Strategies to Reduce Heat Strain During Tennis Match-Play in Hot, Humid Conditions

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Abstract

Tennis match play often occurs in hot humid conditions increasing the risk of heat illness incidence, primarily due to increased body temperature and cardiovascular strain. Physiological and perceptual strain causes behavioural thermoregulation and can impair performance. Therefore, strategies which alleviate this heat strain could be beneficial from either a safety or performance perspective, or both. Little research has been conducted on the efficacy of heat alleviation strategies during tennis match play in hot conditions so it is unknown which strategies might be most beneficial. Consequently, the aim of this thesis was to assess the efficacy of acute heat alleviation strategies during simulated tennis match play in hot humid conditions and to better understand current practice and perceptions of heat alleviation strategies. The purpose of study 1 was to design and evaluate the test-retest reliability and validity of a tennis-specific treadmill protocol in temperate and hot, humid environmental conditions to allow confident interpretation of subsequent studies. Tennis players behaviourally increase the between-point rest length during tennis match play in hot humid conditions, therefore the aim of study 2 was to assess the thermal physiological and perceptual responses of this phenomenon. Increasing between-point rest from 20 to 30 seconds attenuated the rise in core temperature but had no effect on thermal perception. The aim of study 3 was to quantify the physiological and perceptual responses to internal, external, and combined internal and external cooling during simulated tennis match play in hot humid conditions. Internal cooling attenuated the rise in core temperature and lowers skin temperature and thermal sensation; external cooling only lowered skin temperature; combined cooling attenuated the rise in core temperature to the same extent but skin temperature and thermal perception to a greater extent than each strategy alone. The purpose of study 4 was to understand heat alleviation strategy current practice and perceptions of tennis players and support staff. Heat alleviation is perceived to be a useful tool for players competing in hot humid conditions and highlighted the importance of practicality. The findings from these studies improved the understanding of the physiological and perceptual responses to these strategies providing evidence that a longer between-point rest and internal cooling can slow the rate of rise in core temperature, and external cooling decreases the perception of the thermal sensation. All these strategies have the potential to enhance performance in hot humid conditions either physiologically or perceptually, in turn affecting autonomic and behavioural thermoregulation. The findings also have implications for future heat policy making and the application of heat alleviation in a hot humid environment.

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List of Abbreviations

$\overline{T}_{sk}$	Mean Skin Temperature
ANOVA	Analysis of Variance
ATP	Association of Tennis Professionals
BASES	The British Association of Sport and Exercise Sciences
BLa	Blood Lactate
BSA	Body Surface Area
BUCS	British Universities and Colleges Sport
CBM	Clothed Body Mass
CV	Coefficient of Variation
GET	Gas Exchange Threshold
ICC	Intra-Class Correlation
ITF	International Tennis Federation
MHP	Metabolic Heat Production
NBM	Nude Body Mass
PBF	Percentage Body Fat
RH	Relative Humidity
RPE	Rating of Perceived Exertion
SD	Standard Deviation
SR	Sweat Rate
SWC	Smallest Worthwhile Change
T_c	Core Temperature
TC	Thermal Comfort
TEM	Typical Error of the Measurement
T_{re}	Rectal Temperature
TS	Thermal Sensation
TSTP	Tennis-Specific Treadmill Protocol
$\dot{V}O_2max$	Maximal Aerobic Capacity
WBGT	Wet Bulb Globe Temperature
WTA	Women's Tennis Association

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1 Introduction

1.1 Introduction

Tennis is a pan-global sport with ~87 million participants (ITF, 2019) and ~10,000 players have a ranking (~6000 juniors and ~4000 professional players) affiliated to one of the sport's governing bodies. The tennis season for professional male players lasts 11 months of the year, 2 weeks shorter for the women's tour, with players competing in tournaments and matches throughout the season. Tournaments are knock-out events, so players who win would be expected to play more matches over a season; however, lower-ranked, and younger players will try to enter as many tournaments as possible attempting to increase their ranking. The biggest events on the calendar each year are the Grand Slam tournaments; Australian Open, French Open, Wimbledon and US Open. These tournaments have the largest draws (128 players) and require a player to win 7 consecutive matches over 2 weeks to win the tournament.

