Request for Proposal:

Research Project: Safe Maximum Water Temperature Limit for Open Water Swimming Competitions

29 January 2026

INTRODUCTION

1. CONFIDENTIALITY

The information contained in this document is provided by World Aquatics and is to be used for the sole purpose of evaluating and promoting the health of aquatic athletes, specifically through the prevention of injury and illness.

This material is the property of World Aquatics and may not be disclosed to third parties or the general public, whether in whole or in part, without the prior written approval of World Aquatics.

2. COMPANY BACKGROUND

World Aquatics, formerly known as FINA, is the international federation recognised by the International Olympic Committee (IOC) for administering international competitions in the six aquatic sports of swimming, water polo, diving, artistic swimming, open water swimming and high diving. World Aquatics also oversees "Masters" competition for adult-age competitors in aquatic sports.

3. CONTEXT

Promoting athlete well-being and preventing injury is a core value for World Aquatics.

The discipline of Open Water Swimming (OWS) features individual races of 5 km and 10 km, staged during the World Cup series, the World Aquatics Championships and the Olympic Games (10 km only). These endurance events take place in natural settings: rivers, lakes, or oceans, where athletes must contend with highly variable currents, waves, temperatures, and other environmental stresses.

The swimming times, and therefore exposure times, may vary from 5-10 minutes to around two hours.

World Aquatics currently has a rule for maximum water temperature in competition of 31.0 °C.

In past years, World Aquatics has contributed to several studies on lower and upper water temperature limits, undertaken by external research agencies. The University of Otago, in New Zealand, conducted specific research informing the current upper limit for water temperature, in 2013. This final report is attached for reference.

CHAPTER B – REQUEST FOR PROPOSAL

1. OBJECTIVES

Competitions in OWS require athletes to undertake intense physical efforts. This, along with the duration of the event and the ambient water and environmental conditions, will be factors in the potential development of thermal injury. At its extremes, thermal injury, characterised by deviation of core temperatures and multi-system disturbances, can result in fatality if not recognised and treated urgently. Moreover, open water venues are vulnerable to the natural variations in weather and water conditions. During prolonged races, all modes of heat transfer (convection, conduction, evaporation, and radiation) interact dynamically. Swimmers have limited opportunities to protect themselves from thermal stress during competition.

Recently, our elite and masters swimmers were exposed to high water temperatures during the 2025 World Aquatics Championships in Singapore. Combined with extreme environmental conditions (air temperature and humidity) competition was very stressful for some athletes. World Aquatics has subsequently decided to revisit the issue of thermal heat stress risk in open water swimming across elite, junior, and master's competition.

The water temperature study conducted by Otago University set an upper limit of 31.0°C, and although it employed controlled, outdoor realistic conditions, no in-competition or field data were gathered.

Given the issues mentioned above, the following questions are proposed for further study:

▶ What are the thermal responses in elite athletes undertaking intense activity in warm-water OWS competitions?

▶ What individual parameters (e.g. sex, somatotype, age and experience) might affect the athlete's ability to cope with thermal heat stress in the water?

▶ Does the perceived heat stress of an OWS athlete accurately mirror objective physiological data?

▶ Is there a relationship between athlete core temperature and externally measured temperature sites after warm water exposure e.g. oral, aural and forehead measurements?

▶ What is relevance of the combined effect of air temperature, water temperature, humidity, radiant temperature and wind chill on the athletes during competition?

▶ Is there feasibility in deriving a formula that combines environmental factors (such as combining air temperature, humidity and water temperature) and would this have value in informing conditions for safe OWS competition? If so, describe such formula.

▶ What would be the scientifically-based recommendations for event modification in circumstances suggesting a potential high risk of heat stress injury?

▶ Is the current World Aquatics protocol for measuring and monitoring water temperature in competition fit for purpose?

2. SCOPE OF WORK

It is anticipated that most data should be collected during field studies involving elite, conditioned athletes in events approved by World Aquatics. World Aquatics will facilitate access to groups of elite open water swimmers during its competitions or its members' competitions.

It will be expected that environmental conditions and athlete physiological parameters including skin temperature, core body temperature and heart rate are measured, with correlation to stroke mechanics and intensities, and clinical outcomes.

Interested researchers should develop a formal study protocol, informed by the literature, to be submitted for consideration to World Aquatics.

The research must comply strictly with the high ethical and professional standards of the host research organisation with final approval from World Aquatics.

A formal scientific report will be presented to World Aquatics upon completion. An intermediate report will also be required.

The results of this study will be used in:
- scientific publication(s)
- scientific conferences
- educational tools for athletes, coaches and team physicians
- to support rule changes to improve the health and safety of open water athletes.

It is anticipated the project shall be completed within 12 months.

3. ELIGIBILITY CRITERIA

The research project is open to universities, research institutions, private companies, governmental organisation or non- governmental organisation.

It is expected that this study will be undertaken by an organisation with expertise in this type of research, preferably with experience in aquatics sport.

CHAPTER C – DELIVERABLES OF THE PROJECT AND RFP PROCEDURE

1. DELIVERABLES REQUIREMENTS

- Statement supporting expertise in the field
- Confirmation of required facilities
- Initial proposal of study design supported by the literature and including power considerations
- Project Timeline
- Proposed Budget for delivery of the Project

2. RFP PROCEDURE TIMELINE

26th January 2026	Launch of RFP by World Aquatics
15th April 2026	Deadline for submission of bids by interested providers
15th June 2026	Decision
15th June 2027	Project Completion Date*

(*To be confirmed)

3. EVALUATION PROCESS

All proposals will be reviewed by an internal committee comprising current and former World Aquatics Sports Medicine Committee members and World Aquatics staff.

Furthermore, World Aquatics shall be free in its absolute and sole discretion to select the proposal that most successfully fulfils World Aquatics's objectives and requirements.

World Aquatics is not obliged to give reasons for any decisions made at any stage.

4. CONTACT PERSON

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APPENDIX

- Thermal stress in open water swimming; establishing competition parameters for athlete safety, University of Otago. (2013)

WORLD
AQUATICS

THERMAL STRESS IN OPEN WATER SWIMMING: ESTABLISHING COMPETITION PARAMETERS FOR ATHLETE SAFETY

One year report on studies of swimmers completing 20-, 60- and 120-min swims in water temperatures of 20, 27, 30 and 32°C under outdoor-relevant ambient conditions

University of Otago

January 2013

Attention:

Mr Cornel Marculescu, Executive Director, FINA
Dr Richard Budgett, Medical Director, IOC
Dr Sergio Migliorini, Chair, Medical Committee, ITU

1   EXECUTIVE SUMMARY

This report represents the full findings of our studies as they relate to the first 4 (out of 5) research questions (i.e., the one-year report). It contains data from 24 swimmers undertaking a total of 190 self-paced performance trials (following familiarisation swims) in water temperatures of 20, 27, 30 and 32°C, with exposure durations (20-120 min) corresponding to distances of 1.5 km to 10 km races. Appropriate ambient conditions were created for each of these swims with air temperatures closely matching the respective water temperatures, a relative humidity of 50-70% and a simulated radiant heat load of 400-800 W·m^{-2} in the 32°C water condition. Lab-based testing, while not fully representative of the racing environment, was essential to use in answering the research questions

The mean terminal body core (rectal) temperatures ranged between 36.7°C, for the 2-h swim in 20°C water, and 38.3-38.4°C, for the 1-h and 2-h swims in 32°C water with a radiant loading. The swimmers did not attain core temperatures associated with heat-related fatigue (cessation of exercise) in well-trained terrestrial athletes in lab environments, but heat stress reduced performance by an average of 5.6% (20 min), 7% (1 h) and 4% (2 h); the effect was clear in the 20 min and 1-h trials only. Impairments of this order are also found in terrestrial endurance events. Sweat rates and dehydration were substantial and comparable with those for terrestrial events, despite the heat loss benefits of sweating being nullified in swimming. We cannot be certain that rectal temperature responses closely reflect those of other temperature-sensitive organs during swimming, despite preliminary validation trials in this study and supportive data from a previous swimming study in warm water. Further validation work is required in this respect, some of which we hope to complete for the final report.

Whereas 32°C water did not cause heat intolerance or body core temperatures to exceed our ethically-approved upper limit of 40°C, by contrast, swimming in 20°C water led to intolerance in as little as 20 minutes in the leanest swimmers (one of whom is a current Triathlon age-group world champion). No clear relation was evident between swimming velocity and rise in core temperature in warm water, or reductions in cool water. No early warning signs were evident in the cool or hot water swims for those with the largest

excursions in core temperature. In the report we describe a potential safety problem with open-water swimming competitions being conducive to causing autonomic conflict and sudden cardiac death, which may be especially relevant for lean swimmers in cool water.

Prior to undertaking this study we had been concerned that warm aquatic environments might prevent swimmers receiving complete thermal information for driving thermoregulatory behaviour (esp. reducing exercise intensity to limit hyperthermia in racing). However, perceptions of body temperature and thermal discomfort were appropriately related to rising body core temperature, and swimmers' feeling state declined accordingly. These responses were perhaps even more sensitive than in terrestrial environments. Therefore, swimmers clearly receive the appropriate thermal cues with which to thermoregulate effectively. Finally, swimmers' perceptions or actual core temperature responses to swimming were unaffected by the imposition of a large increase in their training load.

It is of utmost importance that open water swimmers, like terrestrial athletes competing in thermally stressful conditions, are strongly advised to act on their thermal perceptions, because the research indicates that these are valid reflections of their thermal status. Behavioural thermoregulation is therefore critical to the safety of individual swimmers and of equal importance to the oversight and vigilance of race organisers and athlete support staff. In addition it should be noted that cool water is potentially as problematic as warm water, and is deserving of further research to more fully characterise the physiological (esp. thermoregulatory) strain. However, an important risk which would not be discernible from such research is that most swimming deaths arise in cool water, in race environments. If so, then wetsuit usage in open water, competitive swims would not overcome the mortality problem in open water racing.

Whilst the absolute safe upper limit for water temperature in open water swimming will remain a contentious issue, it is important to reflect upon comparisons with many intermittent and endurance terrestrial sports. Behavioural thermoregulation is critically important, but depends on the individual athlete's knowledge of the excursions of their own body temperature. By this we mean that all athletes, both aquatic and terrestrial must be

specifically trained to "listen" to their bodies and respond appropriately to signals of impending thermal stress, understanding that these individual perceptions can be altered by such factors as thermal adaptation, failing to successfully adapt to progressive training load, and intercurrent illness or infection.

The authors of this research respect the potential variability in physiological responses to thermal stress that exists between swimmers subjected to laboratory testing versus the true "race" environment. These missing data can only be collected through accurate field studies and this is a strong recommendation for further study.

Three important validations appear warranted: (i) Field validation of core temperature responses to swimming in different water temperatures, esp. >30°C; (ii) the relation of different indices of core temperature in front-crawl swimming; and (ii) modeling of different personal, clothing and environmental circumstances.

Please note that we would be very happy to provide additional information that any of the three parties may be interested in. Furthermore, the nature of the ongoing modelling and warm-water swims for Question 5 means that further data will be generated which may allow further appraisal of these recommendations.

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2   SUMMARY OF LITERATURE

Humans must maintain a relatively constant body temperature, despite facing major thermal stresses caused by movement and the environment. This constancy of temperature is essential for comfort, performance, and survival. Core temperature (T_c) appears to be the regulated variable, and is maintained at approximately 37°C, with a daily circadian rhythm which sees it rise and fall by ~0.5 – 1.0°C every 24 hours. The exact mechanisms by which T_c is regulated or this circadian rhythm is controlled are not fully known. While there is consensus on the structures involved within the central nervous system, different theories have been suggested to explain how T_c is maintained within such narrow limits. The concepts of a thermoregulatory "setpoint", inter-threshold zone and reciprocal cross-inhibition appear to dominate theoretical thoughts around the regulation of T_c and the activation of thermoeffectors for heat loss (sweating and vasodilation) and heat gain (shivering and vasoconstriction) (Benarroch, 2007; Bligh, 2006; Mekjavic & Eiken, 2006). These autonomic responses are activated to appropriately increase or decrease T_c back towards its regulated level.

In humans, behavioural responses are also very important - often most important - to thermal homeostasis. These behavioural responses can include moving to shade or warmth, adding or removing clothing, and increasing or decreasing exercise intensity. The relative roles of T_c and skin temperature (T_{sk}) to autonomic responses appears largely weighted towards T_c as the driving signal (Cabanac, Cunningham, & Stolwijk, 1971; Nadel, Bullard, & Stolwijk, 1971; Weiss, 2008). However, thermal input from the skin and core appears more balanced in driving individuals' perception of their body temperature and the thermal (dis)comfort which drives thermal behaviour. This indicates that T_{sk} may play an important role in initiating behavioural responses before more metabolically costly autonomic responses are activated (Cabanac et al., 1971).

During exercise, T_c typically increases due to the heat production from active muscles. Core temperature can rise as high as 40°C or more in trained individuals performing high intensity exercise, with no ill effects (Byrne, Lee, Chew, Lim, & Tan, 2006; Ducharme & Tikuisis, 1991; Gonzalez-Alonso et al., 1999). Such temperatures approximate those at which heat stroke can occur, but the aetiology of heat stroke is normally more

multi-factorial than temperature alone (Lim & Mackinnon, 2006). This rise in T_c occurs even with significant heat loss through the body's most effective heat loss mechanism – evaporation. Evaporation removes heat at a rate of 2.43 kJ per g of sweat evaporated. Other heat loss mechanisms of convection, conduction and radiation are also active, but these are much less effective compared to evaporation in most ambient conditions, and actually cause heat gain when ambient temperatures exceed skin temperature. In water, however, evaporation is largely nullified due to a fully wetted skin which is has little exposure to the air for vaporisation of water. This raises an interesting question; are individuals who exercise in water more susceptible to increases in T_c because the body's most effective heat loss mechanism, evaporation, is somewhat negated by the water? But, compared to air, water has a very high heat capacity and a much larger thermal conductivity. Consequently, water can store more heat for the same change in temperature, and the body will conduct heat up to 25 times faster into water than it does to air (Nadel, Holmér, Bergh, Astrand, & Stolwijk, 1974; Ramires et al., 1995). Thus, heat loss via convection and conduction can be increased dramatically in water provided that it is not too warm; however, few studies have directly compared this heat loss in water to that achieved through evaporation in air.

Many water-immersion studies have focused on passive immersion, or included light exercise, with most conducted in cool water temperatures (<25°C). Presumably such a focus reflects those water temperatures which are typically experienced by a large percentage of the world's population, and the conditions associated with a high number of deaths and hypothermia-related issues following accidental immersion. Studies of immersion in cool and cold water show decreases in T_c and increases in metabolic rate (~oxygen uptake; $\dot{V}O_2$) proportional to the changes in water temperature, and somewhat dependent on subcutaneous fat thickness (Choi, Ahn, Choi, Kim, & Park, 1996; Holmér & Bergh, 1974; Šrámek, Šimečková, Janský, Šavlíková, & Vybíral, 2000). Further, combined upper- and lower-body exercise and upper-body exercise alone appear to cause a greater decline in T_c compared to lower-body exercise alone, particularly in cool and cold water temperatures (Toner, Sawka, & Pandolf, 1984). Therefore, the primary use of arms in swimming may lead to greater heat losses in water. This also indicates that the results obtained from immersion research using cycling and running exercise (especially if the

running does not include much arm movement) would be erroneously applied to upper-body exercise like swimming, due to these differences in heat loss and other issues such as the head and face also being largely immersed when swimming.

Given that it appears swimming might provide quite different responses to other types of exercise performed while immersed in water, there is surprisingly little research on physiological and psychophysical responses to swimming, particularly endurance swimming. Where studies do exist, the intensity and duration of the swims are relatively low and they are typically performed in a swimming pool without any radiant heat loading. This makes the application of the results to open-water swimming very difficult. Of the few studies that have been conducted – to our knowledge - only two have involved high calibre swimmers who swam for 60 min or more in different water temperatures (Macaluso et al., 2011; Robinson & Somers, 1971). From these studies, it seems that T_c can rise 0.7 – 0.9°C while swimming in water temperatures of ~ 27°C, and 1.1 – 1.3°C in water temperatures of ~ 32°C. However, these studies have used indoor 25-m swimming pools, utilised poor and/or sparse measures of core temperature, have *not* included solar load or psychophysical measures to gain insight into behavioural drive.

Open-water swimming is a fast-developing discipline which encompasses various events sanctioned under different governing bodies. Open-water swimming is defined as any competition that takes place in rivers, lakes, oceans or water channels. Pure open-water and marathon swimming events are typically 5, 10 or 25-km long, while shorter open-water swims (750 m – 3.8 km) are also incorporated as part of Triathlon and Ironman races. Open-water swimming competitions are held in all parts of the world in a huge variety of environmental and water conditions. While some safety guidelines around water and ambient temperatures exist for the postponement or cancellation of races, these are largely related to cold conditions, while specific guidelines around upper-water temperature limits are lacking. Accordingly, it is not uncommon for races to be held in locations where water temperatures can approach 32°C, with ambient temperatures of 35-40°C. Based on extensive terrestrial research on exercise performance in the heat, it appears that such an extreme environment could be very heat-stressful to swimmers, particularly elite swimmers who would be producing large amounts of metabolic heat in this environment for 1-2 hours during a 5 or 10-km race.

Warm water is a special aquatic environment which has received relatively little attention in comparison to cold water. Like cold water, warm water may also present significant physiological and psychophysical challenges particularly to thermoregulation. The reduced evaporative capacity due to fully wetted skin may be compensated by increases in convective and conductive heat loss. This is supported by research mentioned above indicating that T_c changes in warm water may be similar to those typically observed in air, and in some cases may even be less. Further, the typical behavioural thermoregulatory activities seen on land, such as seeking shade and shelter or adding and removing clothing, are less readily achievable in water, particularly open water. Therefore, the primary behavioural thermoregulatory response available when swimming in warm water, is to adjust the exercise intensity. However, what role T_{sk} plays in our thermal perceptions and therefore the control of these behavioural activities in water seems to be unknown. On land, changes in T_{sk} can be a very strong driver of thermal perceptions which lead to behavioural thermoregulatory responses (Cabanac, Massonnet, & Belaiche, 1972; Schlader, Stannard, & Mündel, 2010). However, in water, T_{sk} remains clamped at water temperature with minimal variation, and at levels associated with comfort (~33°C) or being cool (< ~30°C). Therefore, *is this powerful driver of thermal perception and behavioural thermoregulation blunted in water due to the clamping and the reduced range over which T_{sk} can now change?* Given the narrow range that human T_c operates within, and the possible issues facing autonomic and behavioural thermoregulation in water, it is important to consider other factors that may potentiate the T_c response in warm water and place additional stress on thermoregulation. Any influence of these factors may become very significant to individuals swimming in open-water events where they may already be subjected to high radiant heat load, high water (32°C) and ambient temperatures (35°C), and high metabolic heat production. Such factors include inflammation arising from exercise-related endotoxaemia or previous inflammatory state, overtraining or high training load, and limited or inadequate recovery from previous training or races, and their presence could contribute to the ultimate development of heat stroke (Lim, Wilson, Brown, Coombes, & Mackinnon, 2007).

Therefore, the purpose of this study was to examine the physiological, perceptual and functional responses of swimming in various water temperatures, particularly in warm water conditions, and to consider the modulating influences of inflammatory factors and heat adaptation. A key issue was whether swimmers could adequately perceive their own thermal status in the unique circumstance of warm-water swimming. These questions were best able to be answered using conditions in which water and ambient conditions could be adjusted and precisely controlled. Therefore, we used a flume in which water, air and radiant temperatures could be controlled. This allowed us to test effects of different water and ambient temperatures, radiant heat loading, swimmers' physical characteristics, and swimming calibre on performance and safety-related indicators.

2.1   Research Questions

As outlined in the original research proposal document, the following four research questions have been addressed as part of the current study.

1. What effects do swimming distance and water temperature have on behavioural and autonomic thermoregulation, core temperature and performance capacity?
2. What early warning signals of altered thermoregulation could be used to predict a serious challenge to athlete safety?
3. Can individuals accurately perceive their own body temperature when swimming in warm water?
4. Is heat tolerance affected by factors such as recent heavy training load, illness and specific drug use and do swimmers adjust their behaviour accordingly?

For further background information and additional detail on the above topics, a full literature review for this research is also included in Appendix A.

3   METHODS

3.1   Participants

Twenty-four competitive swimmers or triathletes (18-50 years of age) were recruited. Participants were apparently healthy and were screened for exclusion factors including cardiovascular risks, musculoskeletal problems, any contraindicated medication and previous heat illnesses using the PAR-Q medical screening questionnaire. Females in the main study were tested in the follicular phase of the menstrual cycle. Because exercising thermoregulation varies in relation to athletes' fitness, anthropometry and recent training history, it was considered essential to the validity of these findings that a range of calibre of swimmers was tested (with the common requirement that they could compete over durations of at least one hour). See Section 4.1 for more details on the swimmer characteristics. This study was reviewed and approved by the University of Otago Human Ethics Committee (Approval Number 11/250).

3.2   Procedures

3.2.1 Familiarisation testing

A familiarisation session was conducted with all new participants to introduce them to the experimental protocol, measurements and exercise requirements of the study. In this session participants completed a 60-min swim trial in 32°C water, as described below. This session allowed participants to become familiar with swimming in the flume, the warm water temperatures, and their ability to appropriately pace themselves to maximise their swimming distance within a set period.

3.2.2 Swimming economy, $\dot{V}O_2$ peak and anthropometrical testing

The swimming economy and $\dot{V}O_2$ peak of each participant was measured in the swimming flume in the 27°C water temperature. Immediately before this test, participants had their body composition and distribution of adiposity measured using skinfolds and bioimpedance analysis. Participants were then fitted with a heart rate monitor and a swimming snorkel for the economy and $\dot{V}O_2$ peak test. $\dot{V}O_2$ was measured by having participants breathe through a mouthpiece attached to the swimming snorkel, while the inspired and expired volume, O_2 and CO_2 concentrations were analysed (Cosmed Quark b^2 Metabolic Cart, Rome, Italy). Participants were given a 10-min swimming warm up at a velocity close to the slowest swimming velocity to be used in the economy test. Participants then completed four 4-min stages of increasing submaximal intensities to allow swimming economy to be calculated. The intensity of these 4 submaximal stages was calculated for each participant based on their 60-min swim velocity from a previous main swim trial or their familiarisation session. The average velocity maintained during their 60-min swim trial was used as the fastest of the 4 submaximal stages. This velocity (when represented as a 100-m split time) was then used to determine the other 3 stages by incrementally adding 10 s for each stage. These four submaximal intensities had to be completed with an R-value ≤ 1.0 so that accurate energy expenditures could be calculated. Therefore, swimming intensities were adjusted during the economy test if the participant's R-value appeared too high (or low). Immediately after the final submaximal stage, the swim velocity was ramped up by ~3-5 s·100 m^{-1} every minute until volitional exhaustion. $\dot{V}O_2$ peak was taken as the highest O_2 uptake (20 s average) achieved during the test. An average of the final 60 s of each submaximal stage was used to determine the energy cost of exercising at that intensity (swimming economy) and a regression line was plotted through these 4 stages and used to estimate metabolic heat production (based on swim velocity) in each of the main swim trials.

