasing thermal comfort by putting on a menthol-sprayed jersey before the start of a 40-km cycling time trial in the heat did not influence the anticipatory selection of power output. On the contrary, Schlader et al. (18), observed that a more favourable thermal sensation and
thermal comfort due to menthol gel application on the face, did increase the total work completed during a fixed-RPE cycling protocol in a moderate ambient conditions. Our data confirm the results of Barwood et al. Possible explanations for the discrepancy in conclusions regarding the importance of these psychophysiological parameters could be the location of the intervention that elicited changes in thermal perception, the period that the psychophysiological parameters were affected and the differences in experimental protocol. In summary, it can be concluded that scalp precooling leads to a marginal decrease in thermal strain and a sensation of coolness at the start of the time trial. However, pacing and performance benefits during the time trial seem to be limited.

Another interesting observation in this study was the significant difference in RPE between WARM-UP and both SC+WARM-UP and SC+ICE during final stages of the time trial (Figure 6.4). The higher RPE for WARM-UP was accompanied by a significantly lower power output compared to SC+ICE. This finding is not in line with the concept that athletes adjust their work rate to prevent an excessive rise in RPE during exercise to maintain (thermal) homeostasis and to successfully complete the exercise bout (37). According to this theory, the increase in RPE should be similar across conditions since power output is adjusted to prevent differences in RPE between trials of the same length. The higher RPE towards the end of the trial in WARM-UP can possibly be explained by the fact that that subjects experience such an amount of strain in the beginning of the race that the hazard score (38) becomes too high. Down-regulating power output at this point of the time trial is not sufficient to get an RPE similar to the other conditions. However, it remains questionable whether the observed difference in RPE towards the end of exercise is caused by actual (psycho)physiological effects of the warm-up, especially since no effects on the end-spurt phenomenon were observed.

In addition to the performance enhancing effect of precooling, also the carbohydrate content of the ice slurry might have affected performance. The ~18 g syrup that was added to the ice slurry to facilitate ingestion contained approximately 6 g of carbohydrates, providing 100 kJ of (extra) energy to the exercising muscles. It is unlikely that this ingestion of carbohydrates before medium-duration aerobic exercise (<45 min) improves performance by extending body glycogen content, since depletion of already available energy stores is not expected to be a performance-limiting factor (39).
However, it has been reported that ingestion of carbohydrates can also improve performance by a non-metabolic pathways, like the activation of reward centres in the brain and increasing the excitability of the motor cortex (40). Since in our study the higher power output only became apparent in the final kilometres of the trial, it is not to be expected that the carbohydrates that were ingested more than 20 min before the start of exercise caused this increase in work rate.

PERSPECTIVES

In this study, we compared the effect of four preparation regimes with different combinations of active warm-up, ice slurry ingestion and scalp cooling on 15-km cycling time trial pacing in the heat. The preparation regime providing the lowest body heat content and sensation of coolness at the start of the time trial (ice slurry ingestion + scalp cooling) appeared to be most beneficial for pacing in the latter stages. Moreover, precooling the core with ice slurry ingestion seems to be more effective in accomplishing this benefit than increasing the sensation of coolness with scalp cooling. The observation that precooling provides benefits in the final stages of self-paced exercise in the heat is in accordance with previous studies (9; 13; 14). However, in contrast to these studies, overall performance in the current experiment was not significantly improved after precooling. Possible explanation for this could be the limited length of the time trial.

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Chapter 7

Effects of wind application on thermal perception and self-paced performance

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Submitted for publication
ABSTRACT

Purpose
Physiological and perceptual effects of wind cooling are often intertwined and have scarcely been studied in self-paced exercise. Therefore, we aimed to investigate 1) the independent perceptual effect of wind cooling and its impact on performance and 2) the responses to temporary wind cooling during self-paced exercise.

Methods
Ten male subjects completed four trials involving 15 min standardized incremental intensity cycling, followed by a 15 km self-paced cycling time trial. Three trials were performed in different climates inducing equivalent thermal strain: hot humid with wind (WIND) and warm humid (HUMID) and hot dry (DRY) without wind. The fourth trial (W3-12) was equal to HUMID, except that wind cooling was unexpectedly provided during km 3-12. Physiological, perceptual and performance parameters were measured.

Results
Subjects felt generally cooler during the WIND than the HUMID and DRY trials, despite similar heart rate, rectal and skin temperatures and a WBGT of ~4°C higher. The cooler thermal sensation was not reflected in differences in thermal comfort or performance. Comparing W3-12 to HUMID, skin temperature was $1.47 \pm 0.43^\circ C$ lower during the wind interval, leading to more favourable ratings of perceived exertion, thermal sensation and thermal comfort. Overall, power output was higher in the W3-12 than the HUMID-trial (256 ± 29 vs. 246 ± 22 W), leading to a 67 ± 48 s faster finish time.

Conclusion
In conclusion, during self-paced exercise in the heat, wind provides immediate and constant benefits in physiological strain, thermal perception and performance. Independent of physiological changes, wind still provides a greater sensation of coolness, but does not impact thermal comfort or performance anymore.
INTRODUCTION

For optimal performance in hot conditions, athletes need to determine their pacing strategy in such a way that exercise intensity is regulated to maximal level without collapsing prematurely due to heat exhaustion. However, the mechanisms underlying the regulation of exercise in the heat are still largely unknown. Current theories focus on the rating of perceived exertion (RPE) as the controlled parameter during pacing in the heat. It is proposed that numerous afferent signals are integrated into the RPE, mediating exercise pacing by an anticipatory adjustment in work load (1-6). Skin temperature is thought to be one of the main inputs for this regulatory mechanism (7-9).

Whole body wind application cools the skin by increasing evaporative and convective power (10; 11). As a result wind effectively lowers thermal strain and improves thermal perception (11-16). Thermal strain refers to the rise in body temperature and activation of thermoregulatory mechanisms in response to thermal stress (17), the heat load on the body. Thermal perception is the way in which a subject perceives his thermal status, here considered to cover both thermal sensation (TS; how warm/cold do you feel) and thermal comfort (TC; how comfortable do you experience these thermal conditions). As a result of its beneficial thermal effects, wind cooling has been shown to improve exercise endurance time. Head and whole body ventilation have been reported to improve cycling time to fatigue by >50% (11; 12).

It is unclear whether only thermal perception is relevant to obtain such beneficial effects, or that an actual change in skin temperature (and thus thermal strain) is required. Recently, two studies used menthol application to induce a sensation of coolness while keeping a similar thermal state, trying to separate thermal perception and thermal strain. Schlader et al. (18) concluded that thermal perception is capable of controlling thermoregulatory behaviour during exercise. On the contrary, Barwood et al. (19) reported that thermal perception did not drive exercise pacing during a 40 km cycling time trial. These opposing results do not allow any inference regarding the independent perceptual effect of wind on pacing and performance.
Further, the beneficial thermal effects of wind cooling (irrespective of its physiological or perceptual origin) and its consequences for performance, have largely been studied during fixed load exercise protocols (11; 12; 14). Few studies investigated how the effects of wind cooling on thermal perception, pacing and performance translate to self-paced exercise. Yet, self-paced exercise is most common in sports and operational settings. More insight into the relationships between wind, thermal perception and self-paced exercise responses could improve prediction of behaviour and optimize performance, well-being and safety guidelines.