Tennis is a multi-dimensional sport with several determinants of performance (Fernández-Fernández et al., 2014; Kovacs, 2007). Match-play is characterised as bouts of whole-body intermittent sprint exercise (2 to10 s) with short between-point rest periods (10 to 20 s), and with longer change of ends and set-breaks (60-120 s). The mean reported match length is 1.5 h, though matches occasionally last for 5 or more hours (Fernandez-Fernandez, Sanz-Rivas, & Mendez-Villanueva, 2009; Kovacs, 2006, 2007).

Many of the tournaments in the tennis season occur during the summer months of the host locations. There is no consistency in the implementation of heat policies across the various governing bodies with female (Women's Tennis Association, 2021), junior and wheelchair (International Tennis Federation, 2021) players given allowances in the heat, whereas male players are not (Association of Tennis Professionals, 2021). Grand Slam events often take place in hot conditions increasing the risk of heat illness; the Grand Slam Board (2021) do not govern a heat policy, rather allowing each tournament to govern this individually. At the 2014 Australian Open in Melbourne, play was suspended on occasions as the ambient temperature exceeded 40 ˚C. This prompted the Australian Open to update their heat policy in 2015, to include all environmental factors of ambient temperature, relative humidity, radiant heat and wind speed through the measure of wet bulb globe temperature (WBGT); play would be suspended if the ambient temperature exceeded 40 ˚C and the WBGT exceeded 32.5 ˚C. Wimbledon, (London, UK) has reported peaks in ambient temperature of 34 ˚C (2015) and the US Open (New York, USA) also reported peaks of 36 ˚C 50% RH, contributing to a record high of 10 players retiring during the first round (2015). After 5 heat-related male retirements in the first round in 2018 and ambient temperatures peaking ~38 ˚C 50% RH, the US Open implemented a heat policy which included males for the first time; this allowed an extended break between a second and third set for females and juniors and between a third and fourth set for males. However, the thresholds to implement this policy are not obvious and said to be used on a case-by-case basis. In 2019 the Australian Open created the simplified AO Heat Stress Scale (see Figure 1.1), a 5-point scale ranging from temperate conditions through to suspension of play. This policy is based on WBGT and physiological differences for sex, age, and wheelchair tennis, though further detail is not published on how the levels are calculated. Wimbledon also expanded their heat policy allowing an extended break when the temperature reached or exceed 30.1 ˚C WBGT to include males in 2019. The advancements in heat policy demonstrate that player safety in hot conditions is being taken seriously; however, there are inconsistencies between the Grand Slams as there is no central governing heat policy.

At the Australian Open, male (219.6 vs 16.3 rate per 1000 hours for >27.9 ˚C and <27.9 ˚C WBGT, respectively) and female (169.56 vs 48.28 rate per 1000 hours for >27.9 ˚C and <27.9 ˚C WBGT, respectively) players called for cooling devices, such as ice towels, more often in conditions >28 ˚C WBGT. There were also more in-match and post-match heat stress calls and heat stress retirements in conditions >30.1 ˚C WBGT for males (87.3 vs 4.1 rate per 1000 hours for >30.1 ˚C and <30.1 ˚C WBGT, respectively) and females (124.78 vs 24.82 rate per 1000 hours for >30.1 ˚C and <30.1 ˚C WBGT, respectively). There was a clear effect of performance as the heat index increased with male players hitting more aces and approaching the net less. Net approaches also decreased for female players as well as the number of winners and increased double faults. These data suggest that players are changing tactics so they are less physically demanding or unable to sustain the same intensity in hotter conditions. (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018). Simply, the prevalence of heat-related incidents is greater during and post-match when the conditions are above 30.1 ˚C WBGT for both men and women (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018).

