How does a delay between temperature running exercise and hot-water immersion alter the acute thermoregulatory response and heat-load?

Storme Louise Heathcote  
*Southern Cross University*

Peter Hassmén  
*Southern Cross University*

Shi Zhou  
*Southern Cross University*

Lee Taylor  
*Loughborough University*

Christopher J. Stevens  
*Southern Cross University*

Follow this and additional works at: [https://epubs.scu.edu.au/hahs_pubs](https://epubs.scu.edu.au/hahs_pubs)

Part of the [Medicine and Health Sciences Commons](https://epubs.scu.edu.au/hahs_pubs)

**Publication details**


Published version available from [http://dx.doi.org/10.3389/fphys.2019.01381](http://dx.doi.org/10.3389/fphys.2019.01381)
How does a delay between temperate running exercise and hot-water immersion alter the acute thermoregulatory response and heat-load?

Storme L Heathcote¹,², Peter Hassmen¹, Shi Zhou¹, Lee Taylor³,⁴,⁵,⁶ & Christopher J. Stevens¹,²*

¹School of Health and Human Sciences, Southern Cross University, Coffs Harbour, Australia
²Centre for Athlete Development, Experience & Performance, Southern Cross University, Coffs Harbour, Australia
³School of Sport, Exercise and Health Sciences, Loughborough University, Loughborough, United Kingdom
⁴Sport & Exercise Discipline Group, University of Technology Sydney (UTS), Faculty of Health, Sydney, Australia.
⁵Human Performance Research Centre, University of Technology Sydney (UTS), Sydney, Australia.
⁶ASPETAR, Qatar Orthopaedic and Sports Medicine Hospital, Athlete Health and Performance Research Centre, Doha, Qatar.

*Address for Correspondence
Dr Christopher John Stevens
School of Health and Human Sciences
Southern Cross University
Hogbin Dr, Coffs Harbour, 2450, NSW, Australia
Email: Christopher.Stevens@scu.edu.au
Ph: +61 411 797 245

Running head: Time delays between exercise and hot-water immersion
Abstract word count: 272
Text word count: 4373
Tables: 1
Figures: 4
Heat acclimation using hot-water immersion: How does a delay between temperate running exercise and immersion alter the thermoregulatory response and heat-load?

Abstract

Hot-water immersion following exercise in a temperate environment can elicit heat acclimation in endurance-trained individuals. However, a delay between exercise cessation and immersion is likely a common occurrence in practice. Precisely how such a delay potentially alters hot-water immersion mediated acute physiological responses (e.g. total heat-load) remains unexplored. Such data would aid in optimising prescription of post-exercise hot-water immersion in cool environments, relative to heat acclimation goals.

Twelve male recreational runners (mean ± SD; age: 38 ± 13 y, height: 180 ± 7 cm, body mass: 81 ± 13.7 kg, body fat: 13.9 ± 3.5%) completed three separate 40-minute treadmill runs (18°C), followed by either a 10 min (10M), 1 h (1H) or 8 h (8H) delay, prior to a 30-minute hot-water immersion (39°C), with a randomised crossover design. Core and skin temperatures, heart rate, sweat and perceptual responses were measured across the trials. Mean core temperature during immersion was significantly lower in 1H (37.39 ± 0.30°C) compared to 10M (37.83 ± 0.24°C; P = 0.0032) and 8H (37.74 ± 0.19°C; P = 0.0140). Mean skin temperature was significantly higher in 8H (32.70 ± 0.41°C) compared to 10M (31.93 ± 0.60°C; P = 0.0042) at the end of the hot-water immersion. Mean and maximal heart rates were also higher during immersion in 10M compared to 1H and 8H (P < 0.05), despite no significant differences in the sweat or perceptual responses. The shortest delay between exercise and immersion (10M) provoked the greatest heat-load during immersion. However, performing the hot-water immersion in the afternoon (8H), which coincided with peak circadian body temperature, provided a larger heat-load stimulus than the 1 h delay (1H).

Keywords: Heat acclimation; heat stress; hot bath; passive heating; endurance athletes.
Introduction

Exercise in a hot environment increases thermoregulatory and physiological strain (Cheuvront, Kenefick, Montain, & Sawka, 2010) and unpleasant thermal perceptions (Kamon, Pandolf, & Cafarelli, 1974; Stevens, Mauger, Hassmén, & Taylor, 2018), which contribute to deteriorated performances (Guy, Deakin, Edwards, Miller, & Pyne, 2015). Considering that many major sporting events are held under hot and humid conditions, including the upcoming Tokyo 2020 Summer Olympic Games (Kakamu, Wada, Smith, Endo, & Fukushima, 2017), endurance athletes are recommended to employ heat acclimatisation (training in natural heat) or heat acclimation (training in artificial heat) strategies (both abbreviated to HA) to negate heat-mediated performance decrements and possibly provide some protection against exertional heat illnesses (Kakamu et al., 2017; Racinais et al., 2015). Factors central for HA are increased sweating, and elevated core temperature (Tc) and skin temperature responses (Neal, Corbett, Massey, & Tipton, 2016; Périard, Racinais, & Sawka, 2015; Wendt, Van Loon, & Van Marken Lichtenbelt, 2007). As such, acute HA training sessions aim to maximise these responses.

A mean performance improvement from HA programs of 7 ± 7% has been demonstrated across 27 data sets, where 24/27 reported an improvement >1% (Tyler, Reeve, Hodges, & Cheung, 2016). Strategies to implement HA into a program prior to a major competition contingent to travel circumstances are also available (Saunders, Garvican-Lewis, Chapman, & Periard, 2019). As such, the positive benefits on performance and recommendations for implementation of HA are clear, yet evidence-based active HA protocols (typically involving specialised facilities and/or relocation) may be logistically difficult to incorporate into complex training programs and the schedules of elite athletes (Casadio, Kilding, Cotter, & Laursen, 2017). The training sessions themselves can also be onerous, generally involving
exercise in the heat for 30-100 min, preferably on consecutive days, for a minimum duration of one week (Casadio et al., 2017; Houmard et al., 1990; Périard et al., 2015). Despite the ergogenic potential, during the International Association of Athletics Federations (IAAF) World Athletics Championships in Beijing 2015, where hot and humid conditions were predicted, only 15% of athletes engaged in HA prior to competition (Périard et al., 2017), suggesting that implementing HA may be challenging for some athletes.

In response to these challenges, alternative HA strategies have been investigated, including post-exercise sauna bathing (Scoon, Hopkins, Mayhew, & Cotter, 2007) and post-exercise hot-water immersion [HWI; (Zurawlew, Walsh, Fortes, & Potter, 2016)]. A total of 16 original investigations have been performed on the topic to-date (Heathcote, Hassmen, Zhou, & Stevens, 2018); the majority demonstrating beneficial hallmark physiological adaptations of heat acclimation (including lowered resting and exercising \( T_c \) and heart rate, and increased plasma volume) and importantly, these adaptations were demonstrated in both recreationally active and endurance-trained individuals (Zurawlew, Mee, & Walsh, 2018). Further, the use of post-exercise sauna (12x30 min exposures) improved running time to exhaustion by 32% in competitive runners/triathletes (Scoon et al., 2007) and post-exercise HWI (6x40 min exposures) improved 5 km running performance time in the heat by 4.9% in recreationally active individuals (Zurawlew et al., 2016).

Post-exercise HWI therefore presents a practical HA strategy for athletes residing in cooler climates, compared to expensive alternatives requiring artificial heat chambers and/or relocation. Passive heating has typically been applied immediately after exercise training when used for HA purposes (Scoon et al., 2007; Stanley, Halliday, D'Auria, Buchheit, & Leicht, 2015; Zurawlew et al., 2016), with exercise conducted in laboratory settings, enabling
easy access to heating facilities. Practically however, the ability to commence HWI immediately after exercise could be challenging for athletes who lack such facilities near training locations. Indeed, a delay of up to 1 h between training and HWI could easily occur when considering the activities that may prevent immediate immersion (e.g. debrief with coach, stretching, travel, bath preparation, etc.). In other circumstances, athletes may have other commitments during the day, which could delay HWI until the afternoon/evening. Precisely how such a delay and the observed Tc circadian oscillation across a day interact to potentially alter HWI mediated physiological responses (e.g. total heat-load) remains relatively unexplored. Therefore, the aim of this study was to assess the acute physiological responses central to thermoregulatory strain (Tc, skin temperatures, heart rate and sweat rate) when post-exercise HWI (30 min; 39°C) was delayed for 10 min (10M), 1 h (1H) or 8 h (8H) following a temperate treadmill run (18°C). It was hypothesized that both a 1 h and 8 h delay between exercise and HWI, would reduce the thermo-physiological strain (e.g. heat-load) of the HA session.

Materials and Methods

Participants

Twelve male, recreational [i.e. performance level one-two (De Pauw et al., 2013)] long distance runners (mean ± SD; age: 38 ± 13 y, height: 180 ± 7 cm, body mass: 81 ± 13.7 kg, body fat: 13.9 ± 3.5%) volunteered for the study. Females were excluded due to the confounding influence of menstrual cycle mediated Tc fluctuations (Mee, Peters, Doust, & Maxwell, 2017; Wendt et al., 2007). Inclusion criteria stipulated that the participants had performed a 10 km time trial within 6 months prior to the study in ≤ 50 min (mean time: 47 ± 3 min, range: 42-49 min). Exclusion criteria included any contra-indications to exercise as per the Exercise & Sports Science Australia adult pre-exercise screening tool, previous
diagnosis of low blood pressure, history of heat illness or use of prescribed medication during the time of the study. Approval for the project was granted by the Human Research Ethics Committee at Southern Cross University (Approval number: ECN-17-121) and written informed consent was obtained before commencing any testing procedures.

**Experimental Design**

Participants completed a 40-min submaximal treadmill run (Trackmaster TMX425 CP, Carrollton, Texas, USA) before a 30-minute bout of HWI, on three separate occasions, 7-10 days apart. With a randomised crossover design, each trial involved a different time delay between exercise and HWI, including 10 min (10M), 1 h (1H) and 8 h (8H). A schematic of the experimental design is illustrated in Figure 1. During 8H, participants were permitted to leave the laboratory after the run and conduct their normal daily activities, but were instructed to avoid any physical activity (all participants confirmed that they complied with these instructions). Participants were required to avoid alcohol and caffeine during testing days, and to ensure adequate hydration by ingesting 500 mL of water 2 h prior to arrival. Data collection was completed during winter to minimise natural HA. The data collection took place in the Northern Rivers Region of NSW, Australia. The participants generally arrived to the laboratory wearing a tracksuit and they all ran in shorts and a short sleeve top.

**Exercise Protocol**

A 40-min treadmill run [climate controlled laboratory; 18.0 ± 0.9°C; relative humidity (RH) 64.5 ± 4.7 %] commenced in the morning (between 06:00 and 07:30; time held consistent after first laboratory visit), to control for circadian variation of internal body temperature (Słomko & Zalewski, 2016). A pedestal fan set at a wind speed of 10 km·h⁻¹ was placed 2.5 m
in front of the treadmill to replicate the convective cooling of running outdoors. During the first trial, running speeds were self-selected via rating of perceived exertion (RPE) (Borg, 1998). Participants were instructed to run for 10 min at “light” intensity (RPE = 11), 20 min at “hard” intensity (RPE = 15) and further 10 min at “light” intensity. The treadmill speeds were recorded and replicated in subsequent trials so that each participant ran at the same speeds in all trials. Participants consumed water at 33°C *ad libitum* during the run. This temperature was chosen to minimise any cooling effect from the fluid on the ingested capsule while remaining palatable.

**Hot-water Immersion**

The HWI strategy used was 30 minutes at 38.9 ± 0.1°C to the level of the waist wearing shorts. This was implemented using a bathtub (2.3 m long x 1.1 m wide x 0.5 m high) in a bathroom (8 m²; 24.2 ± 2.3°C, 76.3 ± 8.1% RH), with water temperature and flow maintained using a two-tap mechanism. Consumption of fluids during immersion was not permitted. The strategy used was based on piloting that determined 39°C was the highest temperature that was safe for the participants to complete with the specified depth and duration in the environment available (i.e. a small room with high humidity; representing the average bathroom). We note that this HWI strategy is less aggressive than that investigated previously (i.e. 40°C for 40 min to the level of the neck), which was too demanding for 6/10 participants to complete on the first exposure in the previous study (Zurawlew et al., 2016). Hence, the HWI strategy presented here is designed to be safe and achievable for the first exposure, and the demands of the HWI (i.e. increased temperature, depth and/or duration) may be increased toward 40°C for 40 min to the level of the neck in subsequent exposures over time as appropriate for the individual.
Immersion termination criteria was set according to ethical requirements (i.e., reaching a $T_c >39.4^\circ C$, rapid increase in heart rate, light headedness or reporting a thermal comfort rating that reached “very uncomfortable”), however all participants completed the full 30-minute protocol.

**Measurements**

Before each initial experimental trial, participants underwent anthropometrical measurements including body mass by an electronic scale (Charder MS3200, Taichung City 412, Taiwan), stature (S+M Height Measure 2m, Rosepark, SA) and skin-fold measurement by calliper (Harpenden Calipers, Baty International, West Sussex, United Kingdom) at seven sites including the bicep, tricep, subscapular, supraspinalae, abdominal, mid-thigh and medial calf, following the International Society for the Advancement of Kinanthropometry recommended protocol (Marfell-Jones, Stewart, & De Ridder, 2012).

The $T_c$ was measured continuously using an e-Celsius ingestible telemetric capsule (BodyCap, Caen, France). Participants were instructed to ingest the capsule with water immediately prior to sleep the night before each trial (approximately 8 h prior to each trial). Measurements of skin temperature were taken using a dermal thermal scanner (DermaTemp, Exergen Corporation, MA, USA) on dry skin at four sites (forehead, right calf, right hand and lower back) before and after exercise/immersion, which allowed for an estimate of mean skin temperature ($T_{sk}$) according to the following equation (Nielsen & Nielsen, 1984):

$$T_{sk} = 9.429 + (0.137 \times \text{forehead temp}) + (0.102 \times \text{hand temp}) + (0.29 \times \text{back temp}) + (0.173 \times \text{calf temp})$$
Resting body temperature measurements occurred in the climate-controlled laboratory described above (18°C, 65% RH). All participants sat in the climate controlled laboratory wearing exercise clothing for a period of 20 minutes prior to exercise in all trials. During 10M and 8H, participants spent 10 minutes in the climate-controlled laboratory wearing shorts only immediately prior to immersion. In 1H, participants spent the entire 60 minutes in the climate-controlled laboratory prior to immersion; they wore clothing that allowed them to feel comfortable for 50 minutes, and then shorts only for the final 10 minutes.

Nude, dry body mass (accurate to 10 g) was recorded prior to the run (equipment same as above) after emptying the bladder. Body mass was also recorded prior to and after immersion following the same procedure. Water bottles were also weighed before and after the exercise to calculate fluid intake during the run so that sweat rate was estimated with the following equation:

\[
\text{Sweat rate (SR)} = \left[ \frac{(\text{change in body mass} + \text{fluid ingested})}{\text{time}} \right] / \left[ \text{body mass (initial)} \right]
\]

Heart rate responses were measured continuously using a Garmin Forerunner 920XT heart rate monitor (Garmin, Neuhausen am Rheinfall, Switzerland).

Measurements of thermal comfort and thermal sensation were recorded at 5 min intervals during exercise and immersion. A four-point scale (1-4) was used to assess thermal comfort (Gagge, Stolwijk, & Hardy, 1967) and a seventeen-point scale (0.0-8.0) was used to assess thermal sensation (Young, Sawka, Epstein, Decristofano, & Pandolf, 1987).
Statistical Analyses

The data were analysed with General Linear Mixed Models and Tukey post hoc tests with multiplicity adjusted P-values (significance level = 0.05) using GraphPad Prism version 8.0.0 (GraphPad Software, San Diego, California USA). Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality. Results are reported as mean±standard deviation (SD). The magnitudes of any differences between conditions were expressed as standardised differences (effect sizes; ES). The criteria used for interpreting the magnitude of the ES were: ≤0.2 (trivial), >0.2 (small), >0.6 (moderate), >1.2 (large) and >2.0 (very large) (Hopkins, Marshall, Batterham, & Hanin, 2009). The ES are reported with uncertainty of the estimates shown as ±90% confidence limits (CL). If the CL crossed both positive and negative trivial ES values, the magnitude was deemed unclear (Hopkins et al., 2009). A sample size calculation was performed (G*Power 3.1.2) with alpha level set at 0.05 and power set at 0.8, which revealed a sample size of nine participants was required to detect a meaningful change in Tc [0.3°C; Zurawlew et al. (2016)].

Results

There were no significant differences between conditions for any measured variable during the treadmill runs (P > 0.05). The mean treadmill speeds throughout the three running components of the trials were 9.4 ± 0.9 km·h⁻¹, 12.4 ± 1.2 km·h⁻¹ and 9.4 ± 0.9 km·h⁻¹. When all trials were combined, the mean maximum heart rate during the run was 153 ± 12 bpm and the mean sweat rate during the treadmill run was 0.20 ± 0.03 mL·min⁻¹·kg⁻¹. There were no significant differences between conditions for temperature of the water during HWI (P > 0.05).
The mean and individual Tc during the HWI for each condition is illustrated in Figure 2 and the trends in individual core temperature during hot-water immersion across conditions is illustrated in Figure 3. Due to technical problems (the capsule could not connect to the data logger in an 8H trial and we speculate that it had passed), Tc was missing for one participant and therefore data were analysed for 11 participants. The mean HWI Tc was significantly lower in 1H compared to 10M (-0.42 ± 0.33°C; P = 0.0032; ES = 1.70, ±0.72) and 8H (-0.39 ± 0.37°C; P = 0.0140; ES = 1.11, ±0.57). There was no significant difference for mean HWI Tc between 10M and 8H (-0.04 ± 0.20°C; P = 0.8842, ES = -0.14, ±0.43). The peak HWI Tc was significantly higher in 8H compared to 1H (0.49 ± 0.42°C, P = 0.003, ES = 1.25, ±0.74) but there were no significant differences for peak HWI Tc between the other conditions (P > 0.05).

**Insert Figure 2 Here**

**Insert Figure 3 Here**

The time course of the Tc responses throughout the trials is illustrated in Figure 4. The 10M condition resulted in the highest Tc responses initially, which were significantly higher than 1H from 0-15 min (P = 0.0008 – 0.0163; ES = 1.06 – 2.95) and 8H from 0-5 min (P = 0.0099 – 0.0449; ES = 1.67 – 3.03). The Tc in the 8H condition was significantly higher than the 1H condition from 5-30 min (P = 0.0079 – 0.0399; ES = 0.91 – 1.25).

**Insert Figure 4 Here**

The time course of the Tsk responses throughout the trials is illustrated in Figure 5. Due to technical problems, data were missing for two participants and therefore data were analysed for 10 participants. Upon commencing the HWI, 8H resulted in significantly higher Tsk than both 10M (P < 0.0001; ES = 3.27, ±1.52) and 1H (P = 0.0013; ES = 2.74, ±1.44). The Tsk
was also significantly higher for 1H compared to 10M at 0 min (P = 0.0002; ES = 1.90, ±0.92). At the end of the HWI, 8H remained significantly higher than 10M (P = 0.0042; ES = 1.19, ±0.68) but there were no significant differences between the other conditions.

**Insert Figure 5 Here**

A summary of the heart rate, sweat and perceptual responses during the HWI with effect size comparisons is illustrated in Table 1. Due to technical problems, heart rate data was missing for one participant during 8H and therefore data for 11 participants were analysed. The mean heart rate response was significantly higher in 10M compared 1H (36 ± 21 bpm; P = 0.0006) and 8H (45 ± 18 bpm; P < 0.0001). The maximum heart rate response was also significantly higher in 10M compared 1H (41 ± 24 bpm; P = 0.0005) and 8H (52 ± 21 bpm; P < 0.0001). There were no other significant differences between conditions for any other variable.

**Insert Table 1 here**

Discussion

The major finding of the current investigation was that a significantly lower Tc response was measured during HWI following a 1 h delay compared to a 10 min delay (-0.42°C), between exercise and immersion (Figure 2). Further, mean heart rate was also lower following the 1 h delay, compared to the 10 min delay (-36 bpm). Therefore, within the conditions of the current protocol, we accept hypothesis ‘i’ that delaying HWI by 1 h does reduce acute markers of thermo-physiological strain during a post-exercise HWI session. The second major finding was that, within the conditions of the current protocol, the Tc responses were similar between a 10 min and an 8 h delay between exercise and immersion (0.04°C; Figure 2), and peak HWI Tc was greatest in the 8H condition, likely due to a circadian rhythm influence on Tc.
As per Figure 3, the individual participants responded similarly to the HWI between trials (i.e. those with the lowest Tc in one trial generally had the lowest Tc in the others), which may be partly explained by individual anthropometrical characteristics. There were differences in the time course of Tc changes throughout the HWI between trials (Figure 4).

During 10M, the group mean Tc remained stable for the first 15 min of immersion (37.7-37.8°C), before increasing to 38.1°C in the final 10 min. We speculate that the prior exercise and subsequent increased core temperature at immersion onset suppressed the rise in Tc in 10M. For 1H and 8H, pre-immersion Tc was significantly lower prior to immersion compared to 10M due to additional recovery after the exercise (see Figure 4). Hence, the Tc profile increased in a linear fashion in these trials, albeit from a higher starting value in 8H, which was the trial with the highest peak Tc at the end of immersion (38.3°C). Considering that the Tc group mean only surpassed 38°C in the final 10 min of immersion in 10M and 8H (and not at all in 1H), the HA potential was likely low for this specific HWI strategy (i.e. 39°C for 30 min to the level of the waist). It should also be noted that athletes may regularly perform exercise at higher intensities than that prescribed in the current study, which may increase the thermo-physiological responses presented.

The HWI strategy presented in the current study (39°C for 30 min to the level of the waist) was deemed a suitable initial exposure based on piloting, but the strategy should become more aggressive (i.e. increased temperature, duration and/or depth) over time to induce a greater rise in Tc and a more sufficient thermal stimulus for adaptation (which also needs to be maintained) to increase the likelihood of inducing meaningful heat adaptations. A previous investigation on post-exercise HWI that successfully induced heat adaptation and performance improvement in runners, implemented a HWI strategy of 40°C for 40 min to the level of the neck (Zurawlew et al., 2016). However, 6/10 participants could not complete this
protocol on the first exposure and therefore it represents a starting point that is too challenging for many individuals. With this protocol, the researchers demonstrated that core body temperature was increased on average by 1°C throughout the immersion period (following the exercise), across six exposures. In comparison, the current study did not observe such an increase, and instead participants completed immersion with a similar core temperature to that observed at the end of the run. Hence, athletes using this technique should aim to quickly increase the demands of the HWI toward 40°C for 40 min to the level of the neck in subsequent exposures as appropriate for the individual. Immersed athletes should be given clear instructions to discontinue HWI when they feel uncomfortably hot or experience any symptoms of pre-syncope or heat illness (i.e. cramping, vomiting, nausea, severe headache, collapse/fainting). It is also advisable to measure Tc in order to ensure the HWI protocol is both safe and appropriate.

The 8H condition resulted in the highest peak Tc (i.e. at the end of immersion), and a similar mean Tc during HWI compared to 10M. This was somewhat unexpected, but may be explained by the higher circadian Tc that occurs in the afternoon (Slomko & Zalewski, 2016). As per Figures 4-5, there were higher pre-immersion Tc and Tsk in 8H compared to 1H, which does suggest a circadian influence. Considering that all trials commenced at a similar time of day (6:00-7:30am), this meant that the immersion in the 8H trial always commenced between 2:30-4:00pm; a time consistent with the time of day (3:00-5:00pm) that peak circadian rhythm Tc occurs (Slomko & Zalewski, 2016). Hence, the current data suggest that performing HWI during this time is more effective at increasing acute Tc than HWI performed in the morning when there is a delay of at least 1 h between exercise and immersion, and importantly, HA does not appear to be time of day dependent (Zurawlew, Mee, & Walsh, In Press). However, performing HWI at this time should be tested within a
longer-term heat adaptation study before such recommendations are made explicit for athletes
for heat acclimation purposes. Finally, if the HWI is to be conducted in the afternoon, then it
may also be beneficial to conduct the training session at this time as well.

Both the mean and maximal heart rates were significantly increased during HWI in 10M
compared to both 1H and 8H. It is likely that the 10M condition did not allow for complete
heart rate recovery after the exercise, prior to the immersion, and as such the participants
were subject to increased cardiovascular strain during the HWI in 10M. No significant
differences were observed for the sweat responses or the perceptions of thermal comfort and
sensation. However, effect size statistics revealed a moderate increase in sweat loss and rate
in 8H compared to 1H. It was surprising that there were no differences in thermal perception
despite differences in both core temperature and skin temperature, which play a large role in
modulating these thermal perceptions. The other interesting finding was that Tsk was
significantly higher in 1H compared to 10M before immersion (see Figure 5), which may be
explained by the convection and evaporation load associated with running, and/or the
additional clothing worn by participants during the 1 h delay in 1H (despite the use of a short
stabilisation period).

The primary objective of the current study design was to maximise ecological validity to
provide clear guidelines for athletes on the timing of post-exercise HWI when it is to be
implemented outside of the laboratory setting. Indeed, the availability of a hot-bath
immediately after training (i.e. within a few minutes) is not practical for most athletes, but
this has not been considered previously. Post-exercise HWI that is slightly delayed after a
training session (i.e. 10 min or longer) is practical where the athlete has access to a bath at
home. The different time delays chosen in the current study reflected likely delays to occur in
the field, but investigation into other time delays is also warranted, especially delays of
between 20 and 50 minutes, within which there is likely a threshold where the thermo-
physiological response to HWI is reduced, decreasing the potential capacity for HA. Future
research could also investigate the effects of post-exercise HWI when exercise is performed
in the afternoon, in hotter environments, or after exercise in additional clothing (Stevens,
Plews, Laursen, Kittel, & Taylor, 2017). Considering the ecological design, the current
study’s strengths can also be considered as limitations, for example, the athletes drank to
thirst during the exercise, ate their usual diet and completed their usual activities throughout
the day instead of remaining in the laboratory during the delays in the 1H and 8H trials. As
such, hydration, the thermic effect of food and incidental physical activity, which can all
contribute to heat storage, were not highly standardised. Fluid ingestion was not measured
between exercise and HWI and hydration status was not measured either, but the participants
were encouraged to drink during and after the exercise, and there was no difference in
measures of body mass between exercise endpoint and starting HWI. We also highlight that
this study is only an acute study of the physiological and perceptual responses to the different
time delays between exercise and HWI, and more long-term studies are needed to determine
any effects on heat adaptation.

It should also be noted that in the 8H trial, the ingestible capsule was in the gastrointestinal
tract for an additional 8 hours compared to the 10M trial, and possibly moved further along
the tract. However, this is unlikely to have affected the core temperature observations as
previous research determined no differences between measures of core body temperature by
rectal probe and ingestible capsule at 1 hour (0.15 +/- 0.11°C) vs. 36 hours (0.15 +/- 0.14°C),
after ingestion (Ducharme, T.M., Moroz, Buguet, & Radomski, 2001). Another study has
demonstrated some small gastrointestinal temperature gradients, but the most significant
gradient was between the stomach and the small intestine (0.2-0.3°C) and any other gradients were trivial (Kolka, Quigley, Blanchard, Toyota, & Stephenson, 1993). We implemented an 8-hour timeframe between ingestion and the first measurement, exceeding the 6-hour recommendation between ingestion and measurement to ensure that the capsule clears the stomach (Byrne & Lim, 2007), minimising the effects of any gastrointestinal temperature gradient.

Overall the current study provides new recommendations for athletes aiming to maximise the acute thermo-physiological response to post-exercise HWI. Immersion should commence immediately after training (within 10 min) to maximise acute Tc and heart rate responses. If this is not viable, an alternative approach may be to implement HWI in the afternoon when Tc is naturally elevated due to circadian rhythm. In the current design, delays of 1 h between exercise and immersion result in significantly lower Tc responses compared to delays of 10 minutes and 8 hours, and Tc of less than 38°C throughout the whole immersion period (when considering the group mean) and hence, a 1 h delay is not recommended for athletes aiming to maximise the acute thermo-physiological response to post-exercise HWI.

Acknowledgements
The authors wish to thank the participants for their involvement in the study. Erich Wittstock is also thanked for his valuable technical support across the data collection period. We acknowledge that sections from Storme Heathcote’s Master of Science thesis have been incorporated into this publication.

Declaration of Interest Statement
The authors report no conflict of interest.
References


Table 1: Summary of the heart rate, sweat and perceptual responses during hot-water immersion with effect size comparisons.

<table>
<thead>
<tr>
<th></th>
<th>10M (mean ± SD)</th>
<th>1H (mean ± SD)</th>
<th>8H (mean ± SD)</th>
<th>10M-1H (ES, ±CI)</th>
<th>10M-8H (ES, ±CI)</th>
<th>1H-8H (ES, ±CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean HR (bpm)</td>
<td>130 ± 19</td>
<td>94 ± 22*</td>
<td>85 ± 11*</td>
<td>1.35, ±0.46</td>
<td>2.81, ±0.59</td>
<td>0.61, ±0.45</td>
</tr>
<tr>
<td>Max HR (bpm)</td>
<td>143 ± 21</td>
<td>102 ± 24*</td>
<td>91 ± 13*</td>
<td>1.39, ±0.47</td>
<td>2.77, ±0.60</td>
<td>0.60, ±0.44</td>
</tr>
<tr>
<td>SL (mL)</td>
<td>700 ± 376</td>
<td>482 ± 259</td>
<td>665 ± 244</td>
<td>0.51, ±0.68</td>
<td>-0.14, ±0.87</td>
<td>-1.05, ±0.81</td>
</tr>
<tr>
<td>SR (mL/min/kg⁻¹)</td>
<td>0.29 ± 0.16</td>
<td>0.20 ± 0.10</td>
<td>0.28 ± 0.12</td>
<td>0.53, ±0.70</td>
<td>-0.13, ±0.82</td>
<td>-0.97, ±0.76</td>
</tr>
<tr>
<td>Mean TC (AU)</td>
<td>1.8 ± 0.5</td>
<td>1.9 ± 0.5</td>
<td>2.0 ± 0.5</td>
<td>-0.19, ±0.49</td>
<td>-0.43, ±0.63</td>
<td>-0.22, ±0.65</td>
</tr>
<tr>
<td>Mean TS (AU)</td>
<td>5.1 ± 0.6</td>
<td>5.2 ± 0.9</td>
<td>5.4 ± 0.7</td>
<td>-0.01, ±0.24</td>
<td>-0.36, ±0.28</td>
<td>-0.35, ±0.39</td>
</tr>
</tbody>
</table>

10M = 10 min delay, 1H = 1 h delay, 8H = 8 h delay, AU = arbitrary units, bpm = beats per minute, CI = 90% confidence interval, ES = effect size, SD = standard deviation, HR = heart rate, TC = thermal comfort, TS = thermal sensation, SL = sweat loss, SR = sweat rate. *Significantly different to 10M.
**Figure Captions**

Figure 1. Schematic of the experimental design. 10M = 10 min delay, 1H = 1 h delay, 8H = 8 h delay, HWI = hot-water immersion.

Figure 2: Mean and individual core temperature during hot-water immersion for each condition; 10 min (10M), 1 h (1H) and 8 h (8H) intervals (n = 11). *significantly different to 10M and 8H. Lines represent the mean and circles represent the individual responses.

Figure 3: Trends in individual mean core temperature during hot-water immersion across conditions; 10 min (10M), 1 h (1H) and 8 h (8H) intervals (n = 11).

Figure 4: Time course of core temperature changes across the trials for each condition; 10 min (10M), 1 h (1H) and 8 h (8H) intervals (n = 11). *10M sig different to 1H, #10M sig different to 8H, †1H sig different to 8H.

Figure 5: Time course of mean skin temperature changes across the trials for each condition; 10 min (10M), 1 h (1H) and 8 h (8H) intervals (n = 10). *10M sig different to 1H, #10M sig different to 8H, †1H sig different to 8H.