Because of the deficient knowledge on the independent perceptual impact and the self-paced exercise responses of wind cooling, this study has two main purposes: 1) to separate physiological and perceptual climatic effects and investigate whether a windy climate with similar thermal strain but different thermal perception than climates without wind, leads to variations in pacing and performance and 2) to investigate which physiological, perceptual, pacing and performance benefits are provided by sudden whole body wind application during a self-paced cycling time trial.

To address the first purpose, we compared submaximal fixed-paced and maximal self-paced cycling in a hot-humid climate with wind (WIND), a warm-humid climate without wind (HUMID) and a hot-dry climate without wind (DRY) inducing equivalent thermal strain. Equivalent thermal strain could theoretically be accomplished by creating conditions with a similar wet bulb globe temperature (WBGT). The WBGT gives a single measure for thermal stress, including ambient temperature, relative humidity, radiation and wind and may determine whether exercise restrictions are warranted (20). However, there are indications that in practice the relationship between WBGT and thermal strain may not always be consistent, underestimating conditions in which evaporation is limited (20-23). Therefore, pilots using a standardized submaximal exercise protocol were accomplished to find conditions inducing a similar heart rate (HR) response. Because of the similar thermal strain, our first hypothesis was that all conditions would result in a similar thermal perception, pacing pattern and performance.
To address the second purpose, subjects cycled a fourth trial (W3-12) in which wind was unexpectedly turned on from km 3 to 12. The ambient temperature, humidity and protocol were equal to the HUMID condition, which functioned as control condition for this part of the study. We expected an instantaneous decrease in $T_{sk}$ in the W3-12 condition compared to HUMID when turning on the wind. Based on previous research (11; 12; 24), our second hypothesis was that the lowered $T_{sk}$ would decrease thermal strain and improve thermal perception, leading to an attenuation in RPE. Subsequently, work load was expected to be increased in order to maintain the planned RPE template.

**METHODS**

**Subjects**

Ten healthy male recreational cyclers volunteered to participate in this study. Subjects had an age of 24 ± 5 years, height of 186 ± 6 cm, body weight of 81 ± 5 kg and were active in sports for 10 ± 8 hours per week. Each subject was fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate in all testing procedures. Subjects were requested to follow their usual diet and physical activities the last day before each trial. The study was approved by the Research and Ethics Committee of TNO (Soesterberg, The Netherlands).

**Design**

Subjects participated in one familiarization and four experimental sessions in different climatic conditions. All trials involved 15 min submaximal cycling at a standardized incremental intensity, followed by a maximal 15 km self-paced cycling time trial.

The familiarization session took place in moderate conditions of 18°C ambient temperature ($T_{amb}$) and 50% relative humidity (RH). This trial aimed to determine the right bicycle settings, get used to the entire experimental protocol and practice the 15 km time trial in order to get a feeling for the right pacing.
The four experimental sessions took place in strenuous conditions with different combinations of T\(_{\text{amb}}\), RH and wind (Table 7.1). The climatic characteristics of condition 1-3 were established in various pilot sessions, which indicated that these microclimates induced a comparable physiological strain during standardized submaximal exercise, operationalized by HR response. The W3-12 condition was equal to the HUMID condition, except for the wind intervention. The wind tunnel was turned on unexpectedly at the 3 km mark and turned off unexpectedly at the 12 km mark. Subjects did not have any prior knowledge on this intervention. Wind speed was set at 4 m/s, as Saunders et al. (11) showed that most of the reduction in heat storage is realized in the 0-3 m/s range.

The submaximal part of the sessions aimed to determine thermal strain and thermal perception during standardized exercise, the maximal time trial dealt with self-paced performance. The experimental sessions were allocated in a balanced order and subjects were ignorant of the exact test conditions. Each subject performed his sessions on the same time of the day, separated by at least two days of recovery.

**Table 7.1. Climatic conditions of the experimental sessions.**

<table>
<thead>
<tr>
<th>Condition</th>
<th>T(_{\text{amb}})</th>
<th>RH</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIND</td>
<td>33°C</td>
<td>80%</td>
<td>4 m/s (entire session)</td>
</tr>
<tr>
<td>DRY</td>
<td>33°C</td>
<td>40%</td>
<td>-</td>
</tr>
<tr>
<td>HUMID</td>
<td>28°C</td>
<td>80%</td>
<td>-</td>
</tr>
<tr>
<td>W3-12</td>
<td>28°C</td>
<td>80%</td>
<td>4 m/s (time trial km 3-12)</td>
</tr>
</tbody>
</table>

**Protocol**

Just before a measurement session, participants redressed, attached a heart rate (HR) sensor and inserted a rectal probe themselves. Each session started with a 15-min habituation period in the climatic chamber (Weiss Enet, Tiel, The Netherlands), which comprised seated rest. During the habituation period, skin temperature (T\(_{\text{sk}}\)) sensors were attached and after taking place on the bicycle, the oxygen analysis apparatus was connected. This was followed by a 3-min rest measurement. Then the submaximal exercise was executed, consisting of 5x3 min cycling at 80-100-120-140-160 W. During a
A 5-min break the oxygen analysis equipment was removed and subjects prepared for the time trial. Subjects performed a 15 km self-paced time trial with the instruction to finish in the fastest possible time. During the trial subjects were informed of completed distance each kilometre. Finally subjects got 10 min of (active) recovery before ending the measurement. The entire experimental protocol in the climatic chamber, which is summarized in Table 7.2, took on average ~80 min. Subjects were allowed to drink water at libitum. Nude body mass and water bottle mass were measured just before and after the experimental protocol.

Table 7.2. Experimental protocol.

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Activity</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Habituation</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Rest measurement</td>
<td></td>
</tr>
<tr>
<td>15 (5x3)</td>
<td>Submaximal test</td>
<td>80-160 W</td>
</tr>
<tr>
<td>5</td>
<td>Break</td>
<td></td>
</tr>
<tr>
<td>Variable</td>
<td>15 km time trial</td>
<td>Maximal</td>
</tr>
<tr>
<td>10</td>
<td>Recovery</td>
<td></td>
</tr>
</tbody>
</table>

Measurements

Exercise was performed on a Lode Excalibur bicycle ergometer, using Lode Ergometry Manager (Lode, Groningen, The Netherlands) to record power output (PO) during the time trial. The bicycle ergometer was placed in a wind tunnel (DCTLL 850-8, Ziehl-Abegg, Künzelsau, Germany). Wind speed was measured with a flow meter (LV110, Kimo Instruments, France). The WBGT was measured with a heat stress monitor (QUESTEMP°36, Quest Technologies, WI, USA) just before the exercise session, during the break and just after the time trial, after which a single average session value was calculated. Heart rate (HR) was measured using a Polar sport tester (Polar Electro, Finland) at 5 s intervals.