Figure 1.1: The Australian Open Heat Stress Scale

Sweat rates in elite tennis players are estimated to be between 1 and 3.5 L·min^{-1} in hot conditions (Bergeron, 2003; Hornery, Farrow, Mujika, Young, et al., 2007; Ranchordas et al., 2013) and mean core temperatures of 38.5-39.0 ˚C and peak >39.1 ˚C (highest observed peak 39.4 ˚C) across male and female professional players during tournament match play (Hornery, Farrow, Mujika, Young, et al., 2007; Périard, Racinais, et al., 2014b; Tippet et al., 2011). These high sweat rates and high core temperatures demonstrate the importance of the body's cooling system in reducing excessive heat with concurrent high environmental heat load and metabolic rate. The between-point rest length at the Grand Slam tournaments was increased from 20 to 25 seconds in 2018 to match the other tennis tours. This would be expected to reduce some of the heat strain for the players, however, all tennis federations introduced the concept of a shot clock—which times the between-point rest—preventing players from resting longer than 25 s (e.g. 27.6 ± 2.8 s) as previously evidenced in the heat (Périard, Racinais, et al., 2014b). Before the use of the shot clock, umpires were considered more lenient when enforcing time violations for taking too long between points in extreme conditions, but the shot clock reduces this ability.

Heat alleviation strategies such as the extended break seen in the policies above are in place to increase player safety and performance whilst playing in the heat. The evidence base examining heat alleviation strategies within a tennis context is sparse, though methods which might be suited to tennis have been suggested previously (W. M. Adams et al., 2016). The extended break, in place on the Women's Tennis Association (WTA) tour since 1992 as part of their extreme weather conditions rule allows a 10-minute break in between a second and third set when the temperature reaches or exceeds 30.1 ˚C WBGT (Women's Tennis Association, 2020). The efficacy of this break was assessed by Tippet et al. (2011); they reported a core temperature decrease of 0.25 ± 0.20 ˚C after the 10-minute break in an air-conditioned changing room and with a change of clothes.

However, this includes some players that could only take a bathroom break. Separately, the extended break decreased core temperature more than a bathroom break (0.30 ± 0.14 ˚C vs 0.17 ± 0.27 ˚C). The study did not compare to a situation where the extended break was not taken and only involved female players.

Some cooling strategies have been assessed during tennis-specific exercise including ice towels, electric fans, and ice slurries. The cooling strategies were implemented intermittently throughout exercise when players would be 'changing ends'. Ice towels (neck, head and lap) and using an electric fan after skin wetting effectively reduced the rate of rise in core temperature in hot dry (Lynch et al., 2018) and hot humid (Schranner et al., 2017) environments. Ice slurry ingestion led to similar conclusions in a hot humid environment (Naito et al., 2018); all compared to a control of cold-water. In a hot dry environment, an electric fan alone did not influence thermal physiological or perceptual variables. Ice towels were used as the gold standard as the recommended strategy of the WTA (Schranner et al., 2017). However, anecdotally players would not use the full approach and often only opt for the ice towel around the neck, therefore these results might not reflect current practice.

The current practice on the Association of Tennis Professionals (ATP) and the WTA tours are based on the evidence currently available; these include good practice for hydration and heat alleviation. Players and coaches are provided educational resources about pre-, during and post-match nutrition and hydration strategies (Ellenbecker & Stroia, 2014). During WTA and ATP tournaments, facilities are available to assess body mass and hydration through urine specific gravity and urine colour which can be used pre- and post- training and matches. Players are provided with beverages and advised on fluid and electrolyte consumption, and the physiological monitoring associated. Whilst on-court, the current recommendations include electric fans, seeking shade from court structures or umbrellas and ice towels; they are also assisted through advancing technology in clothing (Ellenbecker & Stroia, 2014).

From 2010, there has been an increase in the knowledge and understanding of heat stress in tennis players. Alongside this, the concern for player safety has also increased and strategies to alleviate thermal strain during tennis match play have been more the topic of more research. However, the evidence base is still quite sparse which inhibits players, coaches and other support staff, tournament organisers and governing bodies to make fully informed decisions on topics such as pre-tournament preparation, developing and updating heat policies, tournament scheduling, ensuring player safety through a reduction in thermal strain and enhancing performance. The research investigating the use of on-court cooling strategies is vital to adapt and suggest new strategies to prevent heat illness when competing in the heat (Ellenbecker & Stroia, 2014). Additional research is needed to create a body of evidence to inform decisions and policies made by governing bodies or tournaments. Therefore, this thesis will build on the current evidence (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017) by assessing the efficacy of heat alleviation strategies, as well as begin to understand current practice and perceptions to better inform future the heat policy within tennis.

1.2 Aim

The aim of this thesis was to assess the efficacy of acute heat alleviation strategies during simulated tennis match play in hot humid conditions and to better understand current practice and perceptions of heat alleviation strategies to bridge the gap between research and the applied world.

1.3 Research Questions

1. What is the validity and reliability of a tennis-specific treadmill protocol in temperate and hot, humid environments?
2. What is the effect of increasing between-point rest length on physiological and perceptual thermal strain during a tennis-specific treadmill protocol?
3. What is the effect of internal cooling through ice slurry ingestion on physiological and perceptual thermal strain during a tennis-specific treadmill protocol?
4. What is the effect of external cooling through and ice towel around the neck on physiological and perceptual thermal strain during a tennis-specific treadmill protocol?
5. Is there an additive effect of combining internal cooling and external cooling on physiological and perceptual thermal strain compared with each individually during a tennis-specific treadmill protocol?
6. What are the current heat alleviation practices adopted and advised by players and support staff?
7. What are the current perceptions of players and support staff to heat alleviation strategies?

1.4 Objectives

1. To design and evaluate the reliability of thermophysiological, cardiovascular and perceptual responses to a tennis-specific treadmill protocol.
2. To measure the physiological and perceptual responses to the tennis-specific treadmill protocol in temperate and hot, humid conditions.
3. To assess the efficacy of increasing between-point rest for reducing physiological and perceptual heat strain during tennis-specific exercise.
4. To assess the efficacy of internal per-cooling, external per-cooling and a combined internal and external per-cooling strategy for reducing physiological and perceptual heat strain during tennis-specific exercise.
5. To explore the current practice and perceptions of heat alleviation strategies from the perspective of players and support staff in the applied environment.

1.5 Outline of PhD Programme

This introduction has outlined the prevalence of heat related illness during tennis match play in the heat, the lack of consistency across governing body and tournament heat policies, the lack of tennis-specific heat alleviation research and a need to develop a tennis-specific treadmill protocol (TSTP). This thesis is therefore presented in the following experimental chapters.

1.5.1 *Chapter 4*

To achieve objectives 1 and 2, a tennis-specific treadmill protocol (TSTP) was designed before reporting physiological and perceptual responses and assessing test-retest reliability in temperate and hot, humid conditions. The protocol developed was used in subsequent investigations to assess the effectiveness of interventions.

1.5.2 *Chapter 5*

To achieve objective 3, chapter 5 used the previously designed TSTP and assessed the physiological and perceptual responses to an increased between-point rest length as a very practical and easy heat alleviation method.

1.5.3 *Chapter 6*

This chapter assessed the effectiveness of three per-cooling strategies implemented during the TSTP. The strategies chosen were logistically feasible for tennis match play and allowed a comparison of cooling approaches. External cooling through ice towels, internal cooling through ice slurry and a combined internal and external approach using both allowed any additive benefits to be assessed. The chapter addresses objective 4.

1.5.4 *Chapter 7*

Chapter 7 reached objective 5 by exploring the current practice and perceptions of players and coaches to bridge the gap between research and practice whilst informing education gaps and future research opportunities.

2 Literature Review

2.1 Physiological Responses to Heat Stress

The aim of homeothermic temperature regulation is to maintain a consistent core temperature independent of the ambient environment. This is achieved most of the time through the constant exchange of heat. Humans regulate heat through both autonomic and behavioural mechanisms in response to internal heat production through metabolism and external heat stress and is summarised in the heat balance equation (Mercer, 2001).

Equation 2.1: The heat balance equation

$$\dot{S} = \dot{M} \pm \dot{W} \pm \dot{E} \pm \dot{R} \pm \dot{C} \pm \dot{K} \pm \dot{C}_{res} \pm \dot{E}_{res}$$

$\dot{S}$ is the rate of heat storage (W/m^2); $\dot{M}$ is the metabolic rate (W/m^2); $\dot{W}$ is the rate of heat transfer from the generation of external work (W/m^2); $\dot{E}$ is the rate of heat exchange via evaporation (W/m^2); $\dot{R}$ is the rate of heat exchange via radiation (W/m^2); $\dot{C}$ is the rate of heat exchange via convection (W/m^2); $\dot{K}$ is the rate of heat exchange via conduction (W/m^2); $\dot{C}_{res}$ is the rate of heat exchange from respiratory conduction (W/m^2); $\dot{E}_{res}$ is the rate of heat exchange from respiratory evaporation (W/m^2) (Mercer, 2001).

The rate of heat storage ($\dot{S}$), is simply the body heat gain or loss *i.e.,* when $\dot{S}$ equals zero, thermal balance is apparent. Heat gain occurs through the rate of metabolic heat production is greater than the body's capacity to dissipate heat to the surrounding environment, or when the air or water surrounding the body is at a higher temperature than the capacity of the mechanisms of heat dissipation. Heat loss occurs when the heat dissipation to the ambient environment is greater than the rate of metabolic heat production. As $\dot{S}$ fluctuates, core temperature changes to reflect the imbalance (Cabanac, 1997). The rate of heat storage is influenced by both autonomic and behavioural temperature regulation responses; the autonomic nervous system controls the physiological regulation (S. F. Morrison & Nakamura, 2011) through the activation of evaporative and non-evaporative heat loss mechanisms (Kenny & Jay, 2013), and the behavioural regulation is controlled through conscious behaviour changes to alleviate heat strain (Sawka, Wenger, et al., 2011). Optimal body temperature is achieved through both afferent and efferent feedback to the hypothalamus which then initiates the necessary effector responses (Sawka, Wenger, et al., 2011). Exercise in a hot environment can increase heat production and decrease the heat transfer gradient between the skin and the surrounding environment (Gagge & Gonzalez, 2011). This reduced gradient means the evaporative heat loss is the primary mechanism to maintain thermal balance (Sawka, Leon, et al., 2011).

When exercising in the heat, a redistribution of blood is needed from the viscera to the shell and working muscles when the heat loss mechanisms of increased skin blood flow and evaporative heat loss through sweat are stimulated (González-Alonso et al., 2008; Rowell, 1974). If the exercise bout is prolonged or exercise occurs in a humid environment, thus limiting evaporative potential, the fluid loss through sweat can lead to a reduced central blood volume; placing further stress on the cardiovascular system which is already being competed for between skin blood flow and the working muscles (Montain & Coyle, 1992; Sawka et al., 1993). This reduced blood volume and increased demand causes a reduction in mean arterial pressure, cardiac filling and stroke volume; therefore, heart rate must be increased to maintain cardiac output (Ekelund, 1967; Rowell, 1974). With prolonged exercise, this can lead to reduction in cardiac output and the arterio-venous oxygen difference to widen (Asmussen, 1940; Rowell, 1974; Rowell et al., 1965), potentially limiting oxygen delivery and uptake in the working muscles . These factors decrease absolute $\dot{V}O_2max$, increasing the relative intensity *i.e.* $\%\dot{V}O_2max$ (Périard et al., 2011; Wingo et al., 2005). Cardiac output not being maintained can also lead to an increased rate of heat gain and consequent performance decrements or cessation (Périard et al., 2011; Sawka et al., 1985).

Performance decrements in the heat might also occur through behavioural thermoregulation. The increased perceptions of heat (Gagge et al., 1969) and exertion (Périard et al., 2011; Tucker et al., 2006) as a consequence of the increased physiological strain, and the surrounding environment, are thought to cause a reduction in intensity or exercise cessation to protect against further heat gain (Tucker et al., 2006),

This section has provided a brief overview of the responses to heat stress. Alongisde the aforementioned mechanisms, there are other factors which also influence thermoregulation in the heat including exercise duration and intensity, hydration status, acclimatisation, clothing, and aerobic fitness (Cadarette et al., 1984; James et al., 2017; Kwon et al., 1998; Nadel et al., