Chapter 9

General discussion
The effect of heat stress on exercise performance has been studied extensively. What this thesis adds to the already present body of knowledge is a description of the effect of thermal afferents on the pacing pattern during exercise. A distinction is made between the influences of these afferents at the start of exercise (effect on the pacing strategy) and during exercise (effect on pacing tactics). Moreover, the duration of exercise is proposed as a possible effect modifier. In this final chapter of the thesis, the results of the preceding chapters are summarized and evaluated in relation to existing knowledge about the regulation of pacing strategies during exercise in the heat. Finally, practical implications of the results and suggestions for future research are provided.

**THERMAL SIGNALS AT THE START OF SELF-PACED EXERCISE**

At the start of exercise, inputs from physiological systems are integrated and combined with prior knowledge of the upcoming exercise bout and previous experience to select an initial exercise intensity (Tucker 2009). When exercise is performed in the heat, thermal signals become of particular interest. In chapters 2 and 3 an attempt is made to isolate the effect of starting skin temperature, whereas in chapters 4 and 8, body heat content is experimentally altered before the start of exercise. By applying either pre-cooling or pre-warming, the effect of body heat content and associated thermal perceptions on the pacing strategy could be investigated.

**Skin temperature**

In chapter 2, a water-perfused suit was used to lower the skin temperature of participants before the start of a 7.5-km cycling time trial. Skin temperature decreased from 31.1°C to 29.9°C, whereas rectal temperature remained similar. The cooling provided by the suit resulted in a pronounced decrease in thermal perception as well as thermal comfort. The lower skin temperature combined with the altered thermal perceptions led to a lower mean power output, but no difference in pacing pattern during the time trial. This was likely caused by cooler leg muscles and associated less effective muscle performance (Bennett 1984). Therefore, skin temperature at the start does not appear to be a relevant...
physiological signal for the selection and modulation of the pacing pattern during a 7.5-km cycling time trial. In the third chapter of this study, a 1.6°C higher skin temperature at the start in the heat exposure trials compared to the control trial resulted in a lower exercise intensity at the beginning of the 15-km cycling time trial. This result is in agreement with Schlader et al. (2011b). In that study, eight well-trained cyclists were instructed to perform as much work as possible during a 60-min cycling time trial. The cyclists wore a liquid-perfused suit by which skin temperature was altered during the trial. Skin temperature either started high and was lowered during the trial, or started low and was increased during the trial. Schlader and colleagues observed a greater amount of work completed in the trial when the cyclists started with a cool skin temperature and they attributed this to a higher initial power output. Another study reporting performance benefits associated with a lower skin temperature at the start was conducted by Kay et al. (1999). They pre-cooled cyclists by whole-body cold water immersion after which they were instructed to cover as much distance as possible during a 30-min cycling trial. The pre-cooling-induced 5°C reduction in skin temperature resulted in a covered distance that was almost one kilometer greater than in the control condition (15.8 ± 0.7 vs. 14.9 ± 0.8 km). As the reduction in skin temperature was not accompanied by a reduction in core temperature, the authors concluded that the lower skin temperature was responsible for the improved performance. Taken together, it appears that skin temperature at the start is not a relevant signal for relatively short self-paced exercise bouts (< 15 min), whereas it does appear to become important for trials of longer durations (> 20 min). However, in a study from Barwood et al. (2012) it was found that a difference in skin temperature of approximately 1°C did not affect pacing pattern during a 40-km cycling time trial. A logical explanation for this discrepancy in results could be the magnitude of the difference in skin temperature, which was small in Barwood’s study.

In summary, only a few studies investigated the isolated effect of a skin temperature manipulation before the start on self-paced exercise performance. From these studies, it appears that skin temperature becomes a relevant signal for the selection of initial exercise intensity when the duration of exercise is greater than 20 minutes and when the
The magnitude of the manipulation is meaningful with respect to environmental conditions and the duration of exercise.

**Core temperature**

Many pre-cooling studies aimed to lower core temperature at the start of self-paced exercise. However, manipulating core temperature without also altering skin temperature is hard to accomplish. Especially when an external pre-cooling method is selected (such as cooling garments or cold water immersion), a concomitant decrease in skin temperature is inevitable. Also, when an internal pre-cooling method is selected (for example the ingestion of ice slurry), skin temperature may drop as well because of heat-conserving mechanisms initiated by the lower internal temperature. Ihsan et al. (2010) managed to lower gastrointestinal (core) temperature by means of ice slurry ingestion by approximately 0.5°C, whereas skin temperature remained similar. During the subsequent 40-km cycling time trial in 30°C and 75% RH, split times were faster in the second part of the trial, resulting in a 6.5% improved performance. In a study by Byrne et al. (2011) recreational cyclists consumed 900 mL of cold (2°C) water during a 35-min period preceding a 30-min self-paced exercise trial in 33°C. Compared to drinking water at room temperature in the control condition, rectal temperature at the start of the trial was approximately 0.5°C lower. This resulted in an improved performance during the self-paced cycling trial, evidenced by a greater mean power output. In chapter 8 of this thesis, firefighters were pre-warmed by 20 min of light-to-moderate cycling before starting a simulated firefighting activity. The cycling resulted in a difference in gastrointestinal temperature of 0.6°C between the pre-warming and the control condition at the start of the simulation. Moreover, a trend was visible towards a higher mean skin temperature. In this study, performance benefits of a low core temperature became apparent in the final part of the exercise bout, similar to the results of Ihsan et al. (2010). Therefore, it appears that a lower core temperature at the start of exercise is beneficial for self-paced performance, but the effect only becomes visible later during the exercise bout. The exact mechanism for this delayed effect is still unclear, but it is suggested that the lower muscle glycogen consumption early in the exercise bout may play a role (Febbraio et al. 1996). As
only few studies managed to isolate the effect of starting core temperature on pacing pattern, the influence of environmental conditions and the modulating effect of the duration of exercise are still unknown.

Body heat content

Body heat content is the product of body mass, its specific heat, and the absolute mean body temperature. Although the value itself is of little practical use, changes in body heat content are a representation of either cooling or warming of the human body. Mean body temperature is generally calculated by taking a weighted average of core temperature and mean skin temperature (two-compartment model), and therefore changes in these variables are directly reflected in changes in the body heat content. Many studies looked at manipulations of pre-exercise body temperature (mainly cooling) and its effect on self-paced exercise performance. In a recent meta-analysis, Wegmann et al. (2012) summarized existing pre-cooling literature and quantified the influences of ambient temperature, exercise duration and cooling modality. They observed that the effect of pre-cooling on self-paced performance increases with rising ambient temperature. The same effect was found for increasing exercise duration, although the influence of pre-cooling on exercise bouts lasting longer than 60 min is reduced again. It was also observed that the effect of pre-cooling depends on the cooling modality, with the internal cooling methods showing greater effect sizes. Moreover, there appears to be a dose-response relationship between the reduction in body heat content at the start and performance improvements. The greater heat storage capacity of the body seems to be the most prominent advantage of pre-cooling and results in a greater margin for metabolic heat production associated with a greater exercise intensity. Similar to the studies that only reduced core temperature at the start, the pacing pattern after pre-cooling generally deviates from control conditions close to the end of exercise. More specifically, the reduction in exercise intensity that is frequently observed during the final stages of exercise is diminished.
Thermal perceptions

Not only physiological signals, but also psychophysiological signals at the start of exercise may affect the selection of a pacing strategy for self-paced exercise in the heat. In chapter 4, the lower thermal sensation after ice slurry ingestion combined with scalp cooling resulted in a higher self-selected exercise intensity towards the end of the 15-km cycling time trial. However, it has to be noted that the effect of thermal sensation on pacing and performance was not isolated and co-existed with a lower mean body temperature. Therefore, the precise effect of thermal perceptions cannot be deduced from this chapter.

In studies from other research groups, the effect of thermal perceptions was isolated by the application of menthol spray to the skin and thereby activating the cold receptor TRPM8 (Peier et al. 2002). Gillis et al. (2010) instructed participants to cycle for 45 min in 30°C and 70% RH at 45% of their peak power output after being sprayed with a solution containing menthol or a control spray. They observed that the cyclists felt cooler after being sprayed with the menthol solution but that this did not result in a different RPE during the trial. This indicates that thermal perceptions are likely not that important during fixed-paced exercise. This finding was supported by Barwood et al. (2012), who found that thermal perceptions at the start did not affect the selection of a pacing strategy during a 40-km cycling time trial in 32°C and 50% RH. In contrast to these two studies, Schlader et al. (2011a) observed that thermal sensation and thermal comfort did affect time to exhaustion and caused a reduction in power output during a fixed-RPE (16) cycling protocol. Interestingly, starting exercise intensity was similar and therefore independent of thermal sensation and thermal comfort.

In summary, thermal perceptions (sensation and comfort) at the start of exercise appear to be irrelevant for the initial selection of a pacing strategy. However, there might be a role for these psychophysiological signals towards the end of an exercise bout but more studies are needed to support this concept.
Hydration status

Body water content is a relevant variable for exercise performance in the heat as it is important for the most powerful method of dissipating heat: the evaporation of sweat. A shortage of body water may lead to decreased heat loss, leading to greater heat storage and possibly reduced self-paced exercise performance. However, many athletes start middle- to long-duration exercise bouts mildly hypohydrated to reduce their body mass and avoid voiding during the race (Maughan et al. 2005). Because of these ambiguous consequences of hypohydration, the exact effects of a reduced body water content at the start of exercise on performance is heavily debated. In chapter 6, exercise-induced (1.2% BM) hypohydration at the start of a 40-km cycling time trial in 25°C and 35°C (with realistic facing air velocity) displayed a trend to be detrimental to finish time. Despite the trend on finish time, no effect on pacing pattern was observed as the development of exercise intensity during the time trial was similar from the start to the finish in both 25°C and 35°C. These results appear to be in contrast to previous studies indicating that hypohydration levels at the start of < 2% BM already led to reductions in exercise performance (Armstrong et al. 1985; Bardis et al. 2013; Walsh et al. 1994). An explanation for this discrepancy in results might be the considerable differences in air velocity affecting heat dissipation (and body heat storage) as suggested by Saunders et al. (2005). Taken together, it appears that the effect of hydration status at the start of exercise on pacing and performance depends on environmental conditions that affect heat removal, such as air flow over the body.

Other relevant factors at the start

Apart from the aforementioned signals, there are several other inputs that may be relevant for the selection of a pacing strategy at the start of exercise. These signals include physiological signals such as muscle temperature and muscle glycogen content, but also previous experience, motivation and expectations about the upcoming self-paced exercise bout (Tucker 2009). In chapter 5 of this thesis, the effect of expectations regarding a the thermal load during exercise was investigated. By deceiving cyclists about the occurrence of convective cooling during km 7-13 of a 20-km time trial in the heat, the isolated effect
of this expectation could be investigated during km 0-7, when the cooling was not yet applied. From this chapter it appears that expectations regarding the thermal load are important for the selection of an initial pacing pattern. Therefore, this aspect should always be taken into account when investigating the effect of an isolated manipulation of a thermal signal on pacing pattern during exercise in the heat.

Summary of thermal signals at the start of exercise

Several thermal afferents at the start of exercise have shown to be relevant for the selection of an initial exercise intensity or the modulation of exercise intensity during self-paced exercise. An overview of the effects of these afferents is provided in Figure 9.1. It appears that skin temperature is mainly relevant for the selection of an initial intensity,
whereas core temperature and body heat content primarily affect the exercise intensity later on during an exercise bout. The effect of thermal perceptions on pacing and performance is still unclear. Other signals at the start of self-paced exercise such as knowledge of an upcoming thermal challenge or hydration status likely also affect the selection and modulation of exercise intensity, but study results on this topic are equivocal.

MODULATION OF THERMAL SIGNALS DURING EXERCISE

Signals that are relevant for the selection of a pacing strategy at the start of self-paced exercise in the heat may be of interest during exercise as well. Within this thesis, skin temperature and hydration status are manipulated during exercise and the effect on self-selected intensity is investigated. In this section of the general discussion, the effects of manipulations of thermal afferents and hydration status during exercise on pacing pattern are reviewed. The thermal afferents are discussed in sub-sections highlighting the effects of skin temperature, core temperature, body heat content and thermal perceptions.

Skin temperature

In chapters 2 and 3 of this thesis, radiant heat stress was applied to abruptly increase skin temperature during a 7.5-km (chapter 2) and a 15-km (chapter 3) cycling time trial. Because the panel that was used to apply the radiant heat was configured identically in both chapters, the applied radiant heat stress was similar in both chapters. Therefore, not only the effect of the duration of the exposure, but also the possible effect modification of the duration of the time trial could be investigated. As the radiant heat amounted to 1100 W·m⁻², which is comparable to maximal solar radiation on earth, the exposure can be considered extreme and was barely tolerable by the cyclists. Although a slightly higher skin temperature at the start combined with the knowledge of the upcoming exposure down-regulated power output, the extreme exposure during the time trial did not affect pacing pattern. Therefore, it can be concluded that an abrupt increase in skin temperature during self-paced exercise is not a relevant thermal signal, at least during exercise bouts of
relatively short lengths. A higher skin temperature during a 60-min time trial and a fixed-RPE exercise protocol lasting >30 min have been linked to a reduced performance (Schlader et al. 2011b; Tucker et al. 2006). However, because of the differences in exercise protocols, the effect of skin temperature manipulations during exercise on the pacing pattern for the longer distances remains relatively unknown. In general, there appears to be less of an influence for durations < 30 min, whereas skin temperature does appear to become important for longer durations. Moreover, the duration and magnitude of the manipulation appear to be of little relevance for short lengths and remains unknown for longer distances.

**Core temperature**

Core temperature increases during exercise mainly as a result of heat generated by the exercising muscles and a delayed response of the heat loss mechanisms. The greater the exercise intensity, the greater the metabolic heat production. Because of the difficulties associated with cooling only the core, and not the skin, during exercise in the heat, the precise effect of an isolated core temperature modulation during exercise remains unknown. Possibly, the ingestion of ice slurry during self-paced exercise is a way to accomplish this, but so far only one study investigated this concept. In this study by Stevens et al. (2013), triathletes consumed ice slurry during the cycling leg of a Olympic distance triathlon and this improved subsequent 10-km running performance. The lower gastrointestinal temperature was suggested to be the most plausible explanation for the selection of a greater exercise intensity.

**Body heat content**

Only few studies manipulated mean body temperature (expressed as changes in both core and skin temperature) during exercise in the heat and investigated the effect on self-paced performance. In a review by Tyler et al. (2013) it is shown that reducing body heat content during exercise improved performance during both compensable and uncompensable heat stress. All the studies included in this review paper used an external cooling method. Consensus of these studies is that self-paced performance can be
improved by lowering mean body temperature during exercise. When this information is
combined with information from the isolated skin and core temperature manipulations it
appears that it is mainly core temperature that serves as an intensity-modulating factor
during exercise in the heat.

**Thermal perceptions**

Very few studies investigated the effect of a manipulation of thermal perceptions during
exercise on pacing and performance. The only studies that managed to create an isolated
difference in thermal perception between experimental conditions during exercise
created this difference before the start of the exercise bout (Barwood et al. 2012; Gillis et
al. 2010; Schlader et al. 2011a). As these studies did not used a self-paced exercise
protocol (Gillis et al. 2010), observed no effect (Barwood et al. 2012), or did not report a
detailed pacing pattern (Schlader et al. 2011a), it is still unclear what the effect of an
isolated manipulation of thermal perception during exercise is.

**Hydration status**

In chapters 6 and 7 of this thesis, the role of exercise-induced dehydration on pacing and
performance during a 40-km cycling time trial in the heat is discussed. In chapter 6, the
hypohydration that was created before the start was further expanded to > 3% of initial
body mass at the finish of the trial. Compared to starting euhydrated, a trend was visible
towards a lower average exercise intensity but no difference in pacing pattern was found,
indicating that it was mainly the hydration status at the start that was relevant for the
selection of a pacing strategy and the observed trends towards a lower mean power
output. This finding is confirmed in chapter 7, in which the cyclists started hypohydrated
and were allowed to drink according to their thirst sensation (ad-libitum) during the 40-km
cycling time trial. Although the thirst sensation of the cyclists was markedly reduced when
they were allowed to drink during the time trial, overall performance, pacing pattern, and
(thermo)physiological variables were unaffected. As mentioned earlier, the high facing air
velocity could have prevented the lower body water content from becoming a
performance-limiting factor. As this velocity was even slightly lower than the cycling
speed, it is expected that during real-life out-of-doors cycling the hydration status is a relatively unimportant factor for the regulation of exercise intensity. This notion is confirmed in a review by Goulet (2011), who showed that exercise-induced dehydration up to 4% BM does not impair cycling performance as long as there is adequate opportunity for heat dissipation. When there is less possibility for heat dissipation, for example because of a lower speed of travel (running), hydration status may become relevant. However, Dion et al. (2013) found no performance benefit of a drinking regime aiming a maintaining fluid balance <2% body mass loss, despite favorable effects on thermoregulation. Therefore, the hydration status during exercise appears to be of little relevance for the modulation of exercise intensity.

FUTURE RESEARCH

In this thesis the effect of thermophysiological signals on the selection and modulation of self-selected exercise intensity are discussed. Also, the modification of this effect by the duration of the exercise is evaluated. There are several signals that have not been evaluated in detail within this thesis. Mainly the isolated modulation of core temperature and thermal sensation during exercise are still lacking and warrant further investigation. Also isolated skin temperature manipulations during long-duration (>30 min) exercise bouts can further improve the understanding of the relevance of thermal afferents on the modulation of self-selected exercise intensity in the heat.

Research aimed at clarifying the influence of a specific thermal afferent on pacing pattern during exercise in the heat should ideally isolate this afferent and manipulate it without altering other signals. As in real-life competition rarely one signal is manipulated whereas other thermal afferent remain unaltered, the findings of these more fundamental studies should not be over-interpreted. The studies give a good idea of the relative importance of several signals, but it is generally the combination of effects that eventually determines the performance response. Therefore, more studies are needed that determine the influence of these signals in ecologically valid studies with well-trained individuals. That is
what matters in the end. Lab studies on exercise performance in hot conditions should employ realistic (=high) wind velocities to simulate out-of-doors conditions. Moreover, the selection of exercise protocols should reflect realistic competitive exercise events.

From a fundamental scientific point of view it would be very interesting to investigate brain activity during self-paced exercise and the effect of temperature manipulations on this activity pattern. Although some studies have used EEG as a method to clarify brain activity, this setup only gives very superficial information. Because of the practical difficulties associated with testing, only one study used fMRI during cycling exercise (Fontes et al. 2013). Using this visualization method of brain activity can provide very useful information and gain new insights into the central regulation of exercise intensity in the heat.

PRACTICAL APPLICATIONS

Sport setting

Adopting pacing strategies during exercise in the heat can be an easy and successful way to reduce the detrimental effect of heat on performance. Starting an exercise bout at a slightly lower intensity, can reduce or prevent the pronounced decrease that is often seen towards the end of aerobic exercise trials and this can improve overall performance. Because of the known effect of skin and core temperature at the start on performance, action should be undertaken to start relatively cool and increase the margin for metabolic heat production, favoring performance. It would be even better to combine the lower body heat content with a lower thermal sensation and comfort. Therefore, with regards to the preparation regime before the start of a sporting event of relatively long duration (>20 min), pre-cooling should be preferred over pre-warming.

The importance of starting hydration status should be evaluated in combination with the possibilities of heat dissipation during exercise. When heat removal during exercise is not expected to be a limiting factor, starting slightly hypohydrated may be favorable. If heat
removal is expected to be a limiting factor, starting euhydrated should be preferred. Of course, this also depends on the exercise intensity and the expected duration of the exercise bout.

The limited amount of studies on the effect of cooling during exercise makes it hard to provide solid guidelines for cooling during exercise. The practical difficulties associated with cooling during exercise at this moment favor pre-cooling over cooling during exercise. One possibility for cooling during exercise can be considered and that is the ingestion of ice slurry instead of water. As ice slurries extract more heat from the body, a greater thermal reservoir is created and this can possibly lead to improved performance in the heat. Because the consumption of large amounts of cold slurry can cause gastrointestinal distress, consuming slurry during exercise should be incorporated in training sessions of athletes to get accustomed to this method and prevent performance limitations.

Although deceiving cyclists about the thermal load during exercise may be useful to improve performance, it is not advised to apply this in real life competition. As individuals can only be deceived one time, employing a deception can seriously harm the relationship between coach and athlete in future events.

**Occupational setting**

Adopting pacing strategies during exercise in the heat can be an easy and successful manner to reduce the detrimental effect of heat on performance. This is true not only for the sport setting but also for the occupational setting. Workers that are exposed to hot environments and/or have to perform work in personal protective clothing can benefit from adopting pacing strategies. Generally, starting at a lower intensity will reduce the heat storage in the body and thereby prevent the reduction that is generally observed during the end of exercise bouts. Especially when individuals have to perform multiple consecutive bouts of exercise it is important to reduce body heat content in-between these bouts to optimize performance. Combining conscious pacing with cooling before
and during exercise can optimize performance, increase work effectiveness and in the end even safe lives.

Occupations that are characterized by long periods of low intensity work period and short periods of high-intensity exercise during which performance needs to be optimal (for example firefighting) need to carefully schedule the low-intensity activities. If these activities cause increases in body temperature, the subsequent high-intensity performance may be hampered, both mentally and physically.