Rectal temperature ($T_{re}$) was measured using a rectal thermistor (Yellow Springs Instruments 400 series, Yellow Springs, OH, USA). The rectal thermistor was calibrated before data acquisition in a thermal water bath (TLC 15, Tamson Instruments, Bleiswijk,
The Netherlands) using a Pt100 digital temperature indicator (P650, Dostmann Electronic, Wertheim-Reicholzheim, Germany) with resistance temperature probe (PD-13/S, Tempcontrol, Voorburg, The Netherlands). This certified combination of calibration instruments had an accuracy of ± 0.03°C. The rectal probe was inserted to a depth of 10 cm beyond the anal sphincter and the end was fixed to the lower back with tape. The sensor was attached to a custom-made data acquisition system (VU University Amsterdam, The Netherlands), consisting of a data logger with a medical power supply and Labview software (National Instrument, Austin TX, USA). Sample frequency was set at 1 Hz.

$T_{sk}$ was measured at eight locations with a sample frequency of 0.1 Hz using iButtons (DS1922L, Maxim Integrated Products Inc, Sunnyvale, CA, USA). A weighted average of the eight iButtons resulted in the mean $T_{sk}$, as described by ISO 9886 (25).

$T_{S}$ and $T_{C}$ were measured on a 9-point and 5-point scale respectively (26), just before the submaximal and maximal exercise tests, at the end of each submaximal exercise step and at every 5 km mark during the 15-km time trial. RPE was measured at the end of each submaximal exercise step and at every kilometre of the time trial on a 20-point scale (27). Nude body mass (BM) and water bottle mass was determined on a weighing scale (Sartorius F300S, Göttingen, Germany) with resolution of one gram, directly before and after exercise. From these weightings, sweat rate and fluid ingestion could be determined.

**Data analysis**

Average HR and body temperature values were calculated across the final minute of the rest measurement (rest) and each fixed-paced exercise step, as well as across the final 30 s before the start of the time trial (start) and the final 30 s of the recovery period (rec). Regarding the time trial, the percentage of trial completion was determined for each sample dividing the amount of work performed at that moment by the total amount of work for the trial. As percentage of completion reflects distance, mean PO, HR, respiratory values and body temperatures per kilometre could be determined.
Statistical analysis was performed using SPSS (SPSS 17.0, SPSS Inc., Chicago, IL, USA) and Statistica (version 10, StatSoft Inc., Tulsa, OK, USA) statistical software. In a first analysis, the experimental conditions WIND, DRY AND HUMID were compared to cover our first research question. A second analysis compared the conditions HUMID and W3-12 to cover our second research question.

One-way ANOVAs were used to evaluate effects of experimental condition at separate data points (rest, each fixed-paced exercise step, start, each time trial kilometre and/or rec), as well as to determine significance of overall effects for fluid parameters and finish time. Further, overall differences over time were determined for HR, $T_{re}$, $T_{sk}$, RPE and PO during both the fixed interval (rest and fixed-paced exercise) and the self-paced interval (time trial), using two-way ANOVAs for repeated measurements with two within-subject factors (experimental condition and trial phase). For PO, interaction with time was evaluated to detect any pacing differences.

For the analyses including three conditions, post-hoc calculations were applied using Bonferroni correction to adjust for multiple comparisons. Statistical significance was set at the 5% level for each analysis. Values are reported as mean ± standard deviation (SD).

RESULTS

In each substudy (climate comparison and wind cooling), two subject had to be excluded due to physical issues, preventing a valid comparison of the trials. As a result, all analyses have been done on eight subjects, seven of which are included in both substudies.

The temperature and relative humidity settings of the climatic chamber were very close to the measured values. During all experimental conditions, $T_{amb}$ was on average 0.13 ± 0.13°C and RH 2.28 ± 1.28% higher than the set value. This resulted in the following WBGT values: WIND 30.7 ± 0.16°C; DRY 26.4 ± 0.15°C; HUMID 26.5 ± 0.08°C; W3-12 26.0 ± 0.04°C and 26.4 ± 0.07°C with and without wind respectively.
Climate comparison (WIND vs. DRY vs. HUMID)

Heart rate and thermal responses (Figure 7.1)
In accordance with our purpose to compare 3 climates inducing similar physiological responses, there were no differences in HR and $T_{re}$ between WIND, DRY and HUMID during the fixed interval of the protocol. However, across this entire interval $T_{sk}$ in WIND and DRY was higher than in HUMID ($\Delta T_{sk}$: 0.70 $\pm$ 0.35°C and 0.91 $\pm$ 0.36°C respectively; $p<0.01$). During the time trial, HR, $T_{re}$ and $T_{sk}$ did not show any overall effects, but there were slight HR and $T_{sk}$ differences during some separate kilometres.

Perceptual responses (Figure 7.2)
WIND resulted in a more favourable TS score than DRY and HUMID at the higher intensities of the fixed-exercise protocol, as well as just before the start of the time trial ($p<0.01$). TS for WIND remained more favourable than HUMID the entire time trial ($\Delta TS$ 0.9 $\pm$ 0.5; $p<0.01$), whereas WIND felt only cooler than DRY at 10 km ($\Delta TS$ 0.9 $\pm$ 0.8; $p<0.01$). TC did not differ during the fixed-exercise test or time trial, although HUMID tended to be less comfortable than DRY at 160 W ($\Delta TC$ 0.7 $\pm$ 0.7; $p=0.05$). RPE did not show any differences between conditions over time nor at separate measurement points during the entire trial.

Performance responses (Figure 7.3, Table 7.3)
In Figure 7.3 the pacing profile of the 15 km time trial is shown. There were no differences in PO between conditions across the entire time trial ($p=0.24$), although PO was higher in the DRY condition during a few separate kilometres ($p<0.05$). Logically, finish times did not differ either.

Fluid balance (Table 7.3)
Sweat rate during the HUMID condition was lower than during DRY ($\Delta$ sweat rate: 0.12 $\pm$ 0.08 L/h; $p<0.05$) but was just not significantly different from WIND ($p=0.052$). As fluid ingestion did not show any differences between conditions, percentage BM loss was also lower for HUMID than for DRY ($\Delta$ BM loss: 0.19 $\pm$ 0.23%; $p=0.04$), but not different between HUMID and WIND ($p=0.20$).
Figure 7.1. Average patterns of heart rate (A), rectal temperature (B) and skin temperature (C) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; b: WIND significantly different from HUMID; c: DRY significantly different from HUMID.
Figure 7.2. Average patterns of thermal sensation (A), thermal comfort (B) and rating of perceived exertion (C) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; b: WIND significantly different from HUMID.
Figure 7.3. Average patterns of power output during the 15 km time trial. Error bars indicate SEM. The depicted conditions include WIND (33°C, 80% RH, 4 m/s wind), DRY (33°C, 40% RH, no wind) and HUMID (28°C, 80% RH, no wind). a: WIND significantly different from DRY; c: DRY significantly different from HUMID.

Table 7.3. Mean power output (PO), finish time, sweat rate and BM loss ± SD.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean PO (W)</th>
<th>Finish time (min:s)</th>
<th>Sweat rate (L/h)</th>
<th>BM loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIND</td>
<td>249 ± 31</td>
<td>26:09 ± 3:26</td>
<td>0.87 ± 0.19</td>
<td>0.50 ± 0.36</td>
</tr>
<tr>
<td>DRY</td>
<td>248 ± 30</td>
<td>26:05 ± 3:37</td>
<td>0.90 ± 0.17</td>
<td>0.53 ± 0.41</td>
</tr>
<tr>
<td>HUMID</td>
<td>244 ± 26</td>
<td>26:37 ± 3:10</td>
<td>0.79 ± 0.25*</td>
<td>0.29 ± 0.44*</td>
</tr>
</tbody>
</table>

*Significantly different from DRY
Wind cooling (HUMID vs. W3-12)

Heart rate and thermal responses (Figure 7.4)
As expected in equal conditions, no significant differences were observed before the start and during the first 3 km of the time trial. Regarding the wind interval, HR did not show an effect over time ($p=0.08$), but was lower for W3-12 during km 9, 10 and 11 (mean $\Delta$HR: $4.6 \pm 4.4$ bpm, $p<0.05$). $T_{re}$ was similar for both conditions across the wind interval and during each separate kilometre. However, wind application induced a clear difference in $T_{sk}$, with a main effect across the wind interval ($\Delta T_{sk}$: $1.47 \pm 0.43^\circ C; p<0.01$). $T_{sk}$ also differed at each separate kilometre from km 4 to 15, being maximally $2.00 \pm 0.57^\circ C$ lower for W3-12 during km 12 ($p<0.01$).

Perceptual responses (Figure 7.5)
Also for TS, TC and RPE, no differences were observed before the start of the time trial. But during the time trial, the W3-12 condition resulted in a more favourable TS and TC at both measurement points (mean $\Delta$TS: $1.8 \pm 1.3; p<0.01$ and mean $\Delta$TC: $0.8 \pm 0.7; p<0.01$), with TS still being rated slightly better at 15 km. RPE showed a main effect across the wind interval, W3-12 being $0.7 \pm 0.6$ lower ($p<0.05$). At separate kilometres, RPE was lower in km 8 to 11, with the largest difference (1.0) at km 10.

Performance responses (Figure 7.6, Table 7.4)
Across the entire trial, subjects had a higher PO in the W3-12 than the HUMID trial (256 ± 29 vs. 246 ± 22 W; $p<0.01$), leading to a $67 \pm 48$ s faster finish time. There was no effect across the first three km interval ($\Delta$PO: $4 \pm 7$ W, $p=0.10$), but there was during the wind interval ($\Delta$PO: $13 \pm 9$ W, $p<0.01$). Per kilometre, PO differences between conditions were detected in km 4 to 14. These differences were largest in km 12 and 13 (20 W).

Fluid balance (Table 7.4)
There were no differences between conditions regarding sweat rate, fluid ingestion or BM loss.
Figure 7.4. Average patterns of heart rate (A), rectal temperature (B) and skin temperature (C) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). Error bars indicate SD. The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference at separate measurement points.
Figure 7.5. Average patterns of thermal sensation (A), thermal comfort (B) and rating of perceived exertion (C) during the experimental protocol of rest, fixed paced submaximal exercise, 15 km time trial and recovery (rec). The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference.
Effect of wind application on thermal perception and performance

**Figure 7.6.** Average patterns of power output during the 15 km time trial. Error bars indicate SEM. The depicted conditions include HUMID (28°C, 80% RH, no wind) and W3-12 (28°C, 80% RH, 4 m/s wind from 3-12 km). * denotes a significant difference at separate kilometres.

**Table 7.4.** Mean power output (PO), finish time, sweat rate and BM loss ± SD.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mean PO (W)</th>
<th>Finish time (min:s)</th>
<th>Sweat rate (L/h)</th>
<th>BM loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HUMID</td>
<td>246 ± 22</td>
<td>26:22 ± 2:40</td>
<td>0.77 ± 0.27</td>
<td>0.26 ± 0.44</td>
</tr>
<tr>
<td>W3-12</td>
<td>256 ± 29*</td>
<td>25:15 ± 3:11*</td>
<td>0.75 ± 0.20</td>
<td>0.27 ± 0.30</td>
</tr>
</tbody>
</table>

*Significantly different from HUMID

**DISCUSSION**

The main purpose of this study was to investigate the effects of wind application on thermal perception, pacing and performance during exercise in the heat. We can largely accept our first hypothesis: although we found that a climate with wind felt cooler, it was not more comfortable than windless climates that induced a comparable thermal strain nor did it change perceived exertion, pacing and performance. This suggests that thermal sensation itself does not affect exercise performance. Our second hypothesis was confirmed: when wind temporarily reduced thermal stress during a time trial interval, it provided immediate benefits in $T_{sk}$, thermal perception and RPE, leading to an increased PO. These benefits were maintained throughout the race without imposing a higher
thermal strain. It is proposed that deviations in the RPE pattern were followed by adjustments in PO.

**Climate comparison**

All climates resulted in similar HR and $T_{re}$ responses during rest and standardized submaximal exercise. Therefore, the intention to impose climates with a comparable thermal stress was successful. Nevertheless, $T_{sk}$ was significantly lower (~0.5-0.9°C) in the HUMID than the other conditions. As the lower $T_{sk}$ is not reflected in HR and $T_{re}$, it is presumed to have limited meaning regarding thermal strain. Increased skin wettedness in combination with lower $T_{amb}$ may explain the lower $T_{sk}$ measurements. Similar HR and $T_{re}$, but lower $T_{sk}$ responses in humid vs. dry conditions at equivalent WBGT (29°C) have been observed before (28).

Previous research showed that thermal perception and exercise performance are related to microclimatic conditions, including $T_{amb}$, wind speed and RH (12; 16; 29; 30). However, climatic factors have scarcely been balanced at equivalent thermal stress to enable the separation of physiological and psychological effects. Even though physiological responses are similar, the perception of strain may differ. In this study, it appears that wind has a beneficial effect on TS, independent of differences in body temperatures and HR. In contrast to previous reports using wind cooling (24), this finding indicates that TS is not necessarily dependent on $T_{sk}$. Apparently the air movement itself is sufficient to trigger cold receptors in the skin.

TC displayed another pattern than TS, with no differences between conditions up to 140 W. So the more favourable TS of the WIND condition did not translate into a more favourable TC. Possibly, the 5-point scale was not sufficiently sensitive, with only one score on the ‘positive’ side (i.e. comfortable). On the other hand, a similar disagreement between TS and TC was visible during the time trial when ratings were spread over the entire scale. Further, TC is reported to depend on both core and skin temperature (31). The similar core temperatures and lack of large $T_{sk}$ differences, apparently led to similar TC ratings. Yet, note that HUMID tended to be judged less comfortable at 160 W. As TC is determined by skin wettedness above a certain threshold (15), this likely explains the higher TC rating at 160 W. Summarizing, wind and humidity are able to induce perceptual effects independent of absolute $T_{sk}$.
During the time trial, TS in the WIND condition continued to be lower, but all other physiological and perceptual measures were comparable. Pacing and performance did not show substantial differences either, so self-paced performance appeared not to be driven by TS. This agrees with the conclusion of Barwood et al. (19) that TS, manipulated by menthol spray, is not a driver of early pacing during a 40 km time trial. However, the similar conclusion they drew on TC cannot be confirmed, as TC was not affected in our time trial.

With a high water vapor pressure and a lack of wind, HUMID was the most difficult condition to evaporate sweat. The resulting increase in skin wettedness apparently attenuated the drive to sweat during the trial, leading to a more than 10% lower sweat rate. It has been reported that sweat loss can even be one-third less than in humid than in dry climates with similar WBGT (32). As drinking behaviour did not differ between conditions, this indicates that thermally comparable conditions that facilitate evaporation by low humidity and/or wind, seem to bear more risk for dehydration than humid low-wind conditions.

**Wind cooling**

Unexpected wind application during a time trial in warm humid conditions substantially reduced thermal strain, despite a nearly stable WBGT value. Wind instantly induced a decrease in $T_{sk}$ and an improvement in thermal perception and RPE. This resulted in a direct increase in PO, although it cannot be excluded that a psychological reflex, increasing PO to maintain speed when facing head wind, also plays a role. Wind cooling fully compensated for the rise in $T_{sk}$ during the HUMID condition, leading to a 2°C lower $T_{sk}$ in the wind trial. It confirms the capacity of wind as a cooling strategy, increasing evaporative power (10; 13).

The higher PO was maintained throughout the wind interval at similar $T_{re}$ and at similar or lower HR values than during the HUMID-trial, reflecting the lower thermal stress imposed on subjects during the wind trial. The consistency in $T_{re}$ response despite a climate induced performance difference, is in agreement with Tatterson et al. (30) who studied 30 km self-paced cycling in 23°C and 32°C. It suggests an important role for core temperature in regulating PO. Tucker et al. (4) postulated that not absolute temperature, but rate of heat storage mediates an anticipatory adjustment in exercise.
intensity. As absolute $T_{re}$ was relatively low, but rate of heat storage substantial, the current data support this notion. It is generally accepted that hyperthermic fatigue has a central origin (33; 34), so it could be speculated that the brain senses the rate of heat storage and consequently adjusts the drive to exercise by neurophysiological mechanisms (30).

Obviously, wind improves the rating of TS and TC during fixed paced exercise (12; 14; 16). This study showed that also during a self-paced time trial, subjects felt cooler, more comfortable and slightly less exerted when wind was present, despite a higher PO and similar $T_{re}$. The wind intervention shows that a change in $T_{sk}$ is clearly related to a similar change in TS. So although the first part of this study showed that TS is not necessarily dependent on $T_{sk}$, a change in $T_{sk}$ does affect TS. This is in line with multiple studies indicating that TS is predominantly determined by $T_{sk}$ (24). Again, the TC pattern seems to agree with the notion that TC depends on both skin and core temperature (24; 31). However, the observation that TC habituates to a decrease in $T_{sk}$, following the dynamic behaviour of the cutaneous cold receptors (24), could not be confirmed.

The RPE pattern of the wind trial is partly in accordance with the theory stating that RPE mediates exercise pacing (3). The initial change in RPE pattern at the fourth kilometre was counterbalanced by an instant rise in PO. However, the slight RPE deviation in the following kilometres was not reflected in PO until the 10$^{th}$ km. It suggests that subjects are restrained to prematurely deviate from their original pacing template. They seem to ‘save’ some energy until a certain threshold in RPE deviation and/or distance is passed. This threshold might be represented by the hazard score, which is the product of RPE and fraction of the trial remaining (35). In addition, the conservative RPE pattern in the wind trial may also be explained by the core temperature, which increased at a similar rate as in the control condition and may have inhibited the central drive to accelerate early in the trial. Further, subjects may have feared for more unexpected interventions, and may have limited their PO likewise.

Notably, turning off the wind at 12 km did not result in substantial pacing adjustments, although all wind-induced benefits on physiological and perceptual measures were
nearly or completely abolished during these last 3 km. Probably, time to finish was sufficiently short at that moment to ignore these adverse signals. Further, both conditions showed the well-known end spurt phenomenon to a similar extent. At last, moderate wind cooling during the middle 60% of the race resulted in a significant 67 s time benefit, emphasizing the potential of wind cooling for performance improvement.

The improved performance results of the W3-12 condition are in line with previous studies precooling the skin independently by whole body immersion (36). It suggests that a lower Tsk and the accompanying benefits for thermal strain and perception improve self-paced performance in the heat. However, it cannot be concluded from our study whether Tsk or TC is most influential in the regulation of pacing. Schlader et al. (9; 18) concluded that thermal (wind) and non-thermal (menthol application) face cooling had a similar performance enhancing effect in a clamped RPE protocol, suggesting TC regulates pacing independent of Tsk. It should be investigated whether improving TC without changing Tsk during a self-paced time trial will result in similar performance improvements.

WBGT

The WBGT value required to induce comparable physiological responses was >4°C higher in the WIND condition than in the DRY and HUMID condition. In addition, the W3-12 condition was only 0.5°C WBGT lower than HUMID, while inducing more favourable responses. The observation that a single WBGT value may lead to different physiological responses dependent on the actual temperature, wind speed and humidity, is in line with the statement of Budd (20) that “conditions with similar levels of WBGT may be far more stressful when the evaporation of sweat is restricted (by high humidity or low air movement) than when evaporation is free”.

The issue that thermal strain increases disproportionately at low wind speeds has already been observed a long time ago. Clothed men exercising and resting for several hours increased time to exhaustion significantly when some wind (0.8 m/s) was applied, apparently because the lack of wind reduced evaporative capacity to one-third of the former value (37). Occupational experience resulted in recommendations to separate WBGT limits for air velocities above 1.6 m/s, differing about 3°C (23). ISO 7243 (38) partly followed these recommendations, in establishing separate limits at moderately
high and high intensity work (differing 1°C and 2°C, respectively). In view of our results, these differences in limits are still quite conservative for high intensity self-paced performance. In any way, WBGT values should be treated with caution when wind is present and adjusted limits are warranted.

Literature regarding the extra stress of humid conditions at equivalent WBGT is unclear. During a 2 h fixed paced walking test, a higher strain has been observed for high vs. low humidity at WBGT 31.7°C, but differences were much smaller at WBGT 29.4°C (21). Wright et al. (28) did not observe physiological or perceptual differences between 10% and 60% RH at WBGT 29°C. The current study does not show a clear difference between HUMID and DRY conditions at similar WBGT either. Possibly, humid conditions only impose more thermal stress than dry conditions at very high equivalent WBGT values (>30°C). In that case, separate limits might be required.

Conclusions

In conclusion, this study shows that wind is an effective tool to provide immediate and constant benefits in thermal strain, thermal perception and performance during self-paced exercise in the heat. When physiological strain is kept equivalent, wind application still improves thermal sensation, but not thermal comfort. The difference in thermal sensation alone does not lead to improvements in pacing strategy or performance. Apparently, decrements in $T_{sk}$ and/or improvements in TC are required for that purpose. Finally, the considerable impact of wind cooling should be acknowledged in judging WBGT values.

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Chapter 8

Heat strain and performance in ice hockey goalies

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Submitted for publication
ABSTRACT

Purpose
High metabolic activity combined with reduced heat loss in protective equipment predisposes ice hockey goalies to heat strain. This could have a negative impact on their performance. Therefore, we explored the level of heat strain experienced by ice hockey goalies during practice and its association with performance.

Methods
Six ice hockey goalies were tested on gastrointestinal (T\textsubscript{gi}) and skin (T\textsubscript{sk}) temperature, heart rate and fluid loss during a regular practice (~60 min, 11.9°C, 62% relative humidity). A vigilance and shoot-out task pre- and post-practice aimed to reveal any association with cognitive function and performance.

Results
Heart rate averaged 141 ± 14 bpm (maximum 173 ± 12 bpm) during practice. T\textsubscript{gi} averaged 38.1 ± 0.3°C and T\textsubscript{sk} was 32.8 ± 0.6°C, attaining average maximum values of 38.4 ± 0.4°C and 34.2 ± 0.6°C respectively. Local T\textsubscript{sk} values on the scapula rose up to >36°C. Sweat rate over the practice and performance tests was 1.1 ± 0.5 L/h. With 58% fluid replacement, this resulted in a body mass loss of 1.1 ± 0.7%. Despite the moderate heat strain and decrement in thermal comfort, no decrements in vigilance and shoot-out performance were observed, rather slight improvements.

Conclusions
Ice hockey goalies experience moderate heat strain, body mass losses and thermal discomfort during practice in cool conditions. Associated impairments in cognitive function and performance were not found. In the studied conditions, extra measures for heat strain reduction do not seem necessary from a health and performance perspective.
INTRODUCTION

In contrast to common belief, heat strain may occur even at temperatures as low as -20°C during heavy exercise when wearing protective garments (1). The sport of ice hockey is performed in a moderate to cool climate with a reported ice rink ambient temperature for practices at 10.7 to 12.7°C and professional games at 14.0 to 17.7°C (2). Ice hockey players are required to wear protective equipment which covers their entire body allowing only areas of the face and neck to be exposed. The equipment worn interferes with the subject’s ability to evaporate sweat and causes an increase in core temperature and sweat rate during their exercise. Depending on exercise intensity and permeability of the equipment worn, this can result in measurable heat strain (3). Early signs of heat strain may be experienced with a core temperature of 38-40°C, a skin temperature above 35°C and/or a fluid loss of 2% body mass (BM) (4). Elevated core temperature seems to impair repeated explosive exercise performance (5). Further, research in several team sports (soccer, football, basketball) indicated that 2% BM loss can be detrimental to skill performance (6-9).

Previous research performed on collegiate ice hockey forwards and defenders reported an average gastrointestinal temperature of 38.4°C (10). Average sweat rates ranged from 0.8-1.8 L/h, leading to BM losses of 0.8-1.3% (2; 10-13) with individual losses exceeding 2%. Goalies have been reported to have a higher sweat rate during practice than players, although BM losses seemed quite comparable (12; 13). The higher sweat rate may be caused by the fact that they are the ones wearing the most bulky protective clothing, are continuously involved during practice drills and get less cooling from air movement than players. However, only fluid balance data on a small number of subjects were reported. Further research on ice hockey goalies is sparse, so clear insight in the level of experienced heat strain is lacking.

Possible heat strain and dehydration may affect cognitive function, like gazing behaviour, vigilance and reaction time. Gazing behaviour research shows that a goalie’s focus is intense, with 96.2% fixation on the puck, stick and area of the ice just in front of the puck (14). Their peripheral vision is also used to read the play around them. Further, it has been shown that heat load and dehydration negatively affects vigilance and cognitive task performance (15; 16). It has even been suggested that a fluid loss as little as 1% BM
may have an adverse effect on cognitive function (17) and poses a higher risk of exertional heat Illness (18). Additionally, research in field hockey goalies shows that in hot conditions, reaction times in post-game tests were 0.08 s slower than pre-game tests. In cool conditions no reaction time difference was observed (19).

In summary, ice hockey goalies may experience heat strain due to their protective clothing, possibly deteriorating their cognitive functioning and performance. Therefore, the first aim of this study was to explore the level of heat strain experienced by ice hockey goalies in moderate practice conditions. In additions relations between heat strain, fluid balance and drinking behaviour were investigated. For that purpose, six ice hockey goalies were tested on gastrointestinal temperature ($T_{gi}$), skin temperature ($T_{sk}$), heart rate (HR) and fluid loss during a regular practice. The second aim of this study was to reveal any association of heat strain with cognitive function and performance, tested by a vigilance and shoot-out task. Knowledge on these issues could indicate whether preventive measures should be applied to reduce health risks and/or improve performance.

**METHODS**

**Subjects**

Six goalies averaging 20.0 ± 5.9 years of age and 73.9 ± 13.6 kg body mass, volunteered to participate in this study. Four goalies were part of the Dutch junior talent selection and two goalies played at national senior teams. All subjects and parents were fully informed of the purposes, protocol, experimental procedures and any associated risks and benefits before giving their written consent to participate. The study was approved by the VU University Amsterdam ethics committee.

**Design**

In this observational research, subjects completed a protocol of pre-practice performance tests, usual practice and post-practice performance tests, while physiological parameters were measured. Each subject went through the experimental protocol once; two subjects on day 1 and four subjects on day 2, starting the protocol from weigh-in about 10 min after each other.
Methodology

Experiments were carried out in a standard ice hockey practice centre. Ambient temperature was measured on both days with a digital thermocouple thermometer (Vaisala HM 34, Finland) at chest level in the goal crease. $T_{gi}$ and HR (Equivital Life Monitor, Hidalgo Ltd, Cambridge, UK) as well as $T_{sk}$ (iButton, Maxim Integrated Products Inc., Sunnyvale, USA) were continuously recorded to give an indication of heat strain and exercise intensity. $T_{gi}$ was measured with Jonah ingestible telemetry pills (Philips Respironics, Mini Mitter, Bend, Oregon). iButtons were applied at the right scapula, left hand, right shin and back of the neck. A weighted average of the four iButtons was used as an estimate of the mean skin temperature \cite{20}, giving an overall indication of the micro-environment under the goalies’ protective equipment. An extra iButton (not factored into the mean $T_{sk}$ calculation) was placed behind the ear as an exploratory measurement of the thermal environment under the helmet. Just before and after the complete testing session, nude body mass (BM) and water bottle mass were measured.

Performance tests included the visual vigilance and tracking task (VigTrack) and a shoot-out. The VigTrack is a computer based 5 min dual-task vigilance test that has frequently been used to assess cognitive performance \cite{21, 22}. It is applied to test the goalies’ ability to maintain their attention, measuring reaction time (RT) and control. In the RT task, subjects had to fire when stimuli that appeared in the screen changed shape. Reactions $>1$ s, missed stimuli and false responses were reported as errors. At the control task, subjects were required to control a ball with a joystick while the computer randomly pulled the ball in various directions. Output measure was the number of pixels displacement from the centre of the screen. In order to remove the learning effect, all subjects played the VigTrack three times before the start of the project. Just before the VigTrack test, subjects reported their thermal comfort (TC). TC was measured on a 5-point likert scale \cite{21}; 1 equals comfortable and 5 extremely uncomfortable. The shoot-out consisted of 100 tennis balls from a tennis ball cannon placed 7 m away from the goal line. Tennis balls were shot at the goalie at a speed of approximately 100 km/h in random directions. Through the use of a high speed digital camera (Canon EOS 550D, 60 FPS) and a mirror to see the moment of ball release, RT and save percentages could be determined (Figure 8.1).
Figure 8.1. Lay-out of the shoot-out.

The test protocol (Figure 8.2) used on both testing days began with the goalies swallowing the temperature pill six hours before the start of their on-ice session, as recommended to avoid temperature fluctuations in the upper gastrointestinal tract (24). To ensure euhydration, each subject drank 750 ml of water 1-2 h before arriving at the ice rink, and were asked to empty their bladders before nude body mass was recorded and water bottles were weighed. After the weigh-in, the Hidalgo system and iButtons were applied and the goalies were asked to get dressed before continuing on to the VigTrack (each goalie staggered by 10 min). After VigTrack was completed the subjects gave their thermal comfort rating before entering the ice for a shoot-out, ~60 min usual practice and a second shoot-out. The VigTrack test was repeated when the player left the ice, directly followed by a thermal comfort rating, removal of equipment and weigh-in. The protocol from start pre-VigTrack to end post-VigTrack lasted 1.5-2 h. During this period, it was allowed to drink water ad libitum.
Figure 8.2. A timeline of the test protocol used on both testing days.

Statistical analysis

For $T_{bi}$, $T_{sk}$ and HR, individual and group averages were calculated over the on-ice period from the start of the pre shoot-out to the end of the post shoot-out. In addition separate averages of these measures were determined for the VigTrack and shoot-out sessions. Ingested fluid was determined from pre/post water bottle mass. Sweat loss was calculated by summing BM loss and ingested fluid, subtracted by any urine output. Sweat loss divided by the time interval of the practice and performance tests resulted in the sweat rate. Loss of respiratory water and substrate mass are known to have negligible effects on this calculation and have been ignored (22). Replacement was calculated as the percentage sweat loss that was replaced by ingested water. Finally absolute and relative BM loss were determined, the latter being a percentage of pre-practice BM. Correlations between body temperature, sweat, drink and BM parameters were calculated using Pearson’s r.

VigTrack data were analyzed with a custom made Matlab routine, providing RT (s), error (%) and control (average number of pixels deviation from the target). Regarding the shoot-out, RT was measured beginning with first sight of the ball leaving the machine and ending with the first identifiable movement from the goalie to stop the ball. To remove the learning effect and to give the goalies time to adjust to seeing tennis balls instead of pucks, 80 of the 100 shots fired were used to calculate reaction time and save percentages. The 80 shots were selected by removing the first 20 shots. However, shots that were considered not clean (too wide, not ready or moving before shot was fired)
were removed and replaced by shots from the first 20. Paired T-tests were used to reveal pre-post differences of the performance tests, with statistical significance set at the 5% level. Values are reported as mean ± SD.

RESULTS

Ambient conditions on the first day were 11.6°C and 67% RH, on the second day 12.0°C and 59% RH. All subjects completed the protocol, but one temperature pill did not provide any data due to technical failure, so T_gi values are based on five subjects.

Physiological responses

Table 8.1 shows the group average, group averaged maximum and maximal individual values for HR, T_gi, T_sk and T_scapula (warmest skin location) over the on-ice session from start shoot-out 1 to end shoot-out 2. Further, group average and highest individual value for fluid balance parameters are displayed. Absolute BM loss was significantly correlated to absolute sweat loss (r²: 0.84, p=0.036), correlation of the relative BM and sweat losses was borderline significant (r²: 0.81, p=0.053). Further, BM was correlated to sweat rate (r²: 0.90, p=0.015) and HR to T_gi (r²: 0.95, p=0.013). Fluid ingestion was not correlated to any other parameter.

Table 8.1. Session average, average maximum value (average max) and maximal individual value (individual max) for the main physiological parameters. T_gi: gastrointestinal temperature; T_sk: mean skin temperature; T_scapula: skin temperature at the scapula; BM: body mass.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Session average</th>
<th>Average max</th>
<th>Individual max</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR (bpm)</td>
<td>141 ± 14</td>
<td>173 ± 12</td>
<td>187</td>
</tr>
<tr>
<td>T_gi (°C)</td>
<td>38.09 ± 0.31</td>
<td>38.41 ± 0.36</td>
<td>38.82</td>
</tr>
<tr>
<td>T_sk (°C)</td>
<td>32.77 ± 0.62</td>
<td>34.24 ± 0.63</td>
<td>35.18</td>
</tr>
<tr>
<td>T_scapula (°C)</td>
<td>34.87 ± 0.32</td>
<td>36.01 ± 0.66</td>
<td>36.74</td>
</tr>
<tr>
<td>Sweat loss (L)</td>
<td>1.8 ± 0.7</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Sweat rate (L/h)</td>
<td>1.1 ± 0.5</td>
<td></td>
<td>1.9</td>
</tr>
<tr>
<td>Ingested fluid (L)</td>
<td>1.0 ± 0.4</td>
<td></td>
<td>1.7</td>
</tr>
<tr>
<td>Replacement (%)</td>
<td>58 ± 22</td>
<td></td>
<td>85</td>
</tr>
<tr>
<td>BM loss (kg)</td>
<td>0.8 ± 0.7</td>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>BM loss (%)</td>
<td>1.1 ± 0.7</td>
<td></td>
<td>1.9</td>
</tr>
</tbody>
</table>
Regarding $T_{gi}$, the main temperature increase took place in the first 40% of the on-ice session, remaining relatively stable thereafter. The pattern of average $T_{sk}$, its local determinants (right scapula, left hand, right shin and neck) and the extra measurement behind the ear (head) are displayed for a typical (junior) subject in Figure 8.3. It expresses the skin temperature in various areas under the equipment. The intermittent nature of the practice session and occasional removal of equipment is reflected in the fluctuation of the lines. Especially notable is the large decrease in $T_{sk}$ from about half of the practice time due to a 15 min break. The iButton behind the ear, measuring skin temperature under the helmet, showed a pattern similar to the neck.

![Figure 8.3](image)

**Figure 8.3.** Separate and averaged skin temperatures for a typical subject.

**Performance measures**

The results from the shoot-out test are shown in Table 8.2. $T_{gi}$ ($p=0.019$) and HR ($p=0.001$) were higher during the post shoot-out, while $T_{sk}$ tended to be lower ($p=0.084$). Reaction time (RT) ($p<0.001$) and percentage of saves both improved in the post shoot-out ($p=0.001$). During the post VigTrack test, $T_{re}$ ($p=0.041$) and HR ($p=0.002$) were still higher than the pre-test, but $T_{sk}$ was lower ($p=0.027$). Subjects felt less comfortable ($p=0.025$). RT and error percentage did not differ between pre and post, but the number of pixels displacement decreased ($p=0.019$), indicating better control after the ice session.
Table 8.2. Physiological and performance measures of the pre- and post-practice shoot-out and VigTrack session. $T_{gi}$: gastrointestinal temperature; $T_{sk}$: mean skin temperature; HR: heart rate; RT: reaction time; TC: thermal comfort; pix: pixels.

*Significantly different from pre-practice (p<0.05)

<table>
<thead>
<tr>
<th>Shoot-out</th>
<th>Pre-practice</th>
<th>Post-practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gi}$ ($^\circ$C)</td>
<td>37.53 ± 0.28</td>
<td>38.18 ± 0.39*</td>
</tr>
<tr>
<td>$T_{sk}$ ($^\circ$C)</td>
<td>33.09 ± 0.60</td>
<td>32.19 ± 1.31</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>132 ± 8</td>
<td>156 ± 15*</td>
</tr>
<tr>
<td>RT (s)</td>
<td>0.18 ± 0.01</td>
<td>0.16 ± 0.01*</td>
</tr>
<tr>
<td>Saves (%)</td>
<td>76.9 ± 9.3</td>
<td>87.3 ± 4.5*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VigTrack</th>
<th>Pre-practice</th>
<th>Post-practice</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gi}$ ($^\circ$C)</td>
<td>37.45 ± 0.41</td>
<td>38.23 ± 0.40*</td>
</tr>
<tr>
<td>$T_{sk}$ ($^\circ$C)</td>
<td>33.29 ± 0.40</td>
<td>32.09 ± 1.08*</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>85 ± 9</td>
<td>125 ± 19*</td>
</tr>
<tr>
<td>TC</td>
<td>1.3 ± 0.5</td>
<td>2.7 ± 1.2*</td>
</tr>
<tr>
<td>RT (s)</td>
<td>0.63 ± 0.07</td>
<td>0.60 ± 0.09</td>
</tr>
<tr>
<td>Control (pix)</td>
<td>84.3 ± 30.3</td>
<td>66.9 ± 29.1*</td>
</tr>
<tr>
<td>Error (%)</td>
<td>13.8 ± 10.7</td>
<td>14.3 ± 11.3</td>
</tr>
</tbody>
</table>

DISCUSSION

The purpose of this study was to explore the amount of heat strain ice hockey goalies experience during practice and whether or not this heat strain affects their cognitive function and performance. It appears that ice hockey goalies develop moderate hyperthermia and lose a considerable amount of fluid, but a decrement in cognition and performance could not be observed.

Despite the cool practice environment of around 12°C and the rather static and intermittent nature of their exercise, ice hockey goalies experience a moderate level of heat strain. The thermal insulation of the protective equipment, in combination with the high water vapor barrier, makes it difficult to lose body heat and evaporate sweat. Core temperature increased to about 38.4°C with an individual maximum of 38.8°C, which is similar to values found in ice hockey players during practice (10). The core temperatures observed in this study are not alarmingly high and did not pose the goalies at risk for uncompensable heat stress and heat exhaustion. After the initial increase during the pre-shoot-out and start of practice, core temperatures generally reached a plateau for the
rest of the on-ice session. Average skin temperatures reached 34-35°C, while local skin temperatures increased up to >36°C. Skin temperatures fluctuated by the intermittent nature of the exercise and the possibility to remove some equipment (helmet and gloves) during breaks. The hottest spot appeared to be the scapula, which is well protected and hard to ventilate, while the neck and head remained cooler.

The average sweat rate of 1.1 L/h during practice and tests led to a total sweat loss of 1.8 L, with individual losses up to 3.0 L. So despite the cool ambient temperature of 11.9°C, substantial evaporative cooling was required to restore the heat balance. The four goalies in the study of Palmer et al. (13) showed a higher sweat rate of 2.9 L/h during a 1-h practice in ambient conditions of 13.9°C and 66% RH, while the goalies of Logan-Sprenger et al. (11) sweated at a lower rate of ~0.8 L/h during a 2.5-h junior game in 10.8°C, 30% RH. The different sweat rates may be explained by differences in exercise intensity. For example, goalies are presumed to be more constantly involved in the play during practice drills than during a game situation, possibly affecting their sweat rate (11; 13). Unfortunately, HR data have not been reported in these or other previous studies on ice hockey goalies, so the extent of the differences in exercise intensity cannot be established. In addition, the ambient conditions and possibly body size are likely explanations for the observed differences in sweat rate as well.

As reported by previous studies on ice hockey as well as numerous other sports (26), goalies did not ingest sufficient fluid to replace their sweat losses. Fluid was replaced by 58%, leading to 1.1% BM loss with an individual maximum of 1.9%. BM loss was comparable to previous data of goalies (13) and players (2; 10-13). The similar level of BM loss across studies despite different amounts of sweat loss, suggests a relationship between sweat rate and fluid intake. However, within this study fluid intake appeared independent of both sweat loss and BM loss, while the latter two were correlated. So higher sweat loss was not compensated by higher fluid intake and directly affected the hydration status. This in line with most previous studies (27; 28). A relationship between BM loss and Ṫ increase that has been reported previously (29) was not observed in the current study. This relationship could not be shown in ice hockey players at a comparable level of heat strain either (10).
The post-practice shoot-out and VigTrack tests did not reveal any impact of heat strain on cognitive function and/or performance. The level of heat strain attained in this study does not seem to have exceeded the threshold for performance decrement. Although Lieberman (17) suggests that BM losses of 1% may already have adverse effects on cognitive performance, previous research in team sports indicates decreased skill performance at BM losses of ~2% (6-9), which none of the goalies in the current study reached. Further, \( T_{bi} \) was in general only moderately elevated during the post-test, while \( T_{sk} \) even tended to be lower. Therefore it is likely that the shoot-out performance was not compromised by heat-related central fatigue. Post-practice thermal state may even have been beneficial for the shoot-out, as elevated muscle temperature is known to enhance sprint performance (30; 31). In summary, the additional heat strain during the post-test was limited and if it was associated with any detrimental heat-related effect, this test set-up was not sensitive enough to detect it. The test set-up may be improved by testing multiple days after comparable exercise at different levels of thermal stress. In addition, attention should be paid to extensive habituation. Although subjects in this study got 20 ‘habituation-shots’ from the tennis ball cannon and practiced the VigTrack three times before the test day, a learning effect cannot be ruled out. A more specific test device like a puck cannon and establishing normal variation in test performance would also be helpful in that respect.

**Practical applications and conclusions**

At a rather cool practice temperature, the ice hockey goalies in this study became somewhat hyperthermic and experienced substantial sweat loss. Sweat loss was partly replaced, limiting average BM loss to a moderate level around 1.1%. These physiological effects did not lead to performance impairment on a shoot-out and visual vigilance and tracking task. So in the studied conditions, there does not seem to be reason for extra measures to reduce heat strain.

Nevertheless, as the rather cool conditions of this study were sufficient to induce some heat strain, a professional game in temperatures of 14-18°C may have a more serious physiological and performance impact. As mentioned, ambient conditions seem to have considerable impact on at least sweat rate. So far, it seems that most goalies ingest sufficient fluid to prevent detrimental BM losses, but the effect of more strenuous conditions on fluid ingestion and BM loss remains unclear. Further, any larger increases
Heat strain and performance in ice hockey goalies

in core temperature could induce a performance deterioration in repeated explosive exercise performance (5). More research is needed to explore whether or not the level of heat strain experienced by ice hockey goalies interferes with performance at game temperatures. A comparison of exercise intensity, heat strain and performance between strenuous game conditions and cooler practice conditions, using more sensitive performance measures, would be useful.

Currently, dehydration seems to be the primary thermal concern for ice hockey goalies. The individuals at the upper end of the BM loss range in this study came close to the 2% limit. Although the impact of moderate dehydration on health and performance has lately been challenged (32), facilities for hydration ad libitum seem useful. BM was correlated to sweat rate, so heavier subjects should be aware to be at greater risk for dehydration. Further, the decrement in TC observed during the practice session could possibly be limited by equipment improvements, including better ventilation and sweat management. Especially the heavily equipped torso area deserves attention, as the scapula skin appeared to attain the highest skin temperature. More extensive skin temperature and breathability research could provide more information on this issue. Simpler recommendations for improving TC might be the removal of equipment whenever possible, improving evaporation and convection, and storing equipment in a cool and dry environment to ensure an optimal pre-use thermal state.

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