3.2.3 Experimental Protocol – Main swim trials

Design: Each main swim trial involved the same measurements and timings. The trials differed only in the distance to be swum or the temperature of the water. Each participant aimed to complete 11 swims, which included the economy/ $\dot{V}O_2$ peak test and familiarisation session described above, plus 9 main swim trials (see Table 1). The 9 main swim trials comprise a full cross-over of 3 swim distances of 20 min, 60 min and 120 min with 3 water temperatures of 20°C, 27°C and 32°C (Table 1). The anticipated ambient air conditions for each water temperature are also shown in Table 1, and the relative humidity aimed to be maintained between 40-60%. During swims in the 32°C water temperature, solar radiation was added to the environmental heat load on the participants via an overhead lighting rig, as illustrated in a previous report. This was to simulate the additional heat stress experienced in outdoor, open-water swims, by the sun. This lighting rig provided light across appropriate wavelengths and at appropriate intensities to approximate those measured on the Earth's surface in various tropical locations. Briefly, these values are wavelengths of 250 – 2500 nm and a light intensity (irradiance) of 700 – 1000 W·m^{-2}. A few participants also repeated two of the swims in 32°C water *without radiant heat loading* to allow examination of the effect of this additional heat load on physiological and perceptual responses. Additional swims were also completed by some of the participants in 30°C water (60-min swim only) and also in 32°C water without radiant heat loading (20 and 120-min swims only). Participants were asked to maintain a similar diet and exercise regime during the testing period as well as refraining from strenuous exercise in the 24 h prior to testing, and to arrive at the lab hydrated. As these swim sessions are designed for participants to cover as much distance as possible in the allocated time, they were asked to prepare and approach each session as they would a race.

Table 1. A matrix of the 11 swim trials each participant aimed to complete.

	20°C water 20-22°C air No Solar Load	27°C water 27-29°C air No Solar Load	32°C water 30-32°C air Solar Load
Familiarisation (60-min swim)	-	-	✓
20-min swim	✓	✓	✓
60-min swim	✓	✓	✓
120-min swim	✓	✓	✓
Economy/$\dot{V}O_2$ peak	-	✓	-

Protocol within trials: On arrival at the flume, participants were seated while a resting venous blood sample was collected. Participants then changed into their swim attire and personally introduced the rectal thermistor, attached their heart rate monitor, and provided a urine sample. Participants wore their own swim attire, which for most males was a pair of standard swimming briefs, while the females wore a standard one-piece swimsuit. Body mass was recorded using calibrated scales (DIGI, DI-10, Rice Lake Weighing Systems Inc., WI, USA) in dry swim attire only, from behind a screened-off area. Participants were then asked to provide resting measures of the psychophysical perception scales (detailed below) before entering the water. All participants wore a silicon swim cap and goggles throughout each swim. A 10-min warm-up was started with participants free to swim at any velocity, which could be altered at any time through verbal signals of "up/down" or "faster/slower". After a 10-min warm-up, participants were given a chance to stretch, adjust their cap and goggles, and have a drink, as required. They were then asked what swim pace they would like to start the trial at, and the flume was increased to that speed. Participants remained holding on to the side of the flume until a "go" signal was given and the distance recording was started once they began swimming. Throughout the trial, the flume speed remained constant until a verbal signal was given by the participant to increase or decrease the speed. If the participant began dropping further and further back in the flume channel, the speed was also slowed until the swimmer returned to the middle position and requested the speed be increased again. All participants were given feedback on their performance continuously via a large TV screen positioned in a side-viewing window of the flume displaying elapsed time, distance covered and current velocity/pace (shown as a 100-m split time, in seconds). Participants could ask to have any of these feedback displays removed, or only temporarily shown to them. This screen would also display the psychophysical

perception scales which were asked after 10, 20, 40, 60, 90 and 120 min. Participants were also given the opportunity to stop for a drink every 30 min. A commercially-available carbohydrate & electrolyte drink (7.2%) was provided to drink *ad lib* after the warm-up and during these drinks breaks. The volume of drink consumed was recorded and accounted for in body mass changes across the trials. Participants were asked to make all drinks breaks as short as possible, i.e. simply stopping at the side of the flume to quickly consume some fluids and then return to their swim. In addition, during these breaks participants' welfare was monitored by asking questions and noting their demeanor and the "appropriateness" of their responses. The length of each drinks break was recorded and the total was added to the end of the swim trial to ensure all participants swam the full allocated time. At the completion of the trial, participants exited the flume immediately and returned to a seat on the poolside. A post-exercise blood sample was taken and participants' recovery was monitored to ensure core temperature returned toward baseline levels. They were also asked to give recovery measures of the psychophysical perception scales approximately 5 and 10 min after exiting the water. Once this was completed, they were asked to dry off as much as possible and provide a nude body mass from behind the screened-off area. Lastly, participants showered, de-instrumented, changed and were asked to provide a post-exercise urine sample.

3.3   Measurements

3.3.1 Core Temperature

Core temperature was measured using flexible, sterile, and disposable thermistors (Mallinckrodt 400 general purpose, Mallinckrodt Medical Inc. St Louis, USA) positioned in the rectum during all swim trials. Each participant was instructed on the insertion of their own rectal thermistor (10 cm past the anus).   To obtain a comparison, oesophageal temperatures were recorded in suitable participants. Oesophageal thermistors were not used if a participant felt that they have a significant gag reflex or have had previous disruption to their nasal passages.   Oesophageal thermistors were inserted in two

participants to a depth adjacent to the right atrium, as estimated by the formula 0.479 x participant sitting height (cm) – 4.44 (Mekjavic & Rempel, 1990). Disposable thermistors (rectal and oesophageal) were assumed to be factory calibrated and accurate to 0.1°C, but these were subsequently sterilised and reused within participants to ensure consistency. All connector cables on these thermistors were custom-extended so the connector plug was well away from water, because these plugs do not provide accurate data if they are in contact with water, and the small differences in recorded core temperatures are often unnoticeable during testing. Our pilot testing showed that this problem is solved by extending the connector cable and ensuring the plug is maintained well away from the flume and splashes.

3.3.2 Skin Temperatures

Skin temperatures were measured in a few participants at four right-side sites using insulated skin thermistors (Type EU, Grant Instruments, Cambridge, England); 1) Forehead, above the eyebrow; 2) Scapula, just below the inferior angle; 3) Upper arm, lateral surface, midway down the humerus; 4) Thigh, anterior surface, midway down the femur. Mean skin temperature was calculated from standard area weightings as: 0.07 (forehead) + 0.35 (scapula) + 0.19 (arm) + 0.39 (thigh). Temperatures were logged using a Grant 1200 series Squirrel Data Logger (Grant Instruments, Cambridge, England) at 10-s intervals and subsequently downloaded to a PC computer. Skin thermistors were calibrated against a NATO-certified thermometer accurate to 0.1°C in a stirred water bath, across the range 10-40°C, at intervals of 2°C. Restricting this measurement to a few swimmers was because of the combined effects of (a) a relative uniformity of temperatures, (b) the artifact introduced by taping the thermistor to the skin, was necessary for swimming, and (c) the additional drag associated with this measurement.

3.3.3 Venous Blood Samples

Venous blood samples were taken by venipuncture from an antecubital vein. Each sample required the removal of 12 mL of blood directly into tubes containing EDTA-anti-coagulant, and placed on ice. These were analysed immediately for concentrations of blood glucose (Optium Xceed, Medica Pacifica Ltd, NZ), blood lactate (Lactate Pro, Arkray, Japan) and haemoglobin (in duplicate: Hemocue Hb201$^+$, Hemocue AB, Angelholm, Sweden). Two capillary tubes (for duplicate readings) were filled directly from the EDTA vacutainers, then critosealed and centrifuged at 3500 RPM for 10 min. Haematocrit (%) was then read from the capillary tubes by directly measuring the plasma and packed cell lengths with vernier calipers, accurate to 0.2 mm. The remaining blood in the EDTA vacutainers was centrifuged at 4°C and 3000 RPM for 10 min. The plasma was subsequently removed and stored in microcentrifuge tubes of approximately 1 mL aliquots at –80°C until analysis. Stored plasma will be analysed in an overseas lab for various markers of inflammation including TNF-α, IL-6, IL-10, iFAB and LPS, following collection of the swimming data required to address Question 5.

3.3.4 Psychophysical measures

The psychophysical measures were: Perceived body temperature (rated on a 1 – 13 scale), and thermal discomfort (1 – 10), both extended from (Maughan, Shirreffs, & Watson, 2007); overall feeling state (-5 to + 5), and ratings of perceived exertion, using the 15-point (6 – 20) Borg scale (Borg, 1962); and perceptions of thirst and hunger, using a 1 – 10 scale. The latter were recorded before and after each swim, whereas the other scales were additionally presented on the underwater TV monitor at the end of their warm-up and after 10, 20, 40, 60, 90 and 120 min of each trial. Once presented with a scale, participants were instructed to take their time to determine their response then call out the corresponding number, or word, as they took a breath between strokes. As each of the responses was heard and recorded, the next scale was presented on the TV screen. This process of collecting the responses for the 4 perception scales was typically completed in 30-60 s. The scales were

always presented in the same order; Ratings of perceived exertion, Thermal sensation, Thermal discomfort and Feeling, for ease of viewing and interpretation, especially when reading under the water. Participants soon became accustomed to this method of data collection and very quickly developed a reliable method of reporting their scored responses.

3.3.5 Heart Rate

Heart rates in all participants were recorded to a chest strap (Suunto Oy, USA) at 2-s intervals and downloaded later onto a PC computer (Suunto Team Manager software). Pilot trials determined this recording system to be more reliable than the telemetry systems also trialled. No major problems were experienced by flume participants swimming with chest straps in situ, although during field studies the chest strap was less acceptable by athletes in the competitive environment and this is an issue that will deserve further consideration if future field trials are to be considered.

3.3.6 Oxygen Consumption

Oxygen consumption ($\dot{V}O_2$) was measured throughout the economy/$\dot{V}O_2$ peak test using breath-by-breath analysis, as described above. The volume, and fractions of O_2 and CO_2, were calibrated prior to each trial using a 3 L syringe and an alpha-standard calibration gas.

3.3.7 Urine Analysis

Urine samples provided by participants before and after each swim trial were analysed immediately for volume, colour (Urine Colour Chart) and specific gravity (handheld refractometer, Uricon, Atago Ltd, Japan). Approximately 3 mL of urine was stored as 1.5 mL aliquots in microcentrifuge tubes at -80°C for possible future analysis.

3.3.8 Anthropometrical Assessment

Skinfold analysis was performed following ISAK (International Society for the Advancement of Kinanthropometry) anthropometrical methods by an ISAK Level 1 accredited researcher. An ISAK restricted profile was completed which measures 8 skinfold sites – Triceps, Subscapula, Biceps, Iliac Crest, Supraspinale, Abdominal, Thigh and Calf; 5 girths – Relaxed arm, Flexed arm, Waist, Hip and Calf; and 2 bone widths – Humerus and Femur. Body mass was measured using calibrated scales (DIGI, DI-10, Rice Lake Weighing Systems Inc., WI, USA) and height was measured using a stadiometer. Bioimpedance analysis was completed using a multi-frequency, 8-electrode bioimpedance machine, incorporating impedance for each limb (Model 720, Inbody, Seoul, Korea).

4 RESULTS

The following section presents the results of our study which address the first 4 research questions. As such, the key results are presented under the headings of these research questions, with Questions 1 and 3 combined together because they relate to similar data.

4.1 Participant characteristics and swim completions

A total of twenty four participants completed at least one of the main swim trials. The total number of swim trials completed in each of the 9 conditions are shown in Table 2 and a summary of the participant characteristics are shown in Table 3. The swimmers ranged from those who took ~29 min to swim 1.5 km, up to the current ITU age-group Olympic and Long distance triathlon world champion, and New Zealand's top male and female 10-km open-water swimmers. Additional trials were completed by some of these participants in the 32°C water temperature with and without radiant heat loading, before and after a heavy training load, and participants also completed the familiarisation and $\dot{V}O_2$ peak sessions. Together, a total of 190 swim trials have been completed as part of this study. The $\dot{V}O_2$ peak data should be interpreted conservatively, because it is difficult to obtain accurate $\dot{V}O_2$ peak in swimming; not all swimmers adjust well to the constraints of the mouthpiece and headpiece, or to the altered rhythm and stroke pattern without the ability, or need, to roll and breathe. Measurements of swimming economy are affected similarly – esp. with the drag caused by the mask and constrained posture - and will therefore tend to cause an under-estimation of swimmers' actual efficiency profiles.

Table 2. Summary of the number of swim trials completed for each of the 3 swim durations, in each of the 3 water temperatures.

Water Temperature	20°C			27°C			32°C		
Swim Duration (min)	20	60	120	20	60	120	20	60	120
Number of swim trials	11	11	7	13	14	11	16	19	10

Table 3. Summary (Mean ± SD) of participant's anthropometrical characteristics.

	Age (y)	Mass (kg)	Height (cm)	Surface Area (m^2)	Sum of 8 skinfolds (mm)	Body fat (%)	Muscle Mass (kg)	$\dot{V}O_2$ peak (ml.kg^{-1}.min^{-1})	Pace at $\dot{V}O_2$ max (s.100 m^{-1})
Mean	26	74.31	175.3	1.89	114	17.0	36.24	41.2	82
± SD	9	9.62	9.5	0.16	54	8.2	6.24	7.9	8

4.2   Environmental Conditions

The water temperature and surrounding environmental conditions of the swimming flume were maintained as constant as possible for each of the swim trials. Water temperature was well controlled, averaging 20.19°C, 27.09°C, 30.15°C and 32.14°C in the 20, 27, 30 and 32°C conditions, respectively.   Ambient air temperature remained close to the water temperature, averaging 20.74°C in the 20°C water swims, 27.91°C in the 27°C water swims, 30.14 in the 30°C swims and 30.00°C in the 32°C water swims. This was accompanied by an average relative humidity of 57%, 51%, 52% and 56%, respectively. During the 32°C swims, the simulated radiant heat load provided irradiance at the water surface of ~800 W.m^{-2} directly under the centre of the lights, dropping to around ~400 W.m^{-2} at 0.5 m away from the centre of each light. No fans were used in any of the swims to simulate air movement (i.e. wind).

4.3   Research Questions 1 and 3 – What is the effect of the swimming distance and the water temperature on behavioural and autonomic thermoregulation, core body temperature and performance capacity?

4.3.1 Core Body Temperature

Core body temperature (rectal; T_{re}) did not exceed the ethical upper limit of 40°C in any of the swim trials (of which 102 trials were in water temperatures of 30°C or more) conducted across the three different water temperatures and three durations. In fact, the highest recorded T_{re} was 39.55°C at the end of a 60-min swim in 32°C, and only 5% of the swims

resulted in T_{re} exceeding 39.0°C. Further, while most participants felt hot and uncomfortable in the warm water trials (see perceptual responses below), no one voluntarily stopped or displayed any visible signs of distress. Conversely, in the cold water swims (20°C), one participant could not swim for more than 20 min due to extreme discomfort in the cold water (see also Figure 4 – Figure 6) for his rectal and oesophageal temperature traces), and 3 others voluntarily stopped due to discomfort or were removed due to low T_{re} (35.0-35.5°C) after 60-90 min of the 120-min swims. This represents 50% (4 out of 8 participants) who could not complete the 120-min swims in 20°C.

In a water temperature of 32°C, the final T_{re} was similar in all three swim durations (20 min: 38.10 ± 0.43°C; 60 min: 38.26 ± 0.61°C; 120 min: 38.40 ± 0.75°C; P>0.05; Figure 1). Thus, a significantly faster rise was evident during the 20-min swims (0.037°C.min^{-1}) compared to the 60 min (0.015°C.min^{-1}) and compared to the 120 min (0.007°C.min^{-1}; all P<0.01). It should be noted, in Figure 1 it appears that swimming in 30°C water for 60 min led to a greater core temperature than in 32°C. However, this appearance reflects the larger number of subjects included in the 32°C swim, and their influence on this average response. If T_{re} responses are compared directly for the 8 participants who completed the 60-min swims in both 30°C and 32°C water, the 32°C water (with radiant heat load) led to a slightly higher final T_{re}, as might be expected (Figure 2).

While we cannot say with certainty, we do not believe that these T_{re} values in 32°C water represent swimmers' upper critical core temperature (i.e., the maximum which they voluntarily tolerate in those circumstances), for various reasons. For example, (i) the T_c are lower than might be expected of trained athletes, (ii) the exercise intensities did not show concordant patterns, (iii) heat dissipatory responses would have had less time to be effective (and thereby apparent) in the 20-min swim, and (iv) similar variability of final (and max) T_{re} was observed during the 60- and 120-min swims in 32°C water compared to 27°C (p>0.50). Also, the standard deviations observed in the final (and max) T_{re} values are larger than those reported in terrestrial studies examining critical T_c limits (González-Alonso et al., 1999). When taken together, these data indicate that in 32°C water, core temperature is unlikely to be the principle limiting factor. If, however, brain temperatures were consistently higher than rectal temperatures, and reached near-critical (volitionally tolerated) temperature upon completing the respective swims, then the present results might be illustrative of

normal, successful, exercising behavioural thermoregulation. To further cloud these results (and as introduced in our previous report), data obtained from one female participant during the 2012 FINA 10 km World Cup Open Water Swimming event in Hong Kong indicate T_c (measured with intestinal pill thermometry) peaked at 40°C early in the race. We have recently obtained further data off a water-damaged recording unit for a male athlete who completed the 4-km swim at the same Hong Kong event. The data from both athletes is shown in Figure 3. Even though the female athlete starts with a relatively high T_c, it does indicate the possibility that athletes may experience higher T_c in a race situation, possibly related to the various pressures, incentives and competitiveness which cannot be accurately replicated in a lab environment. However, this female athlete has also completed the 120-min swim trial in the flume at 32°C and while she did not receive radiant heat loading (not available at that time), she did start her 120-min swim at a slightly elevated T_{re} of 37.70°C, but ended at relatively modest 39.05°C. Therefore, while the decision to conduct the current study in a lab (flume) environment is still justified by the aforementioned requirement to obtain reliable, informed results, these race data do highlight a requirement for further field testing to confirm these thermal responses under race conditions.

Another key issue we are continuing to address is the appropriateness of T_{re} as an index of the core temperature response in swimmers. Swimming involves largely upper-body work with limited leg action (at least in terms of heat production). Therefore, with large local heat exchanges (production, storage and losses) occurring in the upper body, and the arms in particular, oesophageal temperature (T_{oes}) may provide a better representation of core temperature change than does T_{re}, which normally has more sluggish responses and is further from the primary site of heat production. Ideally we would measure oesophageal temperature (T_{oes}) in all swimmers, but there are also substantial problems with T_{oes}. It causes more discomfort (which may influence swimming performance, perceptions, and commitment and compliance with the study), esp. with cyclic movement of the head. Oesophageal thermistors are also problematic for people who have robust gag reflexes, and the measurements are prone to swallowing artifacts. Therefore, rectal temperature was the index of choice. [Note: Use of gastrointestinal pill thermometers does not overcome validity problems; it also adds enormously to the cost, has some medical contraindications, and would be susceptible to reliability artifacts unless timing of ingestion was able to be standardised for all trials].

We were able to obtain T_{oes} from two participants; one who has previously completed numerous exercise studies using an oesophageal thermistor and thus used it in all swim trials, and another who was willing to insert a thermistor in his final two swim trials. What became obvious from our recordings of body mass changes and T_{oes} responses, and further compounds the issues with T_{oes} measurement in swimming, is that many swimmers regularly swallow water as they turn to breathe, which leads to erroneous T_{oes} recordings. To illustrate this, data traces from our participant who used oesophageal in all trials are shown below (Figure 4 - Figure 6), with a comparison to the concurrent rectal temperature. [Note: This is the participant who became extremely cold and terminated his swim after 20 min in 20°C water, thus there are no data for 60- and 120-min swims in 20°C. He was an exceptionally lean and fit swimmer; Sum of 8 skinfolds 54.9 mm.] The jagged nature of the T_{oes} traces represent this swallowing of water, however, in some trials there are times where recordings stabilised or almost did so (not esp. discernible with the long timescale shown here), which leads us to believe that some of these peaks reflect the 'true' T_{oes} (i.e., an approximation of right atrial temperature). Thus, in many swim trials, both warm and cool, it seems that the true T_{oes} remains similar to, or below, T_{re}. However, collecting T_{oes} from another participant who did not swallow much, if any, water while swimming reveals an uncontaminated T_{oes} response. This swimmer was a skilled masters swimmer, and far more endomorphic than the one described above (Sum of 8 skinfolds 117.3 mm). The T_{oes} response from this participant during his 20-min swim in 32°C and his 60-min swim in 20°C are presented in Figure 7. As is clearly evident therein, T_{oes} can increase well above T_{re}, at least in warm-water conditions. Interestingly, in this same participant T_{oes} remains below T_{re} at all times when swimming in cold water (Figure 7). This trend for a lower T_{oes} (compared to T_{re}) is similar to what we observed in most of the raw data traces from the first participant, and while the first participant did not show the same rise in T_{oes} (above T_{re}) in the warm water, the two indices of core temperature were much closer together than in the cooler water. A potentially more concerning issue is the very low and rapidly falling T_{oes} (possibly around 33.0-33.5°C; Figure 4) recorded in this participant as they terminated their 20°C swim after only 20 min (following a 5-min 'warm up'). If real, this may signal a notable thermal danger for swimmers (particularly lean athletes) when swimming in cold water, esp. if then exiting the water and cycling in cool conditions (a problem which seems to be well recognised in triathlon). The particular concern from our perspective would be the potential

for serious arrhythmias with a cold myocardium per se and the possibility for concurrent autonomic conflict (Shattock and Tipton (2012) (Tipton, 2012) (See Section 4.4 below).

The conundrum of core temperature validity discussed above is not resolvable from existing literature because there has been little previous research on intense endurance swimming in warm (or cold) water, and even less using T_{oes} as the index of core temperature. Nielsen and Davies (1976) measured both T_{oes} and T_{re}, and found that these two indices appear to increase similarly (and to only modest levels) after 60 min of swimming at two different workloads in 30 and 33°C water. However, that study used breaststroke, which is likely to have a differential effect on T_{re} change due to the greater leg involvement compared to front crawl, and will also have a lower overall heat production. So, it does not resolve our reservation about validity of measurement of T_c in front crawl swimming. Therefore, we are planning to obtain more comparative data on this relationship between T_{re} and T_{oes} during the swims that are completed in our next study to address research question 5, thus we should have a more comprehensive analysis and understanding to include in our final report.
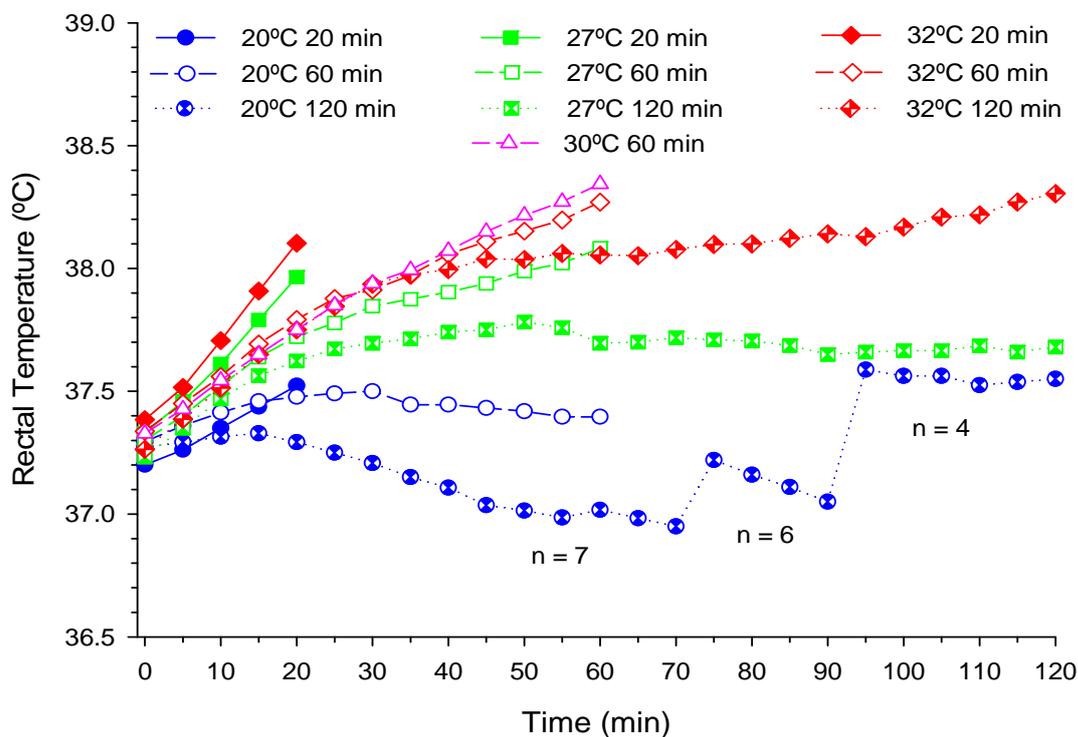
Figure 1. Mean rectal temperature response over time for each of the three swim durations in each of the three water temperatures. Also included is the mean response for the additional 30°C 60 min swim condition. Note: Three of seven swimmers could not complete their 20°C 120-min swims due to low T_{re} or discomfort. Since these participants had the lowest T_{re} responses, their removal from the water leads to an obvious jump in the average T_{re}, hence, this plot is supported by text indicating how many participants remain in the average over the last 60 min of the 20°C 120-min swim trial.
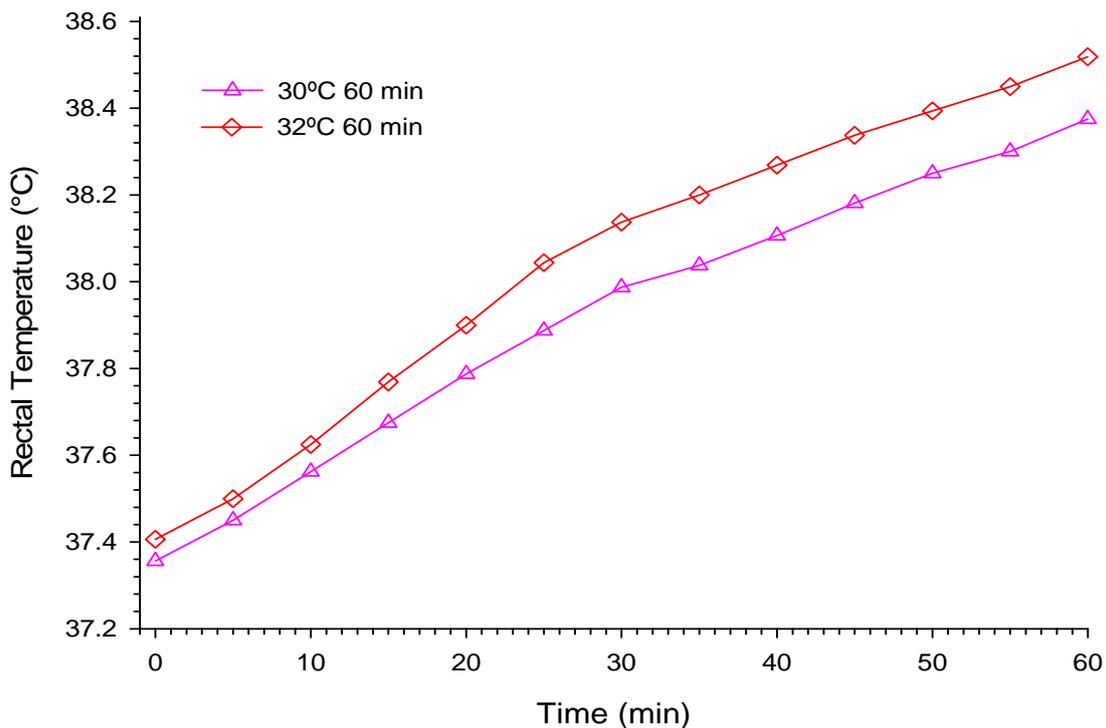
Figure 2. Comparison of the rectal temperature response during the 60-min swims in 30°C (without lights) and 32°C (with lights) for the 8 participants who completed both of these swims.
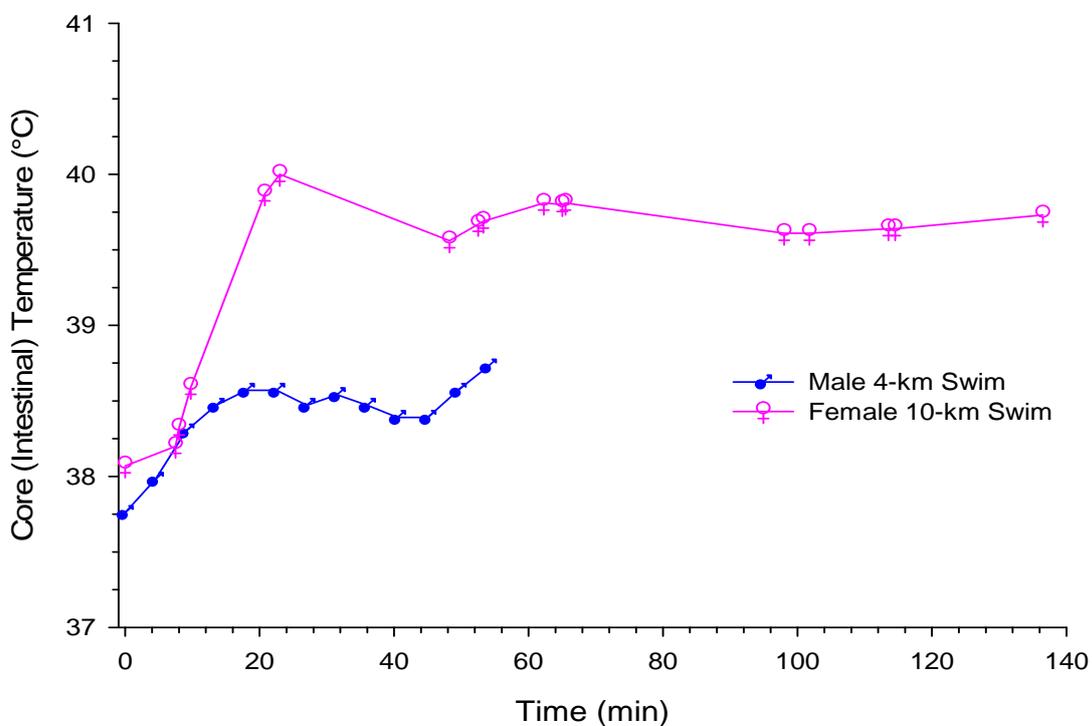
Figure 3. Core temperature response (measured via intestinal pill thermometry) during a World Cup 10-km Open Water Swim race in one female athlete and during a 4-km Open Water Swim race in one male athlete. The female athlete had a high starting core temperature in this race, which is also mirrored by a slightly high starting core temperature in her 120-min trial in the flume.
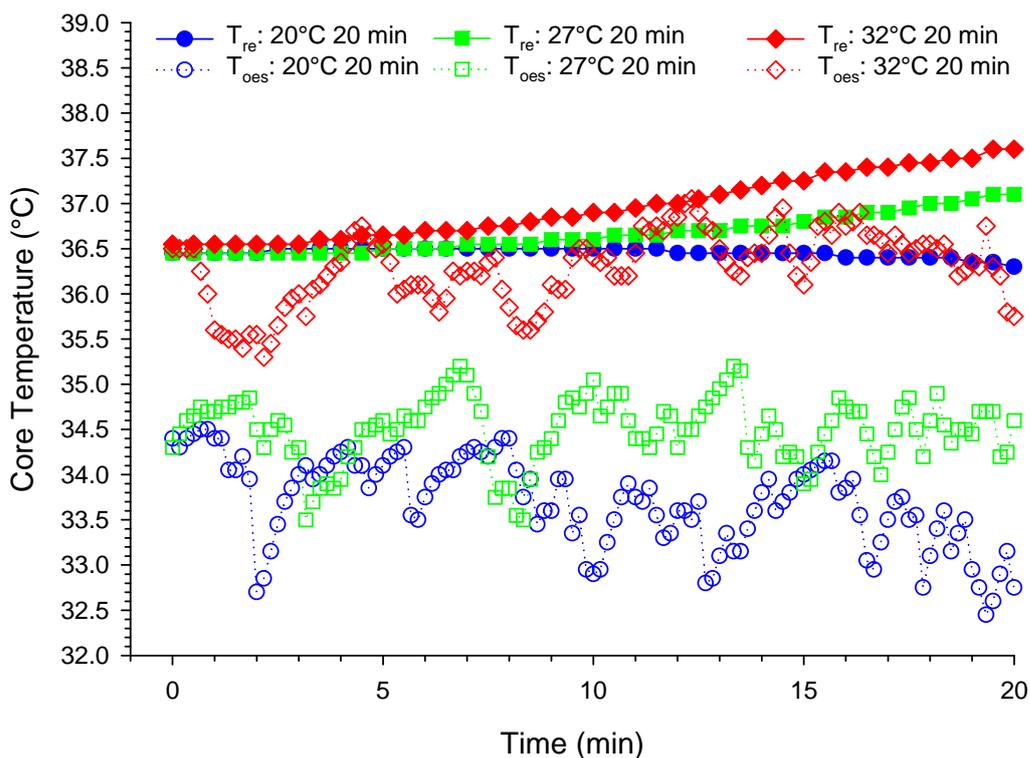
Figure 4. Comparison between the rectal temperature (T_{re}) and oesophageal temperature (T_{oes}) response for the same participant swimming for 20 min in three different water temperatures. Note: Time 0 is the start of the main swim trial, after a 10-min warm-up in the same water temperature. For data from the same participant swimming for 60 min and 120 min, see Figure 5 and Figure 6, respectively.
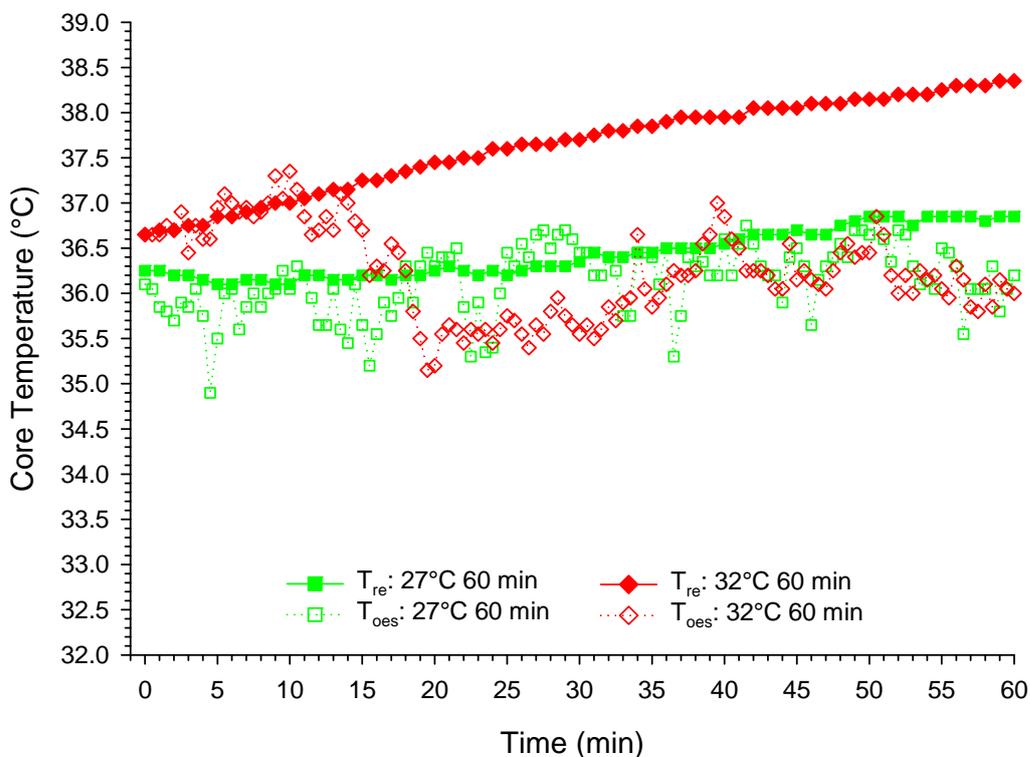
Figure 5. Comparison between the rectal temperature (T_{re}) and oesophageal temperature (T_{oes}) response for the same participant swimming for 60 min in two different water temperatures. Note: Time 0 is the start of the main swim trial, after a 10-min warm-up in the same water temperature. For data from the same participant swimming for 20 min and 120 min, see Figure 4 and Figure 6 respectively.
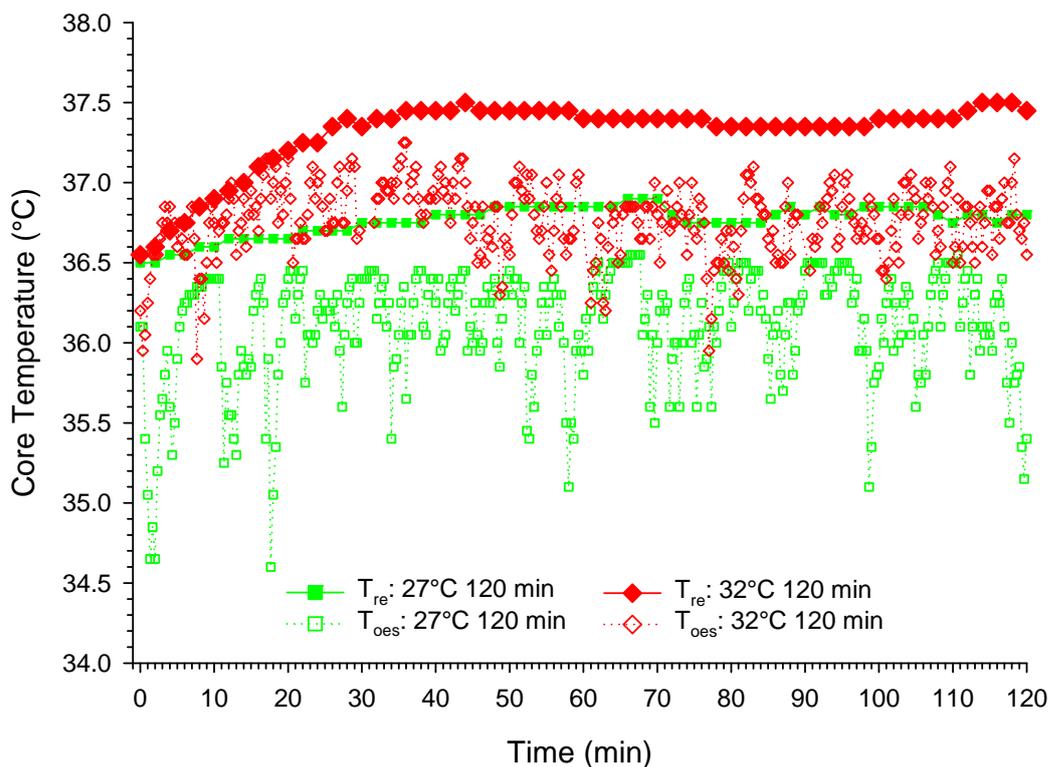
Figure 6. Comparison between the rectal temperature (T_{re}) and oesophageal temperature (T_{oes}) response for the same participant swimming for 120 min in two different water temperatures. Note: Time 0 is the start of the main swim trial, after a 10-min warm-up in the same water temperature. For data from the same participant swimming for 20 min and 60 min, see Figure 4 and Figure 5, respectively.

Figure 7. Comparison between the rectal temperature (T_{re}) and oesophageal temperature (T_{oes}) response for one participant swimming for 60 min in 20°C water and 20 min in 32°C water. Note: Time 0 is the start of the main swim trial, after a 10-min warm-up in the same water temperature.

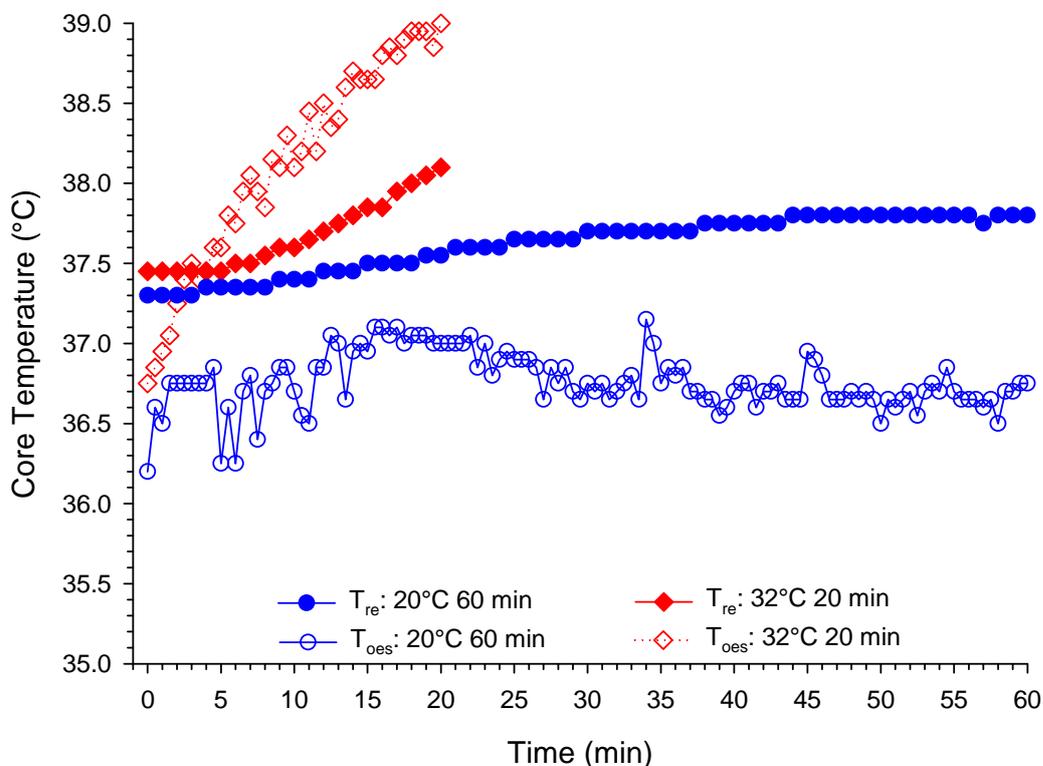In addition to the core temperature data recorded in the current study, we have also undertaken an additional project, assisted by colleagues with expertise in thermodynamic modelling (incl. Prof Wissler), to further refine and validate the well-known Wissler thermo-physiological model. We consider this important in that it will allow validation to different circumstances (e.g., of clothing, radiant loading, adiposity, fitness, and water conditions) and will help resolve the reservations expressed above. This is still in a developmental stage, however a detailed report on the application and current state of this modelling project is included here as Appendix B.

4.3.2 Performance Capacity

It does not appear that the better athletes (i.e. faster swimming speeds and therefore greater heat production) are more likely to be in danger of excessively high core temperatures as there is no obvious (and dangerous) relationship between swimming speed and T_{re} at the end of the swim trials (Figure 9). Nonetheless, the performance capacity of swimmers may be affected in warm water; not due to excessively high core temperatures, rather, a combination of factors which may cause swimmers to feel very hot and uncomfortable even at moderate core temperatures, as is evident for terrestrial exercise (Byrne et al., 2006; Ely et al., 2009). Such factors may include skin temperature, skin wettedness and cardiovascular strain, which could contribute to negative perceptions and discomfort in warm water and invoke behavioural thermoregulation (see 4.3.3). Recent research actually indicates that T_{sk}, or possibly more accurately thermal perceptions (i.e. sensation and discomfort), play a key role in exercise pacing, which itself can be considered a thermoregulatory behavior (Schlader, Simmons, Stannard, & Mündel, 2011a; Schlader, Simmons, Stannard, & Mündel, 2011b). The average heart rate response during each of the swim trials in the current study is shown in Figure 8 and indicates a similar (and high) cardiovascular strain in the 27°C and 32°C water, particularly in the 20- and 60-min swims. It also shows a consistently lower heart rate in the 20°C water across all swim durations, as is expected when exercising with cool skin. Principal among the reasons for the lower heart rate is that the skin is neither competing for nor pooling blood to the extent that occurs when exercising in warm conditions (González-Alonso & Calbet, 2003).

In terms of actual swim performance, differences were observed in the effects of water temperature on the distance swum and average pace across each of the swim durations (Figure 10 and Figure 11). Data from participants who completed a given swim duration in at least two different water temperatures showed that swimming for 120 min in a 'normal' pool temperature of 27°C allowed them to swim, on average, 3.9% further than in 32°C water (95% CI: -2.3 – 10%; range: -4.8 – 12%). However, when compared to 20°C water, participants actually swam an average of 1.5% further in the 20°C water (95% CI: -2.6 – 5.6%; range: -2.1 – 3.9%), provided they were a swimmer who could tolerate the cooler water! The wide confidence intervals signify that the true effect could be either substantially slower or faster in the different water temperatures. Water temperature showed a clearer effect for the 60-min swim; the distance swum in 27°C water was an average of 7% more than in 32°C, with the likely true effect being substantial (95% CI: 4.4 – 9.7%; range: 0.4 – 14.1%). The normal-pool temperature (27°C) also led to a 2.7% greater average distance than in 20°C water, but the true effect was unclear (95% CI: -1.0 – 6.4%; range: -4.9 – 14%). However, interestingly, swimmers went 2.4% *further* over 60 min in 30°C than they did in the 27°C water, but the true difference was unclear (95% CI: -3.5 – 8.3%; range: -2.9 – 19.5%). The shortest duration (20 min) tended to produce larger distances in 27°C water than in either 32°C or 20°C water; by an average, respectively, of 5.6% (95% CI: 3.4 – 7.8%; range: -1.0 – 11.2%) and 1.7% (95% CI: -0.8 – 4.2%; range: -3.2 – 9.9%). Therefore, for most distances and individuals, temperatures around those of normal pool temperatures are both more comfortable and tend to be more conducive to optimal performance.
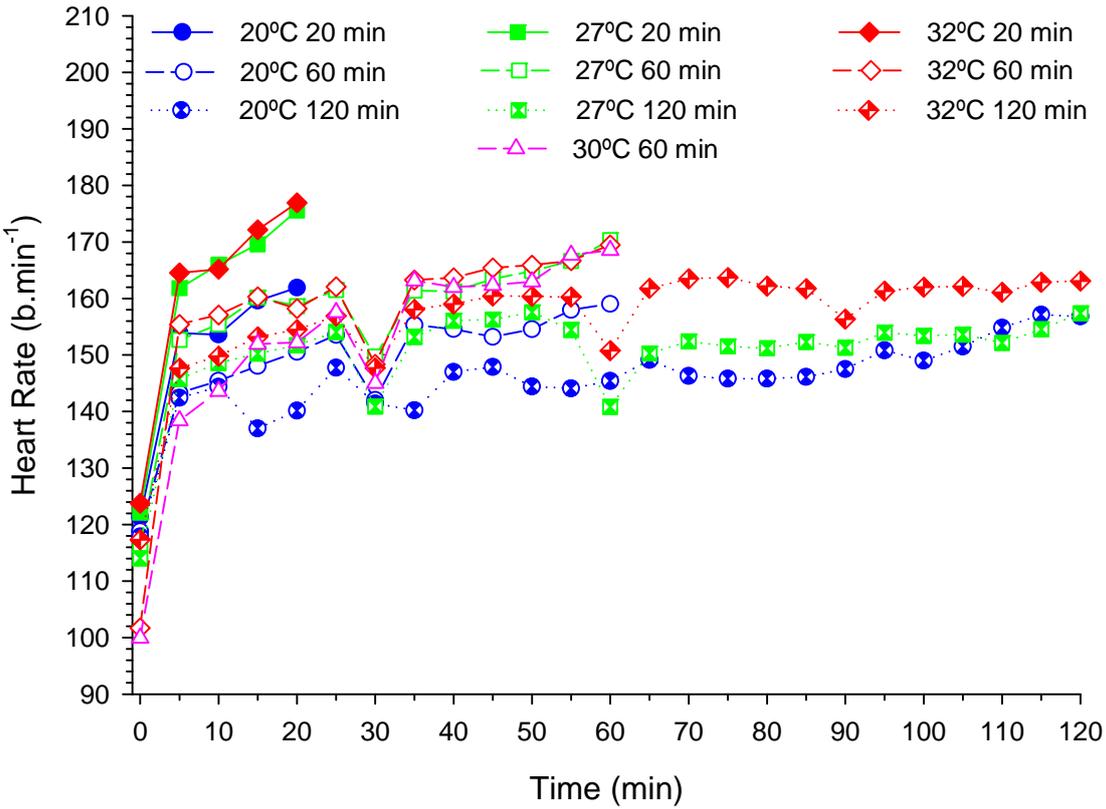
Figure 8. Mean heart rate response over time for each of the three swim durations in each of the three water temperatures. Data are also shown for the additional 60-min swim in 30°C water.
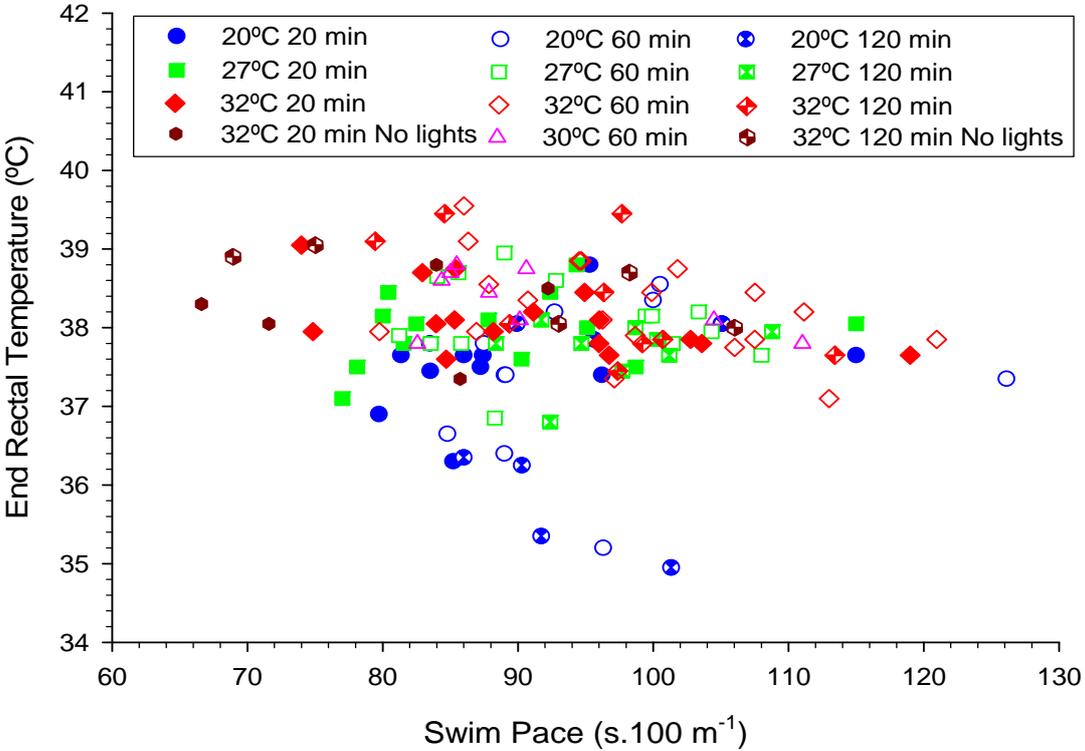
Figure 9. Average swim pace and final rectal temperature at the end of each swim for three different durations in each of three water temperatures. Data are also shown for additional 60-min swims in 30°C water and in 32°C without radiant heat load (No lights).

Figure 10. Mean distance swum by participants for each of the three swim durations in each of the three water temperatures. Additional data are shown for swims in 30°C for 60 min and in 32°C with and without radiant heat load.

Figure 11. Average swim pace of participants during each of the three swim durations in each of the three water temperatures. Also shown are data from an additional swim in 30°C for 60 min.
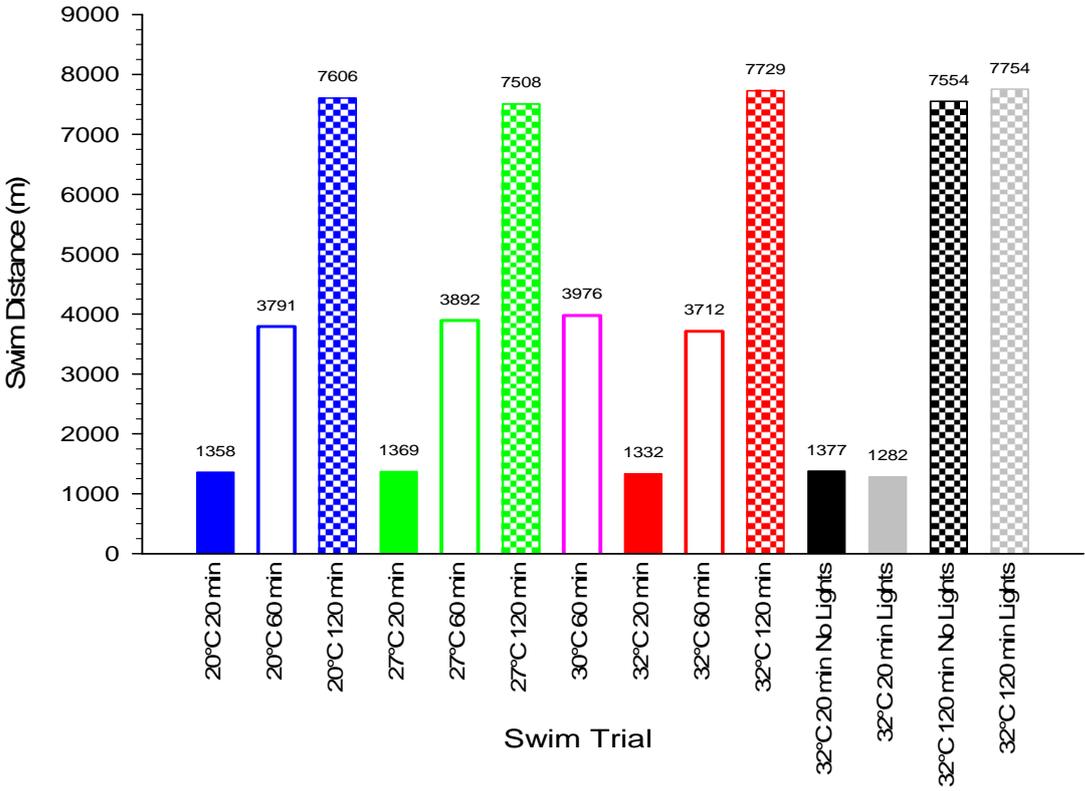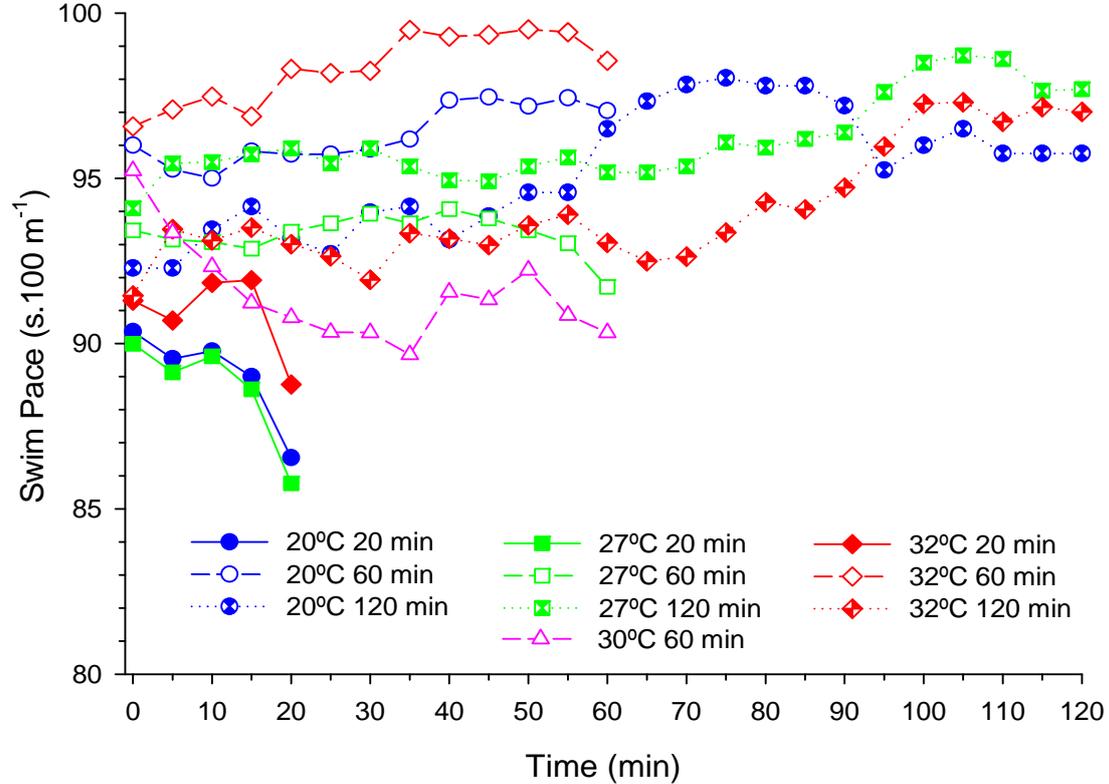
4.3.3 Behavioural and Autonomic Thermoregulation

The results of this study indicate that not only can swimmers accurately perceive changes in their body temperature, but that the thermally-related inputs they are receiving in warm water may actually be stronger than those of terrestrial athletes. Specifically, the positive relationship between the swimmers' perceived body temperature and their actual T_{re} (Figure 12; Panel B) and thermal discomfort (Figure 12; Panel C) indicate that as a swimmer's core temperature increases, the clamping of their skin temperature by the water does not obviously suppress their thermal perception. These changes are further supported by a negative relationship between T_{re} and overall feeling (Figure 12; Panel D). However, as previously mentioned, if brain temperature is increasing faster (or to a greater extent) than rectal temperature then these data should be interpreted with caution as a significant difference between these T_c indices would also negatively influence these relationships. Any such differences aside, interestingly, when compared to some previous data from our lab of participants running and cycling in warm ambient air (at similar skin temperatures to those currently recorded in 32°C water), the slope of the relationship between actual and perceived body temperatures and thermal discomfort is actually *lower* in the terrestrial athletes (Figure 13). This indicates that for the same increase in core temperature, an athlete swimming in warm water seems to feel hotter and more uncomfortable than an athlete exercising in air. It seems possible that the higher perceptual sensitivity in these swimmers (compared to the terrestrial athletes) may be related to some degree of adaptation afforded by their respective training (which is typically in ~27°C). In other words, a terrestrial athlete may be more acclimated or accustomed (and therefore maybe more tolerant) to higher core temperatures as well as skin temperatures, as they regularly experience this in daily training, compared to a swimmer who will likely train regularly at an indoor pool in 27°C water. Nonetheless, this notion will be addressed as part of the next phase of this project, warm water acclimation, which will examine changes in swimmers' perceptions as they become acclimated to warm water conditions.

Since swimmers appear to experience appropriate afferent cues for behavioural thermoregulation, it seems safe to assume athletes may be endangering themselves if they also ignore these indicators of rising body temperature. Consequently, as with terrestrial

athletes, swimmers must share responsibility for their safety by recognising and responding appropriately to such signals. Further, as discussed earlier, no participants reached our ethically approved limit for core body temperature or failed to complete a warm water swim trial due to feeling poor or displaying signs of extreme discomfort. In contrast, four swimmers could not complete swim trials in the cooler 20°C water due to extreme feelings of cold and discomfort. This would indicate that athletes are able to reliably perceive their thermal status and make appropriate behavioural adjustments to thermoregulate. It may also indicate that there is an even greater cause to consider the thermal safety of swimming in cold water temperatures less than 20°C.
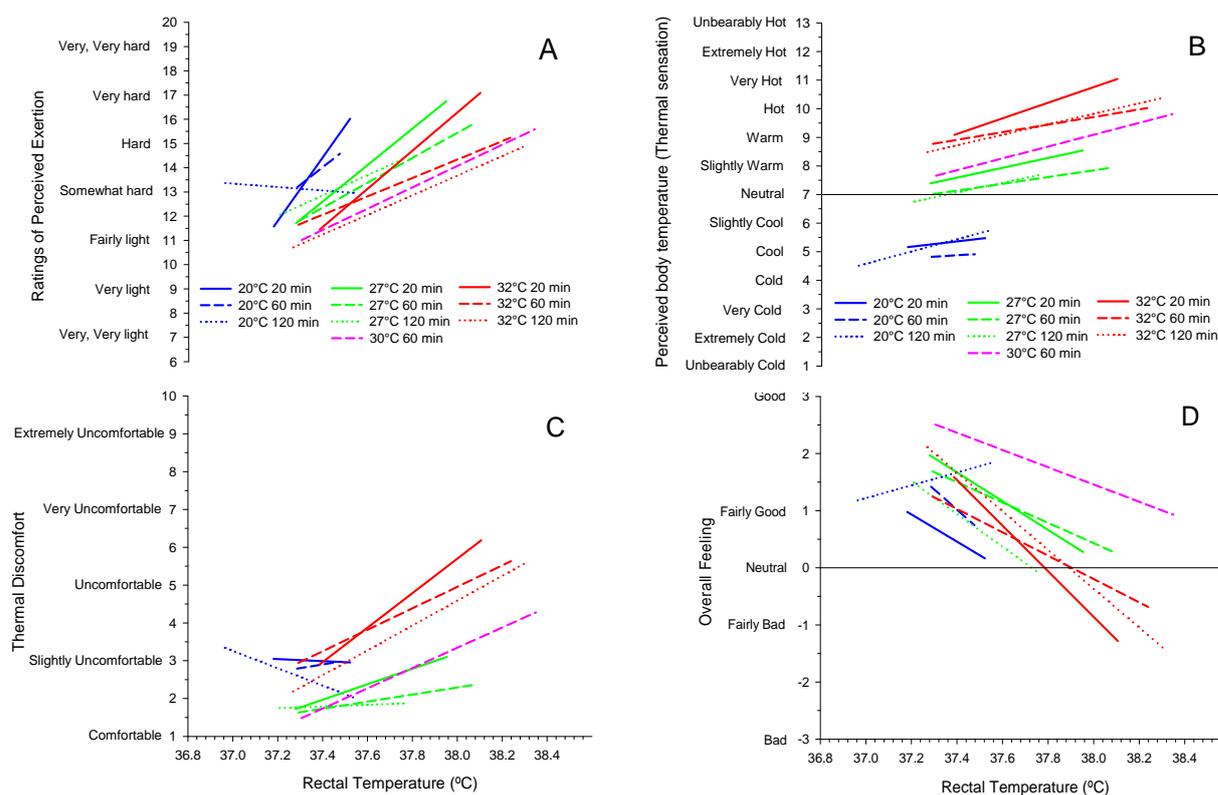
Figure 12. Relationship between actual core body temperature (Rectal temperature) and Ratings of Perceived Exertion (Panel A), Perceived Body Temperature (Panel B), Thermal Discomfort (Panel C) and Overall Feeling (Panel D). The lines represent regression lines of all participant data for each of the three swim durations in each of the three water temperatures as indicated on the legend in panels A and B. Additional data are also shown for participants who swam in 30°C water.
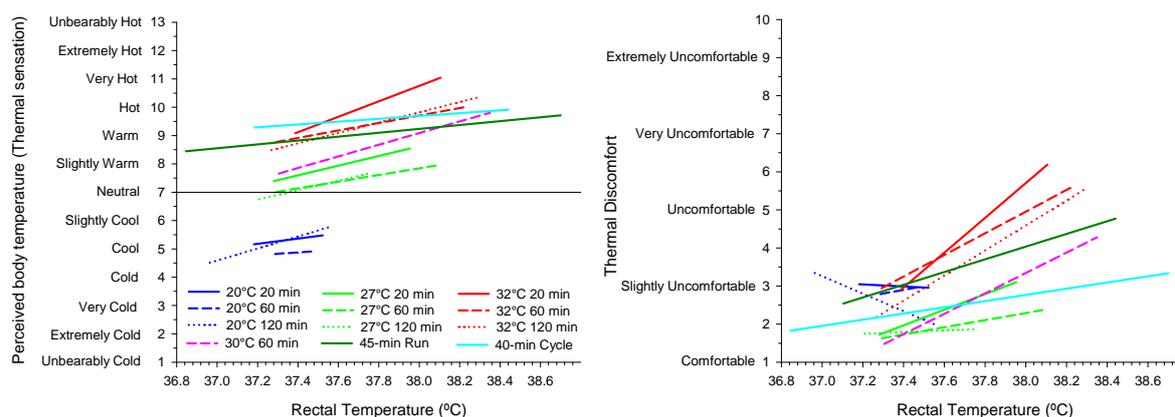
Figure 13. Relationship between actual core body temperature (Rectal temperature) and Perceived Body Temperature (Left) and Thermal Discomfort (Right) as shown in Figure 12, however a comparison to data from terrestrial athletes is overlaid in these graphs. The legend for both graphs is shown on the left.

Changes in body mass may be used to estimate total fluid/sweat loss. However, it became apparent during this study that swimmers may swallow various amounts of water as they turn their heads to breathe. Even in swimmers who do not believe they swallow significant amounts of water, it is likely that drops are regularly entering the mouth and being swallowed over time. A number of participants noted regular gulps of water, with some indicating after a swim that the volume swallowed may have been as much as 300 ml, or more. Given this, it makes the use and interpretation of changes in body mass difficult as the volume of swallowed water is impossible to measure accurately, and therefore these changes in body mass may actually be slight underestimations of sweat loss. Nonetheless, the results indicate that even in water, where the ability to evaporate is greatly reduced and the skin remains wetted, our swimmers showed sweat rates not dissimilar to those observed in a simulated 5-km swim in water temperatures of 23, 27 and 32°C (Macaluso et al., 2011) or those observed in terrestrial athletes i.e., marathon runners (Noakes et al., 1991). For example, in warm 32°C water, average sweat rates were 1.13 L.h^{-1} over 120-min swims, and up to 2.35 L.h^{-1} in the 20-min swims (Figure 14 ; Panel A). This represents an average mass loss of 1.0 – 2.9% in the 20 and 120-min swims, respectively (Figure 14; Panel C). As expected, in the cold water (20°C) mass loss was minimal (less than 1%), with average sweat rates well under 1 L.h^{-1} (Figure 14). We presume that most elite swimmers would already be aware of their mass changes across a race, thus, these magnitudes may not be surprising. However, it should also be noted that athletes need to remain mindful that such changes in

body mass are not a particularly accurate measure of hydration status. Further, given our observation of water ingestion by many swimmers and their similar rates of mass loss compared to terrestrial athletes, an interesting situation may develop for swimmers in sea water events where the swallowing of salty sea water may exacerbate dehydration (transiently) through intestinal absorption of extracellular fluid. This is an area where further research would certainly be warranted.
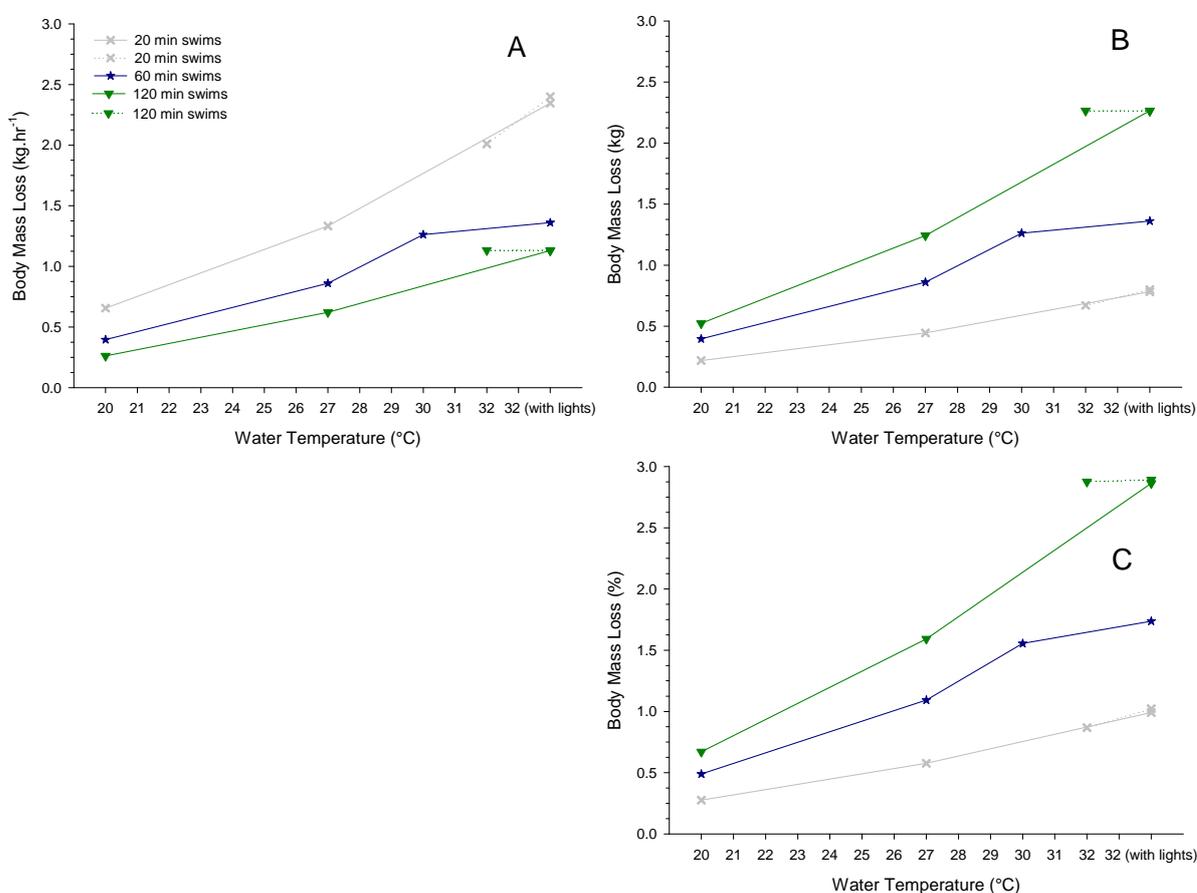
Figure 14. Changes in body mass, presented as rate of mass loss (Panel A), absolute mass loss (Panel B) and % mass loss (Panel C) during each of three swim durations in each of three water temperatures. Data are also shown for the few participants who completed 20- and 120-min swims in 32°C water both with and without radiant heat load. Legend is shown in Panel A.

4.4 Research Question 2 – What early warning signs of altered thermoregulation can be used to predict a serious challenge to athlete safety?

As discussed above, no swimmer became markedly heat strained in any of the ~100 warm water swim trials, either relative to another swimmer or relative to athletes undertaking terrestrial exercise such as running and cycling. Therefore, it is somewhat difficult to identify any early warning signals of an athlete in trouble. Various field studies of sports such as rugby, squash and half marathon have shown that sub-elite and elite athletes can safely and voluntarily tolerate core temperatures of 40-41°C, so it may not necessarily be those with the highest temperatures who are in danger. A high core temperature may simply reflect an individual response to that particular exercise situation. While the situation is unknown for swimming, a few points are worth noting in regard to T_c in terrestrial sports: (i) highly fit individuals have higher critical T_c limits than untrained people (Cheung & McLellan, 1998; Selkirk, McLellan, Wright, & Rhind, 2008); (ii) final T_c during racing is more dependent on exercise intensity over the final stages than on factors such as dehydration; (iii) yet, T_c seems to be lower in highly-fit (faster) than moderately-fit individuals during racing in humid heat (Byrne et al., 2006); and (iv) training and heat conditioning studies have not shown that this upper critical T_c can be improved in the short term. In summary, T_c (or heart rate), or its rise, does not necessarily reveal who is most at risk of heat injury during competitive, heat stressful exercise.

As for safety concerns in cool-water swimming, numerous factors lead to intolerance and termination of swims. First, the cold shock response has some potential to be hazardous acutely, and we have recently shown that this is just as pronounced in competent swimmers as in novices during *rapid-onset* immersion (but recovers more quickly) and may have less impact on brain perfusion (Button, Croft, Graham, Cotter, & Lucas, 2013). The cold shock response is highly trainable – this can be achieved using few immersions, and lasts for many months (Barwood, Dalzell, Datta, Thelwell, & Tipton, 2006; Barwood, Datta, Thelwell, & Tipton, 2007; Tipton, Golden, Higenbottam, Mekjavic, & Eglin, 1998; Tipton, Mekjavic, & Eglin, 2000). Second, cooling of peripheral tissues, muscle (esp. prime movers of the upper arm) and core organs can induce more rapid fatigue, but also strong cold discomfort and voluntary termination of a swim. Such terminations occur relatively frequently, with the

leanest individuals most at risk, because their higher heat production is more than offset by their higher heat loss. In considering early warning signs predictive of serious concern for swimmers' safety, the problem of progressive cooling may have telltale features; an increase in stroke rate and reduction in stroke length (Tipton, Eglin, Gennser, & Golden, 1999). But, a third, more sinister problem appears to have no such markers, and may have led to many fatalities in competitive open-water swimming (Tipton, 2012). A high proportion of triathlon deaths occur in the swim; 30 out of 38 'non-traumatic' athlete deaths in triathlons between 2003 and 2011 (as reported in the recent USA Triathlon (USAT) Fatality Incidents Study). Professor Tipton proposes that they may have been caused by sudden cardiac death arising from autonomic conflict attributable to dual activation of the parasympathetic and sympathetic arms of the autonomic nervous system. Such dual activation may arise due to a combination of factors which can occur in open water swimming races, but not fully in training, i.e., emotional arousal (esp. anger), skin cooling, breath-holding and facial immersion, and the higher exercise intensity. Therefore, in this project it was possible to examine effects of tissue cooling, but not autonomic conflict. An examination of cold shock was not warranted in this study.

To further explore possible predictors of excessive thermal strain in our participating swimmers, an analysis of some key components of swimming technique was undertaken in four participants during 120-min swims in the most thermally stressful swims, i.e., 32°C and 20°C water. Two of these participants did not complete the 20°C swim due to low T_{re} and a third finished, but also with low T_{re} and obvious shivering. The methods and results of this arm of our study are presented together below, with additional graphs included in Appendix C.

4.4.1 Methods – Stroke Analysis

Coordination of arm movements was assessed using the procedures described by Chollet, Chalies and Chatard (2000). An underwater camera was placed ahead of the swimmer to capture frontal plane motion; a second camera was placed behind a glass viewing window to capture sagittal plane motion; a third camera placed above, behind and to the right of the swimmer captured the swimmer's recovery phase. These three camera views were

synchronized with a quad-mixer and a feed from LabChart (v7.3.4, ADInstruments). Video was recorded onto a digital video recorder and later replayed through Kinovea software.

Sample video clips were taken at three times: five minutes after the start, one hour after the start and five minutes before the end of the trial. On each occasion, three complete stroke cycles were analysed (three left and three right strokes). Each arm movement was broken down into four phases: a) glide – from the hand's entry into the water until the start of downward and backward movement; b) pull – from the start of downward and backward movement until the hand crossed the vertical plane of the shoulder; c) push – from the hand crossing the vertical plane of the shoulder until the release of the hand from the water; d) recovery – from the release of the hand from the water until entry into the water on the subsequent stroke. Each phase was calculated as a percentage of the mean stroke duration (the sum of the phases). The stroke length was calculated from the stroke rate and the recorded flume velocity.

The lag time was calculated as the difference between the end of propulsion from one arm and the start of propulsion of the next arm. Five such lag times were calculated from the six complete stroke cycles. Each lag time was expressed as a percentage of stroke duration and then combined to give a mean Coordination Index.

All data were recorded in an Excel spreadsheet (Microsoft, USA) and then subsequently analysed using R (R Development Core Team), including the R packages lme4 and language. Linear mixed effects models were used with Participants as a random effect, and Sample Time (early, middle, late), Water Temperature (20°C, 32°C) and the interaction as fixed effects.

Normality and homogeneity were checked by visual inspections of plots of residuals against fitted values. To assess the validity of the mixed effects analyses, likelihood ratio tests compared the models with fixed effects to the null models with only the random effects. Results were rejected in which the model including fixed effects did not differ significantly from the null model ($p > 0.05$). Monte Carlo Markov Chain (MCMC)-estimated p-values and effect sizes are presented for models that differed from the null model.

4.4.2 Results – Stroke Analysis

Stroke Rate increased across the swim time in the warm water relative to that in the cold water (Figure 15 and Table 4; interaction: p=0.004), but was unaffected by these factors (water temperature or time) when considered in isolation of each other. Correspondingly, Stroke Length decreased more rapidly in the warm water than the cold water (Figure 15 and Table 4; interaction: p=0.005), but was unaffected by time or water temperature if these factors were considered in isolation of each other. The model for Index of coordination did not differ from the null model (i.e. with no fixed effects; p=0.23). The coordination seemed to be quite individual and was not affected by the cold or the duration (Figure 15 and Table 4).

When considered individually (Figure 15), subjects A and E were withdrawn from the 120-min swim in 20°C due to low T_{re}; subject N completed the 120-min swim but with a decreasing T_{re} and obvious shivering at the end; and subject R was comfortable in 20°C and T_{re} increased. Further, as these 120-min trials progressed, the swimming pace of these subjects tended to slow, except in 32°C for subject E and 20°C for subject R where swimming pace increased. Therefore, even though stroke rate appears to *decrease* with time in 20°C water (especially in those with decreasing T_{re}), this may be accounted for by the slowing of pace in these subjects across the trial. Conversely, in the 32°C water where swim pace also decreases across the trial, stroke appears to *increase*. Even though the decrease in stroke rate observed in 20°C water goes against previous research which suggests stroke rate increases in cold water (Tipton et al., 1999), this previous study does observe these stroke rate increases in colder 10°C water, and it used breaststroke, not front crawl. Nonetheless, in a more comparable 18°C water temperature, the same study observed no difference in stroke rate compared to swimming in 25°C, although there does still appear to be a slight increase in stroke rate toward the end of these 18°C swims. The authors concluded that the increase in stroke rate during the 10°C water swims may be related to cold arms and muscle fatigue. Given the swim pace in our subjects was also decreasing, the *decrease* in stroke rate we observed may also be able to be explained by cold upper limbs (and possibly the perception of this) and muscle fatigue. What may be more difficult to explain is the increase in stroke rate seen across the 120-min swim in 32°C which do not appear to be associated

with increases in swim pace. However, this increase in stroke rate (and decrease in stroke length) may be the result of similar factors, i.e. hot limbs (and the perception of it) and muscle fatigue, similar to what was previously observed in very cold water (Tipton et al., 1999).

What this means for using changes in swimmers technique, such as stroke rate, as a warning sign of athletes in difficulty is uncertain. However, it does suggest the use of stroke rate at least may not be a suitable, or sensitive enough, method to use. Nonetheless, we will continue to examine these changes across a greater number of participants and swim trials, particularly during the repeated warm water swims we will be using to address research question 5.

Table 4. Summary of biomechanical variables. Mean±SD from three complete stroke cycles taken from three parts of the 120-min trial in each of two water temperatures.

Sample Time	Early	Middle	Late	Early	Middle	Late
Water Temperature	20°C	20°C	20°C	32°C	32°C	32°C
Stroke Rate (min^{-1})	29.9±1.9	29.6±1.0	28.8±1.6	28.6±2.8	30.4±2.6	31.7±1.8
Stroke Length (m)	2.2±0.26	2.2±0.11	2.2±0.18	2.2±0.38	2.1±0.35	1.9±0.26
Index of Coordination (%)	-6.4±8.5	-5.9±6.4	-5.3±7.1	-6.7±8.0	-6.0±8.2	-5.0±8.1

Table 5. Percentage (%) of stroke time spent in each phase for left and right sides. Mean±SD from three complete stroke cycles taken from three parts of the 120-min trial in each of two water temperatures.

	Sample Time	Early	Middle	Late	Early	Middle	Late
	Water Temperature	20°C	20°C	20°C	32°C	32°C	32°C
Left	Glide	39.7±12.1	38.6±10.6	40.1±9.6	38.2±11.3	37.5±10.9	37.6±11.1
	Pull	19.6±5.8	20.1±4.4	21.4±2.0	21.7±3.5	20.7±4.2	22.9±6.0
	Push	21.5±4.3	21.2±4.2	20.5±5.5	20.2±6.2	21.7±4.4	20.1±3.2
	Recovery	19.1±2.8	20.2±3.7	18.0±3.7	20.0±4.0	20.1±3.6	19.4±3.1
Right	Glide	35.4±12.2	33.8±12.0	33.7±14.1	33.8±11.4	32.7±12.2	32.7±10.5
	Pull	21.1±5.8	20.9±3.5	21.3±3.9	20.0±3.5	18.4±4.8	20.9±5.0
	Push	24.1±3.1	25.1±5.3	25.6±6.7	24.6±6.0	27.2±5.9	25.6±6.9
	Recovery	19.5±3.7	20.3±4.6	19.4±4.0	21.6±2.4	21.8±3.1	20.8±2.7
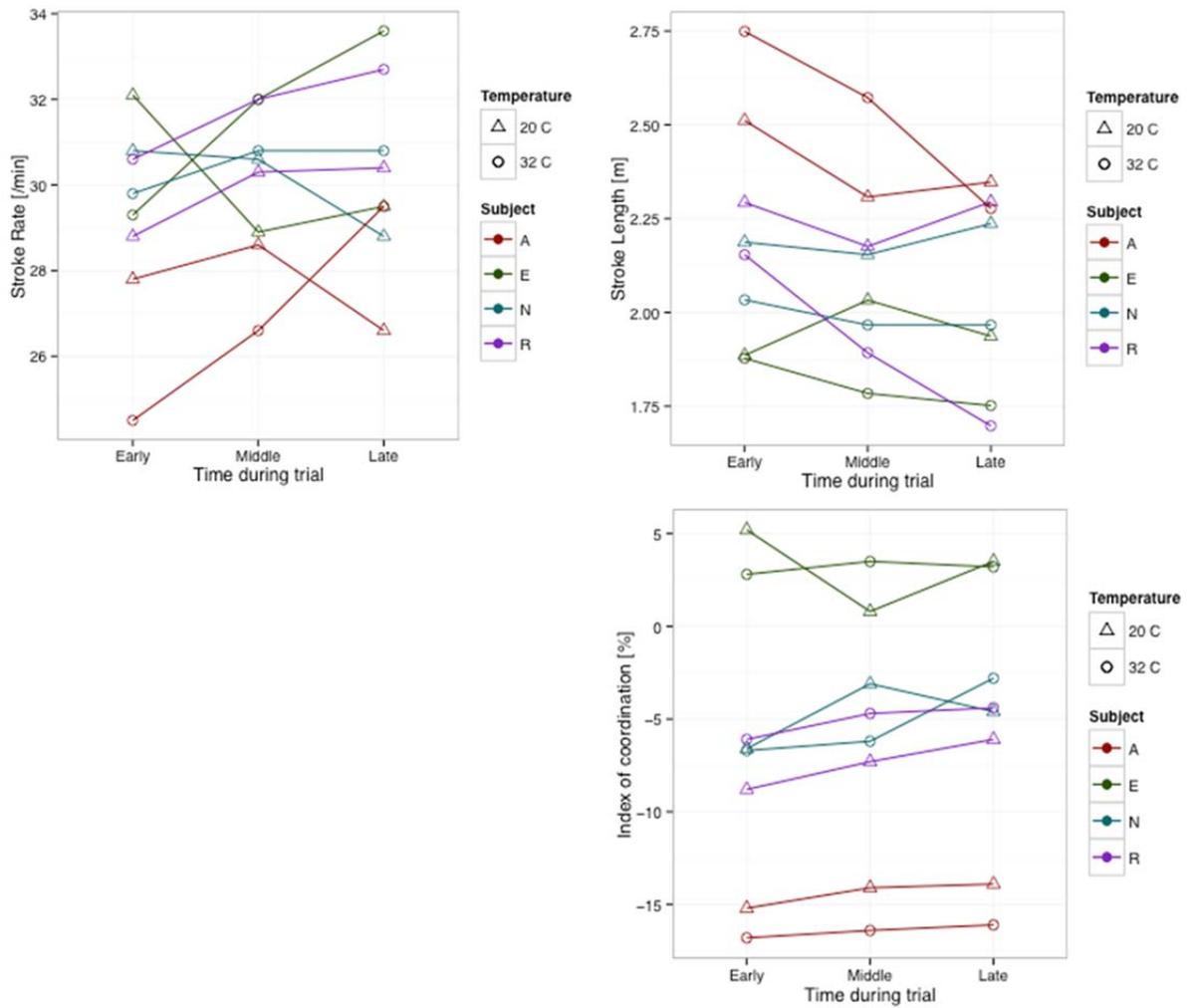
Figure 15. Stroke Rate, Stroke Length and Index of Coordination for 4 participants at three different times during the 120-min swim trial in 20°C and 32°C water temperatures.

4.5 Research Question 4 – Is heat tolerance affected by factors such as recent heavy training load, illness or specific drug use, and do swimmers adjust their behaviour accordingly?

4.5.1 Methods

Our initial plan to address this question was to ask any of our study participants who fell ill during testing to complete an additional swim trial during their convalescent phase, post-illness and fever. However, no participants appeared to fall ill with any fever-generating infections during the study. Therefore, an overtraining model was used to obtain some data on the role of inflammation in the thermal responses to swimming. We took 3 of our current participants and asked them to greatly increase their training volume over 5 consecutive days. Each participant completed a 20-min swim in 32°C water (with radiant load) immediately before and after the increased training load and the same protocols and measurements were used as in the main study.

4.5.2 Results

The results indicate that 5 days of increased training volume (greater than 50% increase) had little effect on heat tolerance or behavioural thermoregulation. The T_{re} response during a 20-min swim in 32°C water was similar before and after the increase in training volume (Figure 16). This is supported by a similar distance swum (Figure 17), even though the pacing profile was slightly different (Figure 18). Anecdotally, the participants felt 'sore and tired' after 5 days of an increased training load, however, there was no difference in the relation between their perceived exertion or perceived body temperature with actual body temperature (Figure 19). The maintenance of this relationship is important, as Skinner, Mitchell and Harden (2009) suggest that various perceptions (such as lethargy, social withdrawal and decreased physical activity) may be more important determinants of fever and inflammation than temperature and many blood markers. Nonetheless, the blood measures collected from our participants before and after this high volume training week will be included with the batch analysis of all blood samples from the main swim trials. These samples will be analysed together (i.e., when the study relating to Question 5 is complete), and we also wish

to collaborate with exercise immunologists in Australia to extend the scope of this blood analysis to include various other important immune markers. Therefore, we have not reported data on circulating concentrations of inflammatory markers in this report.
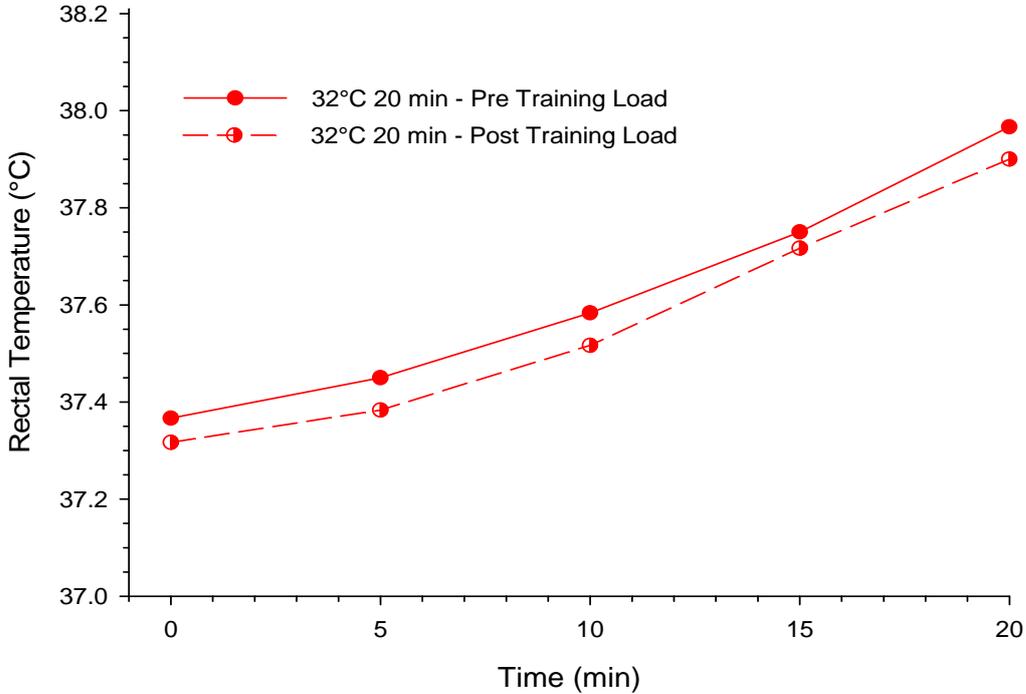
Figure 16. Mean rectal temperature response for three participants during a 20-min swim in 32°C water completed before (Pre) and after (Post) 5 days of increased training volume.
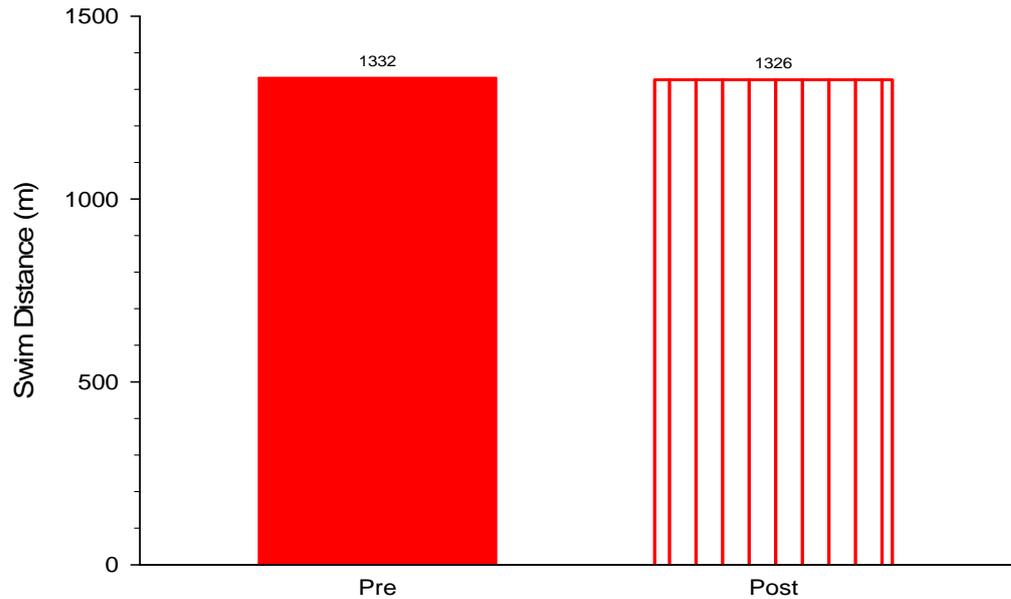
Figure 17. Mean swim distance achieved during a 20-min swim in 32°C water completed by three participants before (Pre) and after (Post) 5 days of increased training volume.
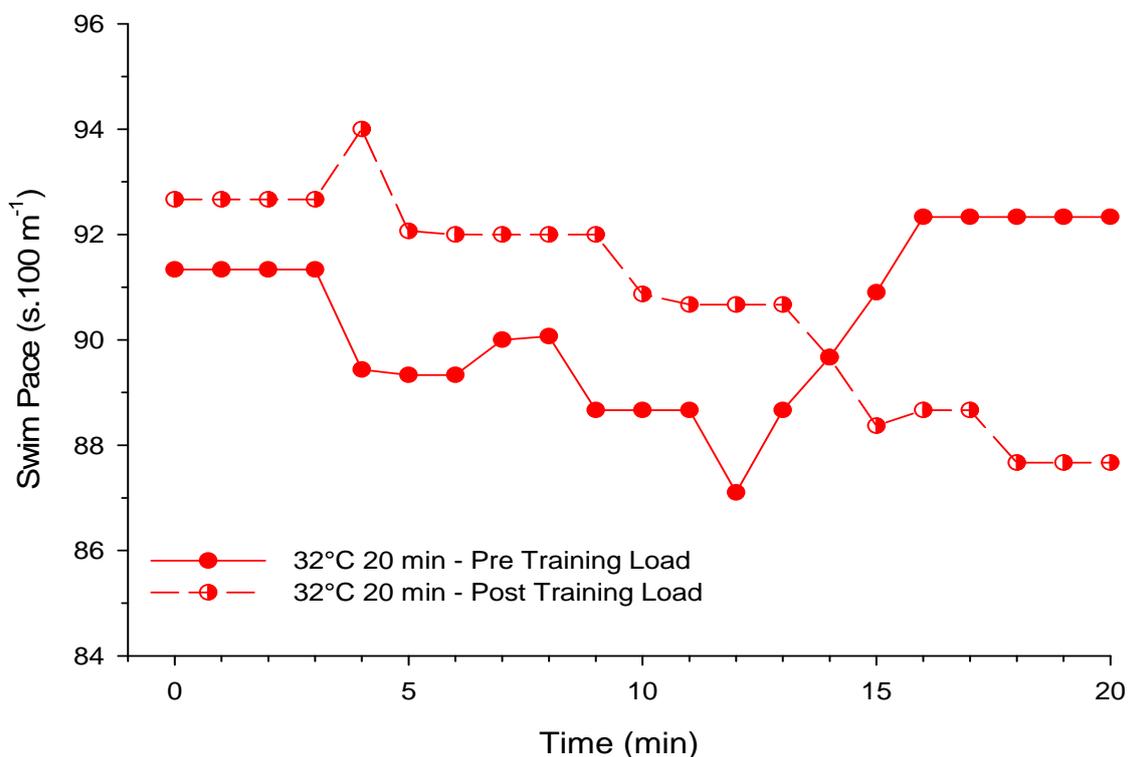
Figure 18. Mean swim pace during a 20-min swim in 32°C water completed by three participants before (Pre) and after (Post) 5 days of increased training volume.
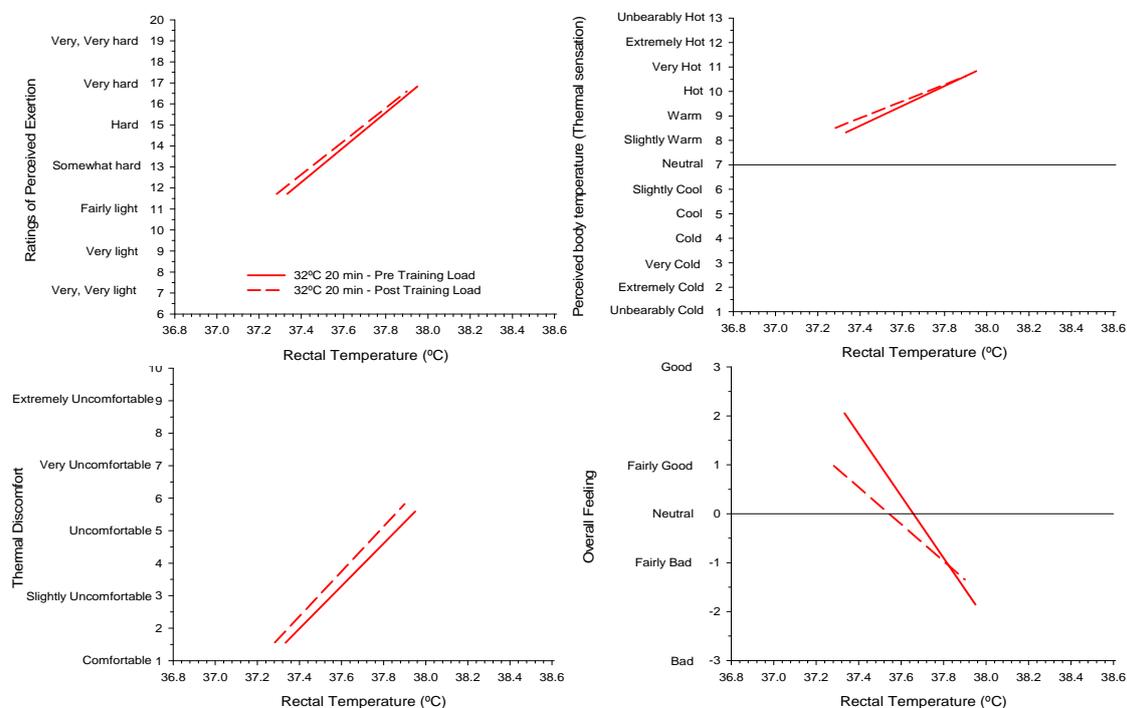
Figure 19. Relationship between actual core body temperature (Rectal temperature) and Ratings of Perceived Exertion, Perceived Body Temperature, Thermal Discomfort and Overall Feeling during a 20-min swim in 32°C before (Pre) and after (Post) 5 days of increased training volume. The lines represent regression lines through the data from three participants. The legend is shown on the first panel.

5 CONCLUSIONS AND RECOMMENDATIONS

We make the following conclusions and recommendations for the first 4 of the agreed research questions, based primarily on the data obtained in conjunction with a comprehensive literature review.

5.1 Research Question 1 – What is the effect of the swimming distance and the water temperature on behavioural and autonomic thermoregulation, core body temperature and performance capacity?

- In 190 swims trials (~100 conducted in water temperatures of 30°C or warmer), only ~5% resulted in core (rectal) temperatures higher than 39.0°C, the highest being 39.55°C. Further, no athletes were removed or voluntarily stopped due to discomfort, distress or ethical end-points in the warm water swims, however, 4/8 swimmers (50%) could not complete the longer (1 or 2 h) swims in 20°C water. One athlete could not tolerate more than 20 min in 20°C (and may have experienced an exceptionally low oesophageal temperature), while three others were either stopped due to T_c dropping to ~35.0°C or voluntarily stopped due to extreme discomfort. Therefore, the ITU's coolest current non-wetsuit water temperatures caused more thermal intolerance than did 32°C water with radiant heat loading.

- In view of current literature suggesting a potential safety problem in cool water due to autonomic conflict in open water swimming competition (but not necessarily in open-water training), and the present findings of core cooling, we believe that some safety issues exist which are not readily solvable through research or policy. Nevertheless, they should be recognised by officials and swimmers.

- It is recommended that more information is obtained at least on athlete's core temperatures and perceptions in both cool and warm open-water competitions, particularly when cycling after swimming.

- Swimming speed was not predictive of larger rises in core body temperature when swimming in heat stressful water and radiant temperatures, nor was it reliably related to changes in core temperature when swimming in cool water (20°C). So, at least for the velocities obtained in this study (67 – 127 s / 100 m), the fastest swimmers did not necessarily experience the fastest rise in core temperature. Our conclusions on core temperature responses are reserved by virtue of the difficulty with interpreting information from different indices (esp. rectal vs oesophageal, as a measure of heart, liver, digestive and brain temperatures) during swimming under thermal stress. We recommend that additional research is undertaken to determine their relations, and we will attempt to gain further such information.

- Thermoregulatory responses (perceptions, pacing and sweating) and core temperature were affected to similar extent in the 60- and 120-min swims. So, no particular endurance swimming distance was conducive to causing the highest levels of physiological or psychophysical strain.

- Behavioural thermoregulation appeared to be functioning effectively across the wide range of thermal stress (esp. water temperatures) and strain (esp. core temperatures) observed in this study. For example, uncompensable cold stress led to swimmers' termination of the task and/or clear perception of their status. Conversely, during self-paced swimming in warm water for up to two hours, no swimmer displayed an uncompensable heat stress, and they had a clear perception of their status.

- Autonomic thermoregulation was studied via body mass changes. Even though the effectiveness of the body's principal autonomic cooling system (i.e. sweating) is nullified in water, it appears from the current and previous studies that swimmers maintain relatively normal sweat rates, similar to those commonly observed in terrestrial athletes. Further, it seems that many swimmers swallow various volumes of water while turning to breathe (consciously and unconsciously) which makes the interpretation of sweating from body mass changes difficult. Both the swallowing of water (particularly if swimming in sea water) and high sweat rates in some swimmers have obvious implications for the hydration status of swimmers and should be considered; esp. for longer competitions in sea water.

- Swimming performance (distance completed) was not affected consistently by swimming in either warm (32°C) or cool (20°C) water, except for cold-intolerant swimmers swimming in cool water, because they're unable to even finish. Generally, across 1.5 – 10-km equivalent swimming durations, 27°C tended to produce the best performances. For races of ~1 hour (~5 km), 27°C water clearly produces better performances than 32°C water. In summary, for most distances and individuals, temperatures around those of normal pool temperatures are both more comfortable and tend to be more conducive to optimal performance.

- The research team appreciates the desire for a recommendation to be produced on what might constitute a maximum safe water temperature for open water swimming. In one respect, it might be concluded that because (a) no intolerance or unusually high exercising core temperatures were observed in 100 instrumented, maximal effort swims in 30-32°C, (b) such water temperatures did not necessarily produce large elevations in T_c in fast swimmers, and (c) swimmers had strong afferent cues as to their rising body temperature, then such water temperatures are to be considered 'safe'. However, we recommend that a more conservative limit – perhaps 31°C – would seem warranted on the following bases: (i) We cannot be certain that T_{re} accurately reflects the temperature of other temperature-sensitive organs during swimming, and such information is methodologically very difficult to obtain; and (ii) swimming in actual open-water competition might produce higher T_c than is produced in lab trials. More importantly, however,

  - swimmers, as with other athletes who compete under severe thermal stress, should use their own thermal cues to help pace themselves to avoid thermal injury (also based on 5.3 below);

  - heat stroke is not necessarily caused by high environmental temperature per se, and is not predicted by any particular core temperature, which again puts some responsibility on the coach and swimmer to be cognisant of their health status and make decisions appropriately.

We would welcome open dialogue on this (or any other) issue, particularly if it helps to resolve different viewpoints.

5.2 Research Question 2 – What early warning signals of altered thermoregulation could be used to predict a serious challenge to athlete safety?

- No swimmers became distressed or excessively hyperthermic in any of the warm water swims, making it difficult to determine predictive behaviours. However, a few participants did not complete the longer swims in 20°C, but stroke analysis, which included a couple of these swimmers, did not reveal major differences in stroke rate or stroke length during the 120-min swims in 32°C and 20°C water.

- The researchers noted shivering, interrupted speech and vasoconstricted skin (cyanosed lips and skin of the fingers, upper back and arms) in participants with low T_c in the 20°C water, thus coaches and athletes themselves need to remain vigilant in monitoring changes during a race.

5.3 Research Question 3 – Can individuals accurately perceive their own body temperature when swimming in warm water?

- Strong, positive relationships were evident between actual body (core) temperature and perceived body temperature (thermal sensation and discomfort), which indicates that swimmers can accurately perceive changes in body temperature while swimming in warm water. These perceptions may also be stronger than those of terrestrial athletes for a similar change in core and skin temperature.

- This afferent information has a clear survival value for both heat stress and cool stress in open-water swimming.

- While addressing question 5 of this study, we will extend these findings to determine whether the perceptual-vs-actual body temperature relation changes as athletes adapt to repeated swimming in warm water. We also hope to extend the obtained relations to higher core temperatures. Obtaining such information for swimmers undertaking open-water races would also be valuable.

5.4 Research Question 4 – Is heat tolerance affected by factors including recent heavy training load, illness and specific drug use and do swimmers adjust their behaviour accordingly?

- Using a short-term training overload model (5 days of heavily-increased training volume: by >50%), no differences were observed in the T_{re} response, distance swum or the relationship between actual and perceived body temperature. Once question 5 is completed, we hope to examine the plasma samples from these trials for their neuroendocrine and immunological profiles. Nevertheless, it would still be valuable to obtain information on core temperature, perceptual and immunological responses for swimmers in the convalescence phase from febrile illness. (That opportunity hasn't arisen in our lab at this time).

6   REFERENCES

Avellini, B. A., Shapiro, Y., Fortney, S. M., Wenger, C. B., & Pandolf, K. B. (1982). Effects on heat tolerance of physical-training in water and on land. *Journal of Applied Physiology, 53*(5), 1291-1298.

Barwood, M. J., Dalzell, J., Datta, A. K., Thelwell, R. C., & Tipton, M. J. (2006). Breath-hold performance during cold water immersion: Effects of psychological skills training. *Aviat Space Environ Med, 77*(11), 1136-1142.

Barwood, M. J., Datta, A. K., Thelwell, R. C., & Tipton, M. J. (2007). Breath-hold time during cold water immersion: Effects of habituation with psychological training. *Aviat Space Environ Med, 78*(11), 1029-1034.

Benarroch, E. E. M. D. (2007). Thermoregulation: Recent concepts and remaining questions. *Neurology, 69*(12), 1293-1297.

Bligh, J. (1998). Mammalian homeothermy: An integrative thesis. *Journal of Thermal Biology, 23*(3–4), 143-258.

Bligh, J. (2006). A theoretical consideration of the means whereby the mammalian core temperature is defended at a null zone. *J Appl Physiol, 100*(4), 1332-1337.

Borg, G. A. V. (1962). Perceived exertion in relation to physical work load and pulse rate. *Kunglia Fysioga Sallsk Lund. Forth., 31*, 105-115.

Buono, M. J., Ball, K. D., & Kolkhorst, F. W. (2007). Sodium ion concentration vs. Sweat rate relationship in humans. *Journal of Applied Physiology, 103*(3), 990-994.

Buono, M. J., Heaney, J. H., & Canine, K. M. (1998). Acclimation to humid heat lowers resting core temperature. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 274*(5), R1295-R1299.

Button, C., Croft, J., Graham, M., J., Cotter, J. D., & Lucas, S. J. E. (2013). *A multifactorial examination of human response to sudden cold-water immersion.* Paper presented at the International Conference on Environmental Ergonomics, Queenstown, New Zealand.

Byrne, C., Lee, J. K. W., Chew, S. A. N., Lim, C. L., & Tan, E. Y. M. (2006). Continuous thermoregulatory responses to mass-participation distance running in heat. *Medicine & Science in Sports & Exercise, 38*(5), 803-810.

Cabanac, M., Cunningham, D. J., & Stolwijk, J. A. (1971). Thermoregulatory set point during exercise: A behavioral approach. *Journal of Comparative & Physiological Psychology, 76*(1), 94-102.

Cabanac, M., Massonnet, B., & Belaiche, R. (1972). Preferred skin temperature as a function of internal and mean skin temperature. *Journal of Applied Physiology, 33*(6), 699-703.

Cheung, S. S., & McLellan, T. M. (1998). Heat acclimation, aerobic fitness, and hydration effects on tolerance during uncompensable heat stress. *Journal of Applied Physiology, 84*(5), 1731-1739.

Choi, J. S., Ahn, D. W., Choi, J. K., Kim, K. R., & Park, Y. S. (1996). Thermal balance of man in water: Prediction of deep body temperature change. *Appl Human Sci, 15*(4), 161-167.

Chollet, D., Chalies, S., & Chatard, J. C. (2000). A new index of coordination for the crawl: Description and usefulness. *Int J Sports Med, 21*(01), 54-59.

Ducharme, M. B., & Tikuisis, P. (1991). In vivo thermal conductivity of the human forearm tissues. *Journal of Applied Physiology, 70*(6), 2682-2690.

Ely, B. R., Ely, M. R., Cheuvront, S. N., Kenefick, R. W., DeGroot, D. W., & Montain, S. J. (2009). Evidence against a 40°c core temperature threshold for fatigue in humans. *Journal of Applied Physiology, 107*(5), 1519-1525.

Fujishima, K., Shimizu, T., Ogaki, T., Hotta, N., Kanaya, S., Shono, T., et al. (2001). Thermoregulatory responses to low-intensity prolonged swimming in water at various temperatures and treadmill walking on land. *Journal of Physiological Anthropology and Applied Human Science, 20*(3), 199-206.

González-Alonso, J., & Calbet, J. A. L. (2003). Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation, 107*(6), 824-830.

Gonzalez-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol, 86*(3), 1032-1039.

González-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T., & Nielsen, B. (1999). Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *Journal of Applied Physiology, 86*(3), 1032-1039.

Hodder, S., & Parsons, K. (2007). The effects of solar radiation on thermal comfort. *Int J Biometeorol, 51*(3), 233-250.

Holmér, I., & Bergh, U. (1974). Metabolic and thermal response to swimming in water at varying temperatures. *Journal of Applied Physiology, 37*(5), 702-705.

Karpovich, P., & Pestrecov, K. (1939). Mechanical work and efficiency in swimming crawl and back strokes. *Arbeitsphysiologie, 10*(5), 504-514.

Kolka, M. A., & Stephenson, L. A. (1997). Effect of luteal phase elevation in core temperature on forearm blood flow during exercise. *Journal of Applied Physiology, 82*(4), 1079-1083.

Kollias, J., Barlett, L., Bergsteinova, V., Skinner, J. S., Buskirk, E. R., & Nicholas, W. C. (1974). Metabolic and thermal responses of women during cooling in water. *Journal of Applied Physiology, 36*(5), 577-580.

Lee, D. H., & Vaughan, J. A. (1964). Temperature equivalent of solar radiation on man. *Int J Biometeorol, 8*(1), 61-69.

Lim, C. L., & Mackinnon, L. T. (2006). The roles of exercise-induced immune system disturbances in the pathology of heat stroke : The dual pathway model of heat stroke. *Sports Med, 36*(1), 39-64.

Lim, C. L., Wilson, G., Brown, L., Coombes, J. S., & Mackinnon, L. T. (2007). Pre-existing inflammatory state compromises heat tolerance in rats exposed to heat stress. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 292*(1), R186-R194.

Lorenzo, S., & Minson, C. T. (2010). Heat acclimation improves cutaneous vascular function and sweating in trained cyclists. *J Appl Physiol, 109*(6), 1736-1743.

Macaluso, F., Di Felice, V., Boscaino, G., Bonsignore, G., Stampone, T., Farina, F., et al. (2011). Effects of three different water temperatures on dehydration in competitive swimmers. *Science & Sports, 26*(5), 265-271.

Maughan, R. J., Shirreffs, S. M., & Watson, P. (2007). Exercise, heat, hydration and the brain. *Journal of the American College of Nutrition, 26*(suppl 5), 604S-612S.

McArdle, W. D., Magel, J. R., Spina, R. J., Gergley, T. J., & Toner, M. M. (1984). Thermal adjustment to cold-water exposure in exercising men and women. *Journal of Applied Physiology, 56*(6), 1572-1577.

Mekjavic, I. B., & Eiken, O. (2006). Contribution of thermal and nonthermal factors to the regulation of body temperature in humans. *Journal of Applied Physiology, 100*(6), 2065-2072.

Mekjavic, I. B., & Rempel, M. E. (1990). Determination of esophageal probe insertion length based on standing and sitting height. *Journal of Applied Physiology, 69*(1), 376-379.

Mekjavic, I. B., Sundberg, C. J., & Linnarsson, D. (1991). Core temperature "null zone". *J Appl Physiol, 71*(4), 1289-1295.

Moseley, P. L. (1997). Heat shock proteins and heat adaptation of the whole organism. *J Appl Physiol, 83*(5), 1413-1417.

Nadel, E. R., Bullard, R. W., & Stolwijk, J. A. (1971). Importance of skin temperature in the regulation of sweating. *J Appl Physiol, 31*(1), 80-87.

Nadel, E. R., Holmér, I., Bergh, U., Astrand, P. O., & Stolwijk, J. A. (1974). Energy exchanges of swimming man. *Journal of Applied Physiology, 36*(4), 465-471.

Nielsen, B., & Davies, C. T. M. (1976). Temperature regulation during exercise in water and air. *Acta physiologica Scandinavica, 98*(4), 500-508.

Noakes, T. D., Myburgh, K. H., du Plessis, J., Lang, L., Lambert, M., van der Riet, C., et al. (1991). Metabolic rate, not percent dehydration, predicts rectal temperature in marathon runners. *Med Sci Sports Exerc, 23*(4), 443-449.

Pendergast, D., Zamparo, P., Prampero, P. E., Capelli, C., Cerretelli, P., Termin, A., et al. (2003). Energy balance of human locomotion in water. *European Journal of Applied Physiology, 90*(3-4), 377-386.

Ramires, M. L. V., de Castro, C. A. N., Nagasaka, Y., Nagashima, A., Assael, M. J., & Wakeham, W. A. (1995). Standard reference data for the thermal conductivity of water. *Journal of Physical and Chemical Reference Data, 24*(3), 1377-1381.

Robinson, S., & Somers, A. (1971). Temperature regulation in swimming. *J Physiol (Paris), 63*(3), 406-409.

Schlader, Z., Simmons, S., Stannard, S., & Mündel, T. (2011a). Skin temperature as a thermal controller of exercise intensity. *European Journal of Applied Physiology, 111*(8), 1631-1639.

Schlader, Z. J., Simmons, S. E., Stannard, S. R., & Mündel, T. (2011b). The independent roles of temperature and thermal perception in the control of human thermoregulatory behavior. *Physiology & Behavior, 103*(2), 217-224.

Schlader, Z. J., Stannard, S. R., & Mündel, T. (2010). Human thermoregulatory behavior during rest and exercise — a prospective review. *Physiology & Behavior, 99*(3), 269-275.

Selkirk, G. A., McLellan, T. M., Wright, H. E., & Rhind, S. G. (2008). Mild endotoxemia, nf-κb translocation, and cytokine increase during exertional heat stress in trained and untrained individuals. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 295*(2), R611-R623.

Shattock, M. J., & Tipton, M. J. (2012). 'Autonomic conflict': A different way to die during cold water immersion? *J Physiol, 590*(14), 3219-3230.

Shido, O., Sugimoto, N., Tanabe, M., & Sakurada, S. (1999). Core temperature and sweating onset in humans acclimated to heat given at a fixed daily time. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology, 276*(4), R1095-R1101.

Skinner, G. W., Mitchell, D., & Harden, L. M. (2009). Avoidance of physical activity is a sensitive indicator of illness. *Physiology & Behavior, 96*(3), 421-427.

Šrámek, P., Šimečková, M., Janský, L., Šavlíková, J., & Vybíral, S. (2000). Human physiological responses to immersion into water of different temperatures. *European Journal of Applied Physiology, 81*(5), 436-442.

Tikuisis, P., Jacobs, I., Moroz, D., Vallerand, A. L., & Martineau, L. (2000). Comparison of thermoregulatory responses between men and women immersed in cold water. *Journal of Applied Physiology, 89*(4), 1403-1411.

Tipton, M., Eglin, C., Gennser, M., & Golden, F. (1999). Immersion deaths and deterioration in swimming performance in cold water. *The Lancet, 354*(9179), 626-629.

Tipton, M. J. (2012). Sudden cardiac death during open water swimming. *British Journal of Sports Medicine, In Press*.

Tipton, M. J., Golden, F. S., Higenbottam, C., Mekjavic, I. B., & Eglin, C. M. (1998). Temperature dependence of habituation of the initial responses to cold-water immersion. *Eur J Appl Physiol Occup Physiol, 78*(3), 253-257.

Tipton, M. J., Mekjavic, I. B., & Eglin, C. M. (2000). Permanence of the habituation of the initial responses to cold-water immersion in humans. *Eur J Appl Physiol, 83*(1), 17-21.

Toner, M. M., Sawka, M. N., & Pandolf, K. B. (1984). Thermal responses during arm and leg and combined arm-leg exercise in water. *Journal of Applied Physiology, 56*(5), 1355-1360.

Toussaint, H. M., Knops, W., De Groot, G., & Hollander, A. P. (1990). The mechanical efficiency of front crawl swimming. *Med Sci Sports Exerc, 22*(3), 402-408.

Toussaint, H. M., Wakayoshi, K., Hollander, A. P., & Ogita, F. (1998). Simulated front crawl swimming performance related to critical speed and critical power. *Medicine & Science in Sports & Exercise, 30*(1), 144-151.

Wallingford, R., Ducharme, M. B., & Pommier, E. (2000). Factors limiting cold-water swimming distance while wearing personal floatation devices. *European Journal of Applied Physiology, 82*(1-2), 24-29.

Weiss, U. (2008). Inflammation. *Nature, 454*(7203), 427-427.

7   APPENDIX A– FULL LITERATURE REVIEW

7.1   Summary

This section reviews the thermoregulation of humans, focusing particularly on the differences between exercising in water and in air. It reviews research examining human responses, both behavioural and autonomic, to immersion and exercise in these very different mediums. As a result, this review aims to highlight gaps in the literature, specifically around endurance swimming exercise, and particularly in warm water environments. When discussing endurance performance in warm environments, heat acclimation is a key consideration, at least for exercise in air. The benefits of heat acclimation protocols in hot and humid ambient conditions have been extensively researched and reviewed. However, it appears to be largely unknown whether similar benefits of heat acclimation (for either water- or land-based athletes) are possible when a warm water environment is used for acclimation. Based on what is known for air environments, interesting differences may arise with acclimatisation in water, and yet swimmers competing in warm environments would presumably benefit from heat conditioning. So, the notion of adapting in air versus water will also be explored and reviewed in this chapter. Lastly, the potential development of inflammatory responses during high intensity or prolonged exercise in water will be considered, because these are also likely to impact on the thermoregulation, behaviour and exercise tolerance of swimmers in warm water. Factors that could contribute to such inflammatory responses are described, as are the pathways through which these could affect human thermoregulation in water.

7.2   Thermoregulation in Humans

Resting core body temperature (T_c) in humans is very tightly regulated at approximately 37°C. This temperature will vary across the day (24-hr) in a natural circadian rhythm by 0.5 – 1°C, typically having a peak in the late afternoon, and a nadir in the early morning. While the structures of the central nervous system (CNS) involved in thermoregulation are largely accepted, the precise mechanisms by which homeostatic

control of body temperature occurs is still incompletely understood. Research has, for more than a century, supported the primary involvement of the hypothalamus, specifically the preoptic/anterior area as the primary thermosensitive area within the CNS (Hodder & Parsons, 2007). Other areas of the CNS have also been identified as providing critical roles in thermoregulation, namely the dorsomedial nucleus of the hypothalamus, periaqueductal grey matter of the midbrain and the nucleus raphe pallidus in the medulla (Benarroch, 2007). As discussed in reviews by Bligh (2006), Mekjavic & Eiken (2006), and Bennarroch (2007), traditional theories held that core body temperature is regulated around a thermoregulatory "set-point" with threshold temperatures immediately above and below this set point, which activate the corresponding heat loss or heat gain effectors. Warm-sensitive neurons and temperature insensitive neurons in the CNS would become more or less activated or excited depending on the temperature of the body, thus activating the appropriate thermoeffectors (i.e. vasomotor tone, sweating, or shivering). The nervous activity was thought to cancel each other out at a core temperature of 37°C (i.e. creating a "setpoint"). However, this theory has come under scrutiny and alternatives have also been discussed. One of these other theories proposes that warm sensitive and cold sensitive temperature neurons (and their associated thermoreceptors in the periphery and core) act in a Reciprocal Cross-Inhibition (RCI) whereby independent sensor-to-effector pathways exist for heat loss and heat production. The responses in each of these pathways are thought to be linked in a way that when one pathway is excited or activated, the other is reciprocally inhibited. These pathways could create a point where they would overlap and neither heat loss nor heat gain effectors would be active; i.e., a null point at which body temperature is regulated (Bligh, 1998). Another theory for the regulation of body core temperature relates to the traditional notion of "setpoint" control, but argues that because sweating and shivering thresholds do not occur at similar temperatures, they must *not* operate from a single thermoregulatory "setpoint". This theory introduced the idea of an interthreshold zone (or "null zone"; Mekjavic *et al.,* (1991) within which no thermoregulatory effectors are active. The size of this interthreshold zone is suggested to be 0.3 – 0.5°C, with the boundaries of this zone reflecting temperature thresholds for initiation of shivering (below) and sweating (above). However, the difficulty that all these theories face is explaining the regulated increase in core body temperature that occurs under various circumstances such as fever (Fujishima et al., 2001), the luteal phase of the female menstrual cycle (Kolka &

Stephenson, 1997) and possibly even exercise itself (Toussaint, Wakayoshi, Hollander, & Ogita, 1998), whereby either no thermoeffectors (as in menstrual cycle effects) or conflicting thermoeffectors (as in fever) are activated at altered T_c.

In addition to these autonomic and metabolic thermoeffector responses, behavioural mechanisms such as moving to a warmer or cooler environment and adding or removing clothing are also important in helping maintain thermal homeostasis. In fact, behavioural thermoegulation is more sensitive and more powerful in humans than is autonomic thermoregulation. This has many advantages, including being more energy efficient and allowing humans to occupy habitats that would not otherwise be possible. Early research examined the relative contributions from T_c and skin temperature (T_{sk}) toward various effector responses, and found that T_c had a much stronger contribution to autonomic and metabolic responses than did T_{sk} (Cabanac et al., 1971; Nadel et al., 1971; Toussaint, Knops, De Groot, & Hollander, 1990). Notwithstanding the differences in heating and cooling protocols and the autonomic response measured (i.e. sweating and skin blood flow), the relative contribution of T_c/T_{sk} reported in these studies varied between 2:1 and 20:1. Nonetheless, it still highlights the lesser influence of T_{sk} in the control of autonomic and metabolic responses. However, Frank *et al.,* (1971) found a relatively equal influence (i.e., ~1:1) from each of these inputs to the perception of body temperature, which may be beneficial to humans in that an individual's perception of body temperature can initiate behavioural thermoregulation before metabolically taxing mechanisms are initiated.   Thus, the role of local T_{sk} should not be underestimated in its importance for thermoregulation because of the larger range over which it has to change compared to T_c and the ability it appears to have in independently driving autonomic and behavioural responses (Cabanac et al., 1972; Tipton et al., 1998). The input from T_{sk} is a primary defence system of the body, protecting the T_c from dramatic changes, thus in certain environmental situations it is possible for T_{sk}, or rate of T_{sk} change, may be a dominant input for effector responses. Further evidence for this notion is seen in thermoneutral environments where changes in forearm blood flow were primarily mediated by changes in T_{sk} (Tipton et al., 2000).

During exercise, metabolic rate can be increased up to 20 times (as much as 84 kJ.min^{-1}). Due to the relatively poor efficiency of energy metabolism, more than 75% of this energy is lost as heat. For example, two thirds of the energy is already lost as heat just in the process of making ATP to power work processes. This heat begins to accumulate in the body, causing body core temperature to rise. This increase in temperature will lead to activation of the thermoregulatory effectors (as discussed above), however, in some situations this can cause conflicts, especially during exercise in the heat. The increase in skin blood flow that occurs as body core temperature rises can lead to a strong competition for cardiac output between the skin (for heat dissipation) and exercising muscles (for oxygen delivery). To further complicate this, the increase in sweating that accompanies this vasodilation as body temperature rises, leads to the loss of body water (and other key minerals such as sodium) that are important in maintaining blood volume. In hot conditions, without adequate fluid replacement, the gradual increase in dehydration through sweating (and therefore blood volume) can further exacerbate this competition between skin and muscle for cardiac output. This will begin to reduce exercise performance in most individuals, although athletes may have a greater ability to tolerate this conflict through increased blood volume. Athletes also seem better able to deal with a greater amount of heat gain/storage, as evidenced by the upper T_c at which many individuals appear to volitionally stop exercise. In most recreational and competitive athletes, a T_c of 39 – 40°C would see them significantly slow or stop exercising. However, this temperature may be as high as 41-42°C in some athletes and it is interesting to note that these higher T_c are often noted in races and competition where differing motivation may contribute to tolerance of higher T_c (Byrne et al., 2006; Ducharme & Tikuisis, 1991; Gonzalez-Alonso et al., 1999; Wallingford, Ducharme, & Pommier, 2000). This may be due to adaptations accrued through regular, intense exercise and high training volumes (specifically the repeated exposure to heat) or the extreme motivation of elite athletes to compete and be successful. Irrespective of one's power or capacity for offloading or storing heat, ultimately all heat must be offloaded, and this is more difficult in some environments and at higher intensities of exercise.

7.3   Mechanisms of heat exchange

Ultimately, all – and only – heat produced by metabolism must be offloaded. Too much or too little exchange leads to hypothermia and hyperthermia, respectively. The human body has a number of methods to exchange heat with the surrounding environment. These are evaporation, convection, conduction and radiation. A related and important mechanism occurs within the body, with the mass transfer of heat in the cardiovascular circulation.

7.3.1 Evaporation

In air, evaporation is the most powerful method to remove heat from the body. The vaporisation of sweat from the skin surface allows the body to lose heat at a rate of 2.43 kJ per g of sweat evaporated (Barwood et al., 2006). Sweat rates of up 1.5 – 2.0 $L.h^{-1}$ (~30 $g.min^{-1}$) are common and can be up to 3 $L.h^{-1}$ or more in some individuals under extreme heat stress. This would allow the body to remove ~73 $kJ.min^{-1}$ of heat in an accommodating environment.   However, hot and humid environments, wearing clothing with low permeability and immersion in water can greatly reduce the effectiveness of this physiological heat loss mechanism because the principal determining factor in the rate of evaporation is the vapour pressure gradient between skin and air.   Therefore, for evaporation to be maximised either the partial pressure of water on the skin surface or in the environment would need to be increased and decreased, respectively, or both.

7.3.2 Convection

As air passes across the body, it is generally cooler than the skin temperature. If so, heat will be transferred from the skin to the surrounding air, which is then taken away by wind (or body movements) or convective currents (generally rising across the body, caused by conductive and convective warming by skin) and replaced with cooler air. In certain conditions, i.e. strong winds or repeated body movements, the convective heat loss can be

quite high, particularly if the skin is cool or wet. This is reflected in environmental charts such as the wind chill index. Importantly, convective heat transfer also occurs within the body between blood vessels and tissues. The processes of convection, and conduction (described below), are largely determined by the thermal heat gradient between objects.

7.3.3 Conduction

Heat loss through conduction is generally limited in the ambient environment as it somewhat requires the direct contact with a solid object. To this end, conductive heat loss primarily applies to individuals working in water or other liquids, handling cold products, or in supine positions (esp. against ground). Thus, the amount of heat transfer that occurs is related directly to the thermal conductivity of the object and the surface area in contact with it. Within the body, conductive heat transfer can also occur, however this is somewhat limited as the tissues need to be adjacent and the thermal conductivity of human tissue is relatively poor. Nonetheless, while the poor conductivity of tissue, such as subcutaneous fat, can limit the effectiveness of conductive cooling from the core to the skin during warm thermal stress, it can minimise the loss of heat during cold thermal stress.

7.3.4 Radiation

This is the loss or gain of heat through electromagnetic (mainly infra-red) waves which are exchanged between the body and objects in the surrounding environment (e.g., sun, road, buildings). Radiation occurs independently of any air movement.

7.4   Water: A unique environment

7.4.1 Mechanisms of heat exchange

Of particular interest to this proposed research are the differences in heat exchange that appear to exist between air and water. In water, evaporation (the body's most effective heat loss mechanism in air) is *non-existent* for continuously immersed skin since it is fully wetted and has no direct air exposure (and hence water vapour pressure gradient) to drive evaporation. In air, evaporative cooling is reduced with high ambient humidity or decreased air flow over the skin surface. This can lead to greater heat storage and rising body temperatures which may limit performance and contribute to the development of heat-related illness. Therefore, *are individuals who exercise in warm water more susceptible to large increases in body temperatures due to the inability to remove heat via evaporation?*

Water has a much higher heat capacity than air does ($4.18 \text{ kJ.kg}^{-1}.°\text{C}^{-1}$ vs. $1.30 \text{ kJ.(m}^3)^{-1}.°\text{C}^{-1}$, respectively) and a thermal conductivity which is 25 times greater (0.6 vs. 0.025 W/(m.K)) (Nadel et al., 1974; Ramires et al., 1995). This means that water will conduct heat from the body 25 times faster than air, and is able to hold/store a much greater amount of thermal energy for the same change in temperature. When exercising in water (swimming or immersed walking, running or cycling), forced convective heat loss is greatly increased by the flow of water over the body. Particularly in swimming, water passes across the whole body surface compared to immersed running or cycling where the main flow of water is primarily on the frontal surface. This increased surface area for convective heat exchange in swimming could also be compared to running or cycling exercise on land where the air flow over the body is largely limited to the frontal areas exposed to the wind or the direction of movement. Therefore, these surfaces are the ones that will have the most effective evaporative heat loss. However, it appears largely unexamined whether a smaller area for evaporation (the body's most powerful heat loss mechanism) on land removes a similar amount of heat from the body compared to a swimmer in water where convective heat loss operates (typically less effective on land, but the most effective method in water), but over a larger skin surface area.

7.4.2 Effects of immersion and exercise in water

Previous research has examined thermal and other physiological responses to exercise or passive immersion in various water temperatures. A large majority seem to have focused on immersion and light exercise only, and in cool and cold water temperatures (< 25°C). This is presumably because these are the water temperatures experienced by most people around the world, and where a large number of accidental immersions occur leading to various hypothermia-related issues. Also, many of these studies have used water immersion simply as a medium to examine other physiological responses such as fluid regulation and cardiovascular effects or to clamp or drive T_{sk} for other purposes.

When simply immersed (to the neck) in water, core temperature falls and $\dot{V}O_2$ increases at a rate proportional to the water temperature and inversely proportional to subcutaneous adiposity (Choi et al., 1996). This relationship was shown across water temperatures of 20, 25, 30 and 35°C; with virtually no change in rectal temperature and $\dot{V}O_2$ at 35°C, but a drop in rectal temperature of 1°C and an increase in $\dot{V}O_2$ of 250 mL.min^{-1}.m^{-2} at a water temperature of 20°C. When the immersed participants were given light leg exercise using a cycling ergometer (which increased metabolic rate by ~60 kcal.h^{-1}.m^{-2}), rectal temperature in 30°C water remained largely unchanged even with an increase in $\dot{V}O_2$ of 250 mL.min^{-1}.m^{-2}. This is compared to light cycling exercise in 20°C water where rectal temperature again dropped by 1°C, even with an increase in $\dot{V}O_2$ of 400 mL.min^{-1}.m^{-2}. These authors concluded that regardless of whether individuals were resting or exercising in water, most experienced a decline in rectal temperature in water temperatures below 30°C (Choi et al., 1996). Similar responses in core temperature and metabolic rate were also observed by Šrámek *et al.,* (2000) during water immersion at temperatures of 14, 20 and 32°C. The cycling exercise used by Choi *et al.,* (1996) is obviously leg-only exercise. While swimming does use both arms and legs, it could be considered primarily an upper body activity. Research has examined the differences between upper-, lower-, and combined upper- and lower-body exercise in various water temperatures (Toner et al., 1984). Participants performed 45-min of arm, leg, or combined arm-leg exercise (cycling and arm cranking) while immersed in water temperatures of 20, 26 and 33°C, with exercise intensity adjusted so that metabolic rate was similar in all three types of exercise. The drop in rectal temperature was smaller when exercise was performed with the legs alone, compared to

arms only and combined arm-leg exercise. This was especially evident in the cool and cold water (i.e., 20 and 26°C). The authors suggested that the differential effects might be due to: 1) a higher convective heat transfer from the body core to the arm with the increased blood flow to the smaller muscle mass of the arms during exercise, coupled with a lower subcutaneous fat layer around the arms vs. the legs; 2) a short conductive distance from within the arm to the skin surface, which may also negatively affect the counter-current heat exchange in the arms, compared to the legs, and 3) the larger surface area-to-mass ratio of the arms causing a greater conductive and convective heat loss at the skin-water interface. Therefore, it is possible that the use of arms in swimming may lead to greater heat loss in water. This may be beneficial in warmer water but possibly detrimental in cool and cold water. Increasing subcutaneous fat thickness appears to be a way to help minimise this drop in body core temperature in cool water. The study described earlier by Choi *et al.,* (1996) further split their participants into lean, normal and obese, based on subcutaneous fat thickness. It became obvious that the rate of cooling of core temperature was lower in those with greater subcutaneous fat thickness, and this is also something that has been shown by many other groups (Holmér & Bergh, 1974; Kollias et al., 1974; McArdle, Magel, Spina, Gergley, & Toner, 1984; Tikuisis, Jacobs, Moroz, Vallerand, & Martineau, 2000).

7.4.3 Effects of endurance swimming in various water temperatures

There are limited studies examining intense or prolonged exercise in water, and even less that look specifically at swimming. Of the studies that have used swimming exercise, different swimming strokes, relatively low and controlled exercise intensities (e.g., 50% $\dot{V}O_2$ max or lower) and short exercise durations (e.g., 30-min or less), make it difficult to apply the results to competitive race swimming, particularly of prolonged duration and in open-water environments. Also, many of these studies have been conducted in a swimming pool as opposed to a swimming flume. The pool environment can restrict the ability to collect physiological data during the swims and also affects the average swim velocities and nature of the swim, due to the turns at each end. The opportunity to test swimmers in a swimming flume allows greater access to the swimmer for physiological testing, as well as enable them maintain a constant velocity. Lastly, no studies have included any source of radiant heat load

when examining warmer water temperatures. These points are especially important if the results (particularly of longer duration swims, i.e., 20 min+) are to be transferred to an open-water swimming environment.

Robinson and Somers (1971) conducted one of the few studies that have used proficient swimmers, in warm water temperatures, with exercise intensities and durations appropriate to endurance swimming events. They took 6 male Olympic level swimmers and had them swim as far as possible in 60 min in three different water temperatures, averaging 33.5, 29 and 21°C. These authors also included a comparison to a single runner on a treadmill (at approximately the same metabolic rate) for 60 min in two ambient temperatures, averaging 9.3 and 25°C. The rectal temperatures of the two fastest swimmers both increased to 38.4°C after 60 min in the 33.5°C water (swimming at a metabolic rate of 500-520 kcal/m^2·h^{-1}). This was an equivalent rise in rectal temperature to that seen in the runner after 60 min (38.6°C) exercising in only 9.3°C air (at a similar metabolic rate of 504 kcal/m^2·h^{-1}). However, the runner appeared to start with a rectal temperature approximately 0.5°C lower, therefore his rise is actually even more than the swimmers. Further, the rectal temperature of the runner in 25°C air ended much higher (39.7°C) than in both of the fastest swimmers in 33.5°C water (38.6°C). In the cold water (21°C), the slightly slower swimmers (working at a metabolic rate of 333-400 kcal/m^2·h^{-1}) showed a small drop in rectal temperature from 37.5 to 37.1°C. However, while also struggling in the cold conditions, the two fastest swimmers (working at a metabolic rate of 480-510 kcal/m^2·h^{-1}) showed a small increase in rectal temperature from 37.3 to 37.9°C. Thus, it appears that after 60 min of intense exercise at a similar metabolic rate, the core temperature of a runner in temperate air (25°C) can rise to a concerning level of 39.7°C, while a swimmer in warm water (33.5°C) appears to remain comfortably at a very moderate core temperature of 38.6°C. However, it should be considered that this may not apply to all swimmers due to likely differences in swimming efficiency and body composition that may contribute to heat production or impact on thermoregulation. Also, no radiant heat load was used, therefore the application of these results to an open-water environment may also be limited. As mentioned earlier, the radiant head load experienced in the outdoors can be significant, so its effect on rising core temperature during intense exercise in the sun needs to be considered.

One of the only other studies to have examined the effects of competitive swimming speeds

over an extended duration is a recent study by Macaluso *et al.,* (2011). Competitive Masters swimmers' completed a 5-km race simulation in three water temperatures, of 23, 27 and 32°C. While this open-water swimming simulation was completed in an indoor 25 m pool, the average split times (94 – 95 s.100 m^{-1}) indicate that the participants were well trained. The attempted rectal temperature measurements (using mercury thermometers before and after each swim) showed minimal change in 23°C water, a rise of 0.9°C in 27°C water and a rise of 1.1°C in 32°C water. The peak rectal temperatures recorded after the 5-km swims in 27 and 32°C water (which took on average 75-80 min) were only ~38°C. While there may be issues with their measurement methods, these recorded temperatures after 75 min of swimming at high intensity in 32°C water are not excessively high.

While there is some research examining the physiological effects of swimming, methodological limitations such as the use of pool swimming, relatively short exercise times, discontinuous measurement of some physiological variables, and a lack of radiant heat load, make the application of these results to longer distance/duration open-water swims difficult. This may be important as it is the immersion and exercise in warm (and cold) water for these extended periods (i.e., greater than 30 min) that could lead to a potentially dangerous situation for swimmers i.e., high or low body core temperatures. Further, there is a lack of research examining whether an individual is accurately able to perceive these changes in body temperature and appropriately thermoregulate (both behaviourally and autonomically) in water. This may be particularly important in water as T_{sk} can play a large and important role in driving these thermoeffectors (particularly behavioural responses), yet it is clamped at water temperature and therefore unable to change over a large range as it can (and does) in air.

7.5   Open-water swimming

Open-water swimming is defined by its governing body, FINA (Federation Internationale de Natation), as any competition that takes place in rivers, lakes, oceans or water channels, except for 10-km events. Further, Marathon swimming is defined as any 10-km event in open-water conditions. Events are typically 5, 10 or 25 km in length, with the 10-km events making up the FINA World Cup and Grand Prix series, as well as the only open-

water event at the Olympic Games. Other long-distance open-water swims typically include crossings (sometimes multiple crossings) of large and famous waterways such as the English Channel, Catalina Channel and Cook Strait. Open-water competitions are governed by a set of rules set out by FINA (Open-water swimming Rules and Regulations; OWS) and are swum front crawl (OWS 6.1). Open-water swimming is also represented over shorter distances in multisport events such as Triathlon and Ironman. In these events, swimming distances are typically 750 m (sprint triathlon), 1.5 km (Olympic or standard triathlon), 1.9 km (Half Ironman) and 3.8 km (Ironman triathlon). The rules governing these events are largely set out by the ITU (International Triathlon Union). The main difference to pool swimming is that there are no turns, so swimming is continuous. Open-water swimming events are longer so feeding stations are provided where swimmers are able to get food and drink as they swim past. Competitions are held in various countries and bodies of water, which means swimmers, particularly the elite performers who will travel the world to compete in these different races, will encounter a large range of environmental racing conditions. Different events can vary greatly in water and ambient temperatures, humidity, water currents, solar radiation, water type and quality, wind and swells. There are currently guidelines for some of these variables that FINA use to determine when events should be cancelled or postponed based on the course conditions. The primary variables that are examined are water and ambient temperatures; however, the thresholds for these variables are given for cool temperatures *only*. For example, it is currently regulated only that events should not be held when water temperatures are below 16°C (measured within 2 hours of race start, at a depth of 40 cm) (OWS 5.5). This is largely because no wetsuits (or any buoyancy aid) are permitted in any FINA open-water swimming events (OWS 6.9).   Similar regulations exist in triathlon events sanctioned by the ITU, where water temperatures (measured within 1 hour of race start, at a depth of 60 cm) of between 13-17°C result in a reduction of the race distances or cancellation. However, in ITU triathlon events, wetsuits are also permitted for any races where the water temperatures are below 20°C and are mandatory for water temperatures below 16°C. Local bodies also enforce their own variations of these rules, such as in USA Triathlon sanctioned events, where wetsuits can be worn in any water temperatures below 25.6°C (78°F). While there is no upper limit for water temperatures enforced by these organisations, it is not uncommon for events to be held in water temperatures of 30-32°C in locations around South-east China and the Middle East. This can

be accompanied by ambient temperatures of 35-40°C and relative humidity of 50-70%. This combination appears to have the ability to produce a very heat-stressful environment for swimmers, particularly elite swimmers, likely to be producing high rates of metabolic heat for ~1 and 2 hours in the 5- and 10-km swim events, respectively. This is potentially highlighted by the death of an elite USA swimmer during a FINA 10-km World Cup event in the Middle East in 2010. Official reports indicate that water temperatures at this event were 29°C, but anecdotal athlete reports suggest it was more likely 31-33°C. The ambient conditions were reported as 35°C and while no humidity was officially recorded, meteorological records suggest the daily humidity ranged from 45-75%.

With the popularity of open-water swimming on the increase world-wide, it seems important to investigate the physiological responses to swimming in potentially heat-stressful conditions. However, as reviewed above, human responses to exercise in warm aquatic conditions are poorly researched and largely unknown, particularly the thermoregulatory responses. In comparison, terrestrial events have a number of commonly used tools which event organisers and athletes can use to determine when an environment may be too heat stressful to compete in. These can include various combinations of ambient temperature, humidity, wind and radiant heat load into a heat-stress index. Different organisations will then use specific thresholds within this index to guide when events should be postponed or cancelled. For example, the International Association of Athletics Federations (IAFF) recommend cancelling or rescheduling races if the Wet Bulb Globe Temperature (WBGT) is above 28°C or Ambient Dry Bulb Temperature is below -20°C (Olympic Movement Medical Code, Appendix 1 – from IAAF website).

7.6 Warm Water: a unique challenge to physiological and behavioural thermoregulation

As reviewed earlier, water is an environment where many of the body's most powerful thermoregulatory responses (i.e., sweating and behaviour) can be affected. A fully wetted skin minimises the ability to evaporate sweat, thus the capacity for evaporative heat loss is markedly, if not completely, reduced in water. However, this appears to be compensated for by an improved ability to use convective and conductive heat loss. Also,

some of our typical behavioural thermoregulatory responses, such as adding or removing clothing or seeking shelter, are largely reduced in most water environments, particularly in open-water. However, whether the behavioural thermoregulation we regularly exhibit on land is just as powerful and sensitive when the body is immersed or exercising in water at various temperatures is unknown. Moreover, whether we are able to sense that we are getting hot or cold, and whether we can respond appropriately with alterations in exercise intensity, heat loss or heat gain mechanisms is also largely unknown. As detailed above, thermal perception appears to be determined from a composite signal of skin and core temperatures. It is this signal which can initiate the various behavioural and autonomic responses in humans. However, it appears that the research in this area has almost exclusively been conducted during rest and exercise in various terrestrial ambient conditions. Very little research, if any, has examined these perceptual responses in a water environment. Water may provide a confusing situation for human thermoregulation whereby skin temperature (which normally fluctuates depending on the environment and the requirement to offload heat) is largely clamped around the temperature of the water. Since skin temperature may play a large role in determining our thermal perceptions in certain situations (as discussed above), it is interesting that it does not appear to have been investigated in a situation where its ability to change over a large range is greatly reduced (i.e., clamped in water). This leads to the question *whether humans immersed in water, both at rest and during exercise, are accurately able to perceive changes in their thermal state, particularly core temperature, and whether there an uncoupling between the perceived thermal state and the actual thermal state?*

Radiant heat load is also something that has often been overlooked in most research projects to date. Laboratory-based studies often control various environmental conditions such as air temperature, humidity, pressure and wind velocity, and apply the results to similar outdoor situations. However, a common element missed from these controlled variables is the heat load added to individuals exercising outdoors by the overhead sun. In certain parts of the world and at certain times of the day, the intensity of the sun can be extremely high such that the additional heat load (and possibly reductions in heat loss) could be very significant. The irradiance (light energy) from the midday sun on a clear day in tropical locations can reach peaks of 1 kW·m^{-2} on the Earth's surface. This additional radiant heat load can be quite significant on individuals working, exercising or competing in exposed

environments, thus it is something that should be included in laboratory-based studies, but generally is not. Nielsen *et al.,* (2012) have shown that exercising outdoors under clear sunny skies (solar radiation intensities of 300 – 700 W·m^{-2}) can impose an additional heat load of ~100 W. This appears to be largely accounted for by increased sweating (evaporation rate), equating to an increased weight loss of ~150 – 180 g·h^{-1} when exercising in the sun. Nielson *et al.* also noted that this additional heat load was associated with an 8 b·min^{-1} higher heart rate and 0.15 L·min^{-1} increase in $\dot{V}O_2$. Other research has shown that the increment of air temperature equivalent for the solar radiation experienced in a desert environment in summer is approximately 7-10°C (Lee & Vaughan, 1964). In other words, the effect of the radiant solar heat load from the sun is equivalent to a 7-10°C increase in air temperature. These results indicate that the influence of radiant heat load is significant and should be included in laboratory-based research with outdoor applications, where possible.

7.7   Factors limiting performance or increasing heat stress in swimming

Given the relatively small range for tolerable increases in core temperature for humans, it seems important to identify and examine factors, not necessarily related purely to exercise hyperthermia, that may influence or contribute to increases in core temperature. These factors could include exercise-related inflammation or previous inflammatory state, overtraining or current high training load, limited or inadequate recovery from previous training or races. Previous research, as described earlier, indicates that swimming in warm water elevates core temperature; however, the extent of this rise with intense and prolonged exercise is largely unknown. Therefore, it is possible that with intense swimming exercise in warm water, the competitive demand for blood flow by the skin and muscles may cause a reduction in gut blood flow, contributing to exercise-induced endotoxemia. Similarly, it is possible that intense swimming exercise of predominantly upper-body muscles may also lead to exercise-induced tissue damage. As detailed below, these may be two pathways that can contribute to the development of heat stroke (Lim et al., 2007). Indeed, a fever-like response may develop during prolonged exercise in hot ambient conditions, possibly due to a small inflammatory response triggered by endotoxemia (gut leakage)

(Toussaint et al., 1998). This appears to increase core temperature by ~0.3°C more than normal exercise hyperthermia. Furthermore, Lim *et al.,* (2007) used a rat model to highlight two pathways of heat stroke; heat-induced endotoxaemia or heat-induced tissue damage, both of which appear to be associated with systemic inflammation. Thus, the authors suggested that exercise may increase local inflammation and this can compromise heat tolerance by increasing the pro-inflammatory cytokine response through endotoxaemia. Further, the authors also suggested that athletes with high training loads may be at increased risk of heat stroke due to a combination of factors such as immunosuppression, musculoskeletal injuries, subclinical infections, and gastrointestinal disturbances contributing to increased pro-inflammatory and decreased anti-LPS activity during heat stress and exercise.

Therefore, while the thermal responses to intense swimming exercise in warm water are largely unknown, available data suggest that T_c can increase significantly. A highly active upper-body muscle mass during swimming, warm water temperatures and, in open water, a high radiant heat load from the sun, appears to provide a highly heat-stressful environment. Thus it seems reasonable that the development of endotoxemia and/or exercise-related tissue damage is possible in such an environment. If this occurs during swimming in such an environment, and it is coupled with others factors such as high training loads, an overtrained or previous inflammatory state, injuries, or infections, then an already large change in T_c due to the exercise hyperthermia may be greatly potentiated. Therefore, the study will aim to quantify the presence and effects of endotoxemia and tissue-related damage during warm-water swimming and may opportunistically obtain data on the effects of other factors such as previous inflammatory states and high training loads.

7.8   Heat acclimation in water (vs. air)

Heat acclimation is an effective way of improving performance and tolerance in hot environments. There is a plethora of research which has examined the physiological changes that occur with heat acclimation, and various protocols have been tried to best elicit these changes. Typical physiological adaptations that are observed following heat acclimation include: lower resting core temperature (Buono, Heaney, & Canine, 1998; Shido,

Sugimoto, Tanabe, & Sakurada, 1999); improved cutaneous vascular function and sweating (Lorenzo & Minson, 2010); decreased sweat osmolality and sodium ion concentration (Buono, Ball, & Kolkhorst, 2007), and increased heat shock proteins (HSP's) (Moseley, 1997). Collectively, these responses lead to improved tolerance of active and passive heat stress in most environments. Different studies have used various heat acclimation protocols, but most involve at least 7 days of heat stimulus for at least 60 min per day. Some protocols have used passive exposure while others have included an exercise component, with the exercising protocols typically showing improved adaptations. The one commonality that appears to exist in all heat acclimation protocols is that they are performed in ambient air. Only one study was found that involved some type of heat acclimation in water. Avellini *et al.,* (1982) took untrained participants and compared physical training (cycling at ~75% $\dot{V}O_2$ max) in water (32°C and 20°C) and on land (conditions not mentioned) for 1 h.day^{-1}, 5 days a week, for one month, to determine adaptations responsible for improving heat tolerance. Following the physical training, a similar decrease in final T_c and heart rate was observed at the end of a 3 h heat stress test (on land) between the 30°C water and land-based training groups. Interestingly, the 30°C water training group also showed an increased sweat rate (by 25%) during the post-training heat stress test. Further, this training protocol was subsequently followed by an actual 10-day heat acclimation period in warm air. The final T_c recorded in a 3-h heat stress test after this acclimation period again dropped a similar amount in both the 30°C water and land-based training groups. These data suggest that repeat exercise exposure in air and in 30°C water can provide similar training benefits and adaptive responses that improve heat tolerance on land. However, this study used untrained participants and the physical training period (discussed here as acclimation) was one month long. Also, the heat stress tests used to examine heat tolerance were also performed on land. Nonetheless, it does provide some evidence for the use of a warm water medium to successfully heat acclimate individuals. Besides this study, no others were found that have used a warm water medium for heat acclimation. Therefore, acclimating swimmers in warm water to examine whether swimming performance or tolerance can be improved in warm conditions appears warranted, given the increased requirement to race in warmer waters (as mentioned above). In addition, whether heat acclimation in warm water can elicit similar physiological changes to those regularly seen with acclimation in air is unknown. Further, the reverse would also be worthwhile examining, for example, is there

any benefit to swimmers performing heat acclimation *upright in air* on swimming performance or tolerance *prone in warm water*. The different body positions and acclimation mediums are likely to have differential effects on some of the physiological changes such as blood volume, core temperature and sweating parameters, thus it may be important to examine which medium can provide the best adaptations to water and terrestrial-based athletes.

This review highlights a lack of literature and gaps in the current knowledge regarding the acute physiological and psychophysical responses to endurance swimming, specifically in warm water, and particularly under conditions that accurately reflect open-water swimming competitions (e.g., with radiant heat load and appropriate exercise intensities). It also highlights that the adaptive responses to heat conditioning with warm water are unknown, even though physiological adaptations improving heat loss and thermotolerance have been shown with conditioning in warm air. Therefore, the purposes of this study are to:

1. Examine the physiological, perceptual and functional responses of swimming in various water temperatures, and whether these responses are affected by inflammatory factors, particularly in warm water conditions;
2. Validate the data collected in a laboratory environment by examining the real-world physiological, perceptual and functional responses of elite athletes in an actual race environment (e.g., realistic rates of metabolic and radiant heat loading, and competition-related conflict for thermoregulatory behaviour), and
3. Determine whether heat acclimation conducted in a water medium can improve systemic heat adaptation, performance and/or thermotolerance during swimming in warm- and cool-water environments.

It is hypothesised that;

1. Swimming in warm water will be associated with 'comfortable' thermal perceptions (due to a clamped skin temperature at modest levels) that do not increase proportionally to the actual change in body temperature.

2. Physiological (core temperature and heart rate) and perceptual (RPE, thermal sensation and discomfort) responses collected a laboratory environment will be lower than those collected in an actual race environment.

3. Heat acclimation using a warm water medium will exhibit similar physiological adaptations (e.g. lower resting and exercising core temperature and heart rate) to those observed in air which will also translate to improved performance, thermal comfort and thermotolerance in warm air and in warm and cool water.

8 APPENDIX B – MODELLING OF SWIMMER'S CORE TEMPERATURE RESPONSE

8.1 Progress

In the third quarter we reported on the numerical modelling of the core temperature response of swimmers by adapting the Wissler-Texas thermoregulatory model. This work is on-going with the continued generous support of Professor Wissler. Provisions have now been included in the model to account for heat transfer changes from local movement of individual limbs, and the model further refined to include thermophysical properties of water to distinguish between swimming in fresh water and sea water.

8.2 Preliminary Findings

The physical model for core temperature response is still in development. However, a number of general observations on the expected behaviour of core temperatures can be made at present. The following predictions are for a male swimmer of weight 73.8 kg and mean skinfold thickness 7.7 mm, starting a swim from a normal resting temperature distribution and completing a 10 km swim. Open clear sky conditions with 1/10 cloud cover, 70% relative humidity and an atmospheric pressure of 1006 hPa has been assumed. A mean stroke rate of 30 strokes per minute has been assumed with each arm spending a time duration of 40% of a stroke period in the air each stroke cycle. The swimming attire has been assumed to be a 0.1 clo swimming trunk and a 0.5 clo swimming cap covering the cranium which is exposed to the ambient air. The ambient air is assumed to be 1°C above the water temperature. Several parameters used to obtain these results are very rough estimates and therefore these results should only be taken as qualitative indicators of expected trends.

Water temperature

Figure 20 shows the effects of water temperature on the core temperature over a 10km swim for an athlete starting with a core temperature of 37.96°C and an incident direct solar radiation flux of 800 W.m^{-2}. The general trends of core temperature response are found to be uniform over the water temperature range of 20°C to 32°C. This figure was produced using a velocity profile for a subject as measured in a flume trial. The slight fluctuations in the core temperature correspond to the variation in swim speed and swim efficiency. In this simulation a linear relationship between swim speed and the mechanical efficiency of swimming was assumed based on the measurement reported (Toussaint et al., 1990).

Figure 20 : Model prediction of the effects of water temperature on core temperature
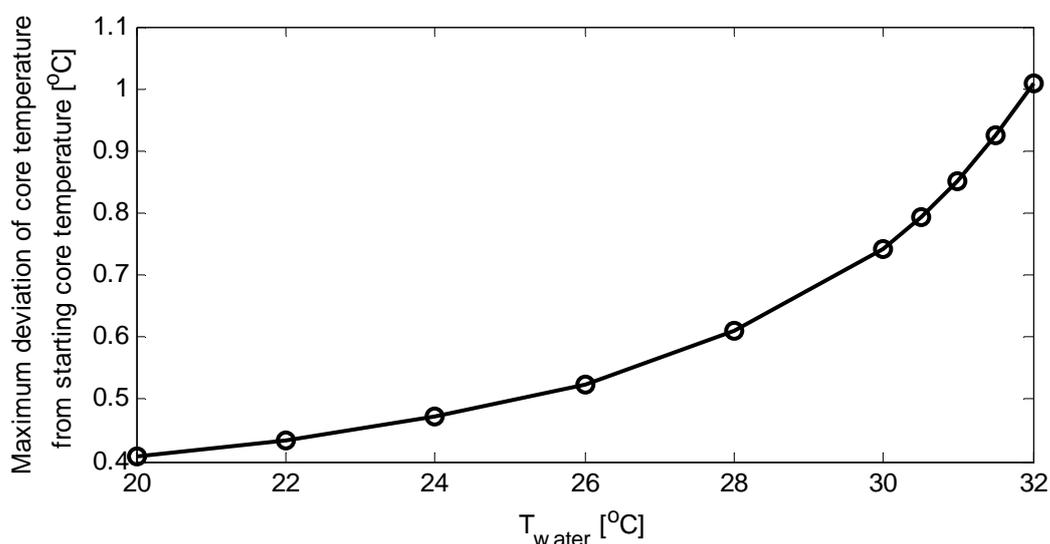
Figure 21 : Maximum deviation of core temperature from starting core temperature

The maximum core temperature is reached in each simulation at a swim distance of approximately 3 km. The maximum deviation of the core temperature from that at the start of the swim is shown in Figure 21, which illustrates that the core temperature rise per unit rise in water temperature is expected to be significantly larger at higher water temperatures than the corresponding temperature rise at lower water temperatures.

8.2.1 Radiation Loading

For an athlete swimming in open water, radiation loading will have components direct from the sun as well as diffuse components from the sun's rays that are scattered by clouds and other aerosols in the atmosphere. Our initial simulations suggest that on a sunny day at noon the total absorbed radiation absorbed at the body surface would be variable near 550 W (320 W.m^{-2} over whole body area) depending on location and atmospheric conditions and that the radiation loading will play a secondary role compared to the effect of water temperature in driving core temperatures high. This can be understood as due to body surface heating being countered by heat carried away from the body surface by the surrounding water flow, which reduces the contribution of incident radiation to core temperature rise.

8.2.2 Swimming Efficiency

In our third quarterly report we noted that the estimation of mechanical efficiency of swimming reported in literature vary widely. Gross mechanical efficiencies ranging from approximately 0.5% to approximately 20% have been reported (Karpovich & Pestrecov, 1939; Pendergast et al., 2003). A lower efficiency means that there will be excess heat to be dissipated leading to increased core temperatures. The general trend is predicted to be linear as illustrated in Figure 22
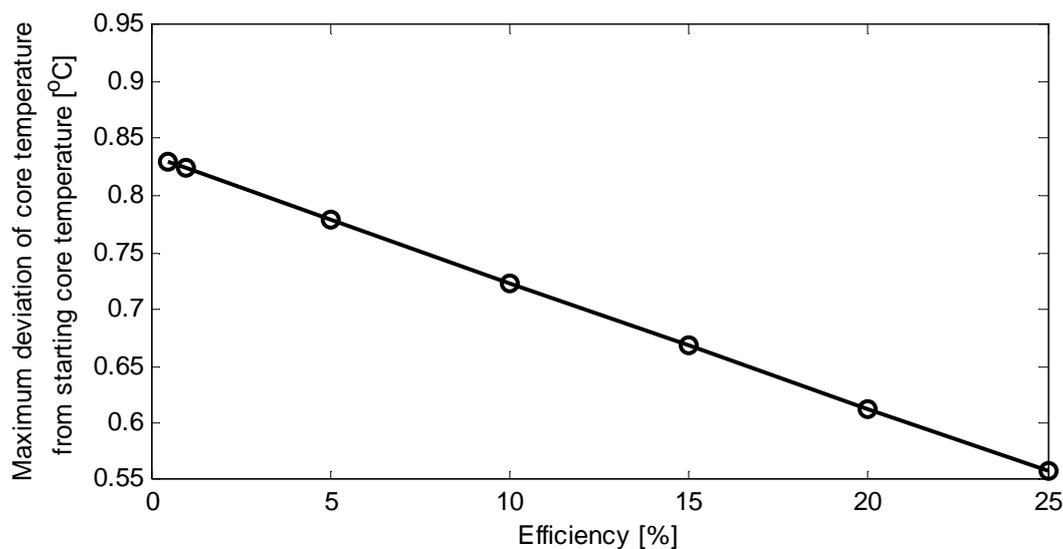
Figure 22 : Lower mechanical efficiency contributes to higher core temperatures

8.2.3 Sea Water

Taking the thermal properties of sea water into account, comparisons were made between swimming in fresh water against swimming in sea water, which was taken to have a salinity of 0.035 kg/kg. These simulations showed that there should not be any significant differences in core temperature response whether the swimming is in fresh water or in sea water. It should be noted here that these simulations did not consider the possible loss of water from the skin via ostomotic potential gradients.

8.3 Future Work

8.3.1 Characterisation of Pre-swim

At present the model starts from a nominal resting temperature distribution. This is unrealistic and therefore a pre-swim activity will be added to the model to raise starting core temperatures to be representative of observed starting conditions. This would allow quantitative verification of the model against measured data.

8.3.2 Model Calibration and Validation

Following the implementation of a pre-swim activity, some of the model parameters that are presently only rough approximations will be adjusted based on experimental data from flume trials. Once this calibration is complete, we will run a broader range of simulations to obtain statistics to quantify the accuracy of model predictions. We will optimise the model for faster simulation times once the model is known to have sufficient accuracy for predicting core temperatures under various climatic conditions.

8.3.3 Systematic Simulations

A systematic study of the core temperature response for a range of climatic and anthropometric parameters will be undertaken once the model has been sufficiently validated.

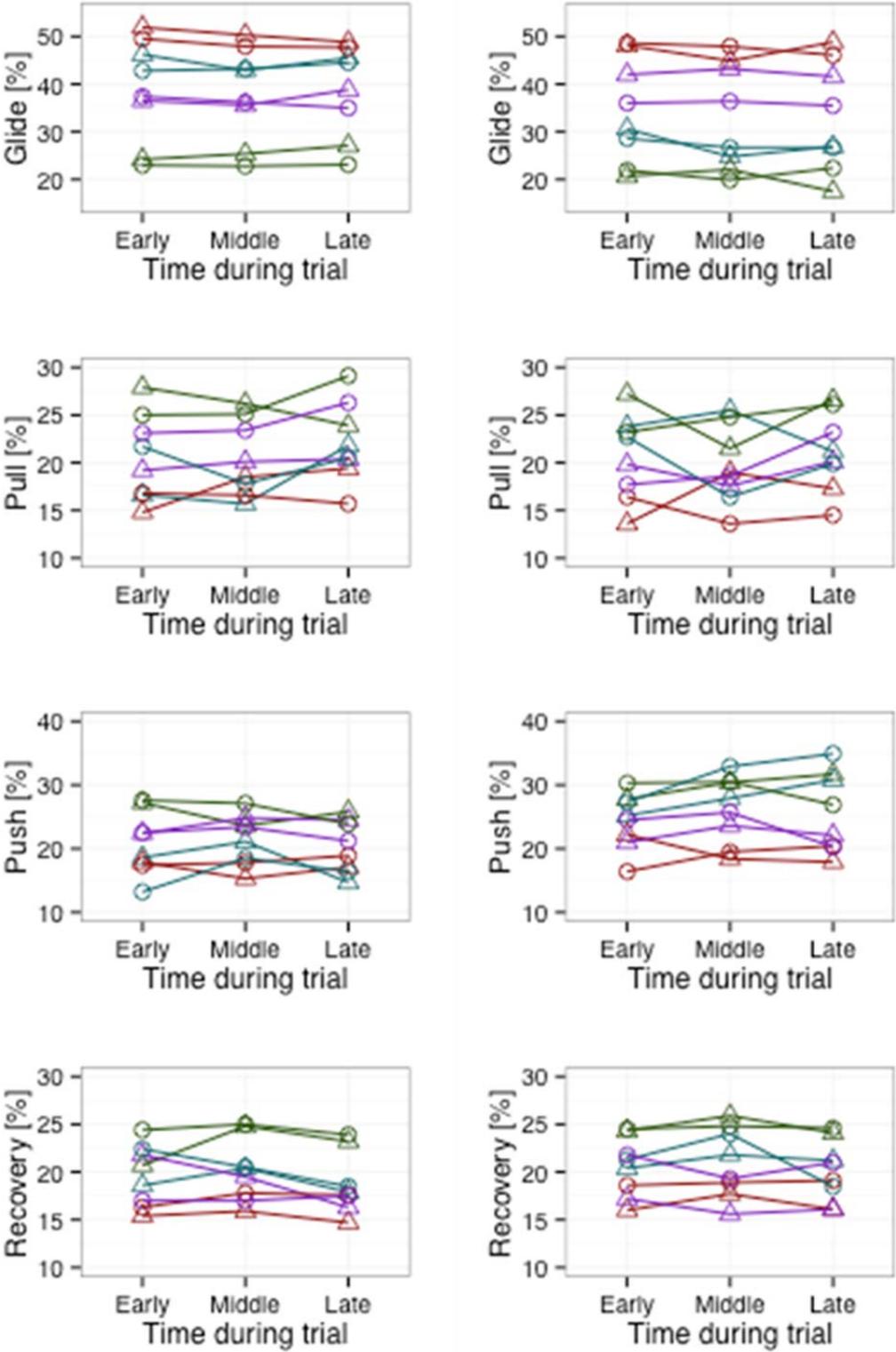# 9 APPENDIX C – ADDITIONAL GRAPHS FROM STROKE ANALYSIS

Figure 23. Relative proportion of each phase at different times during trial in two water temperatures. Left column = left side; right column = right side. Legend is the same as shown in Figure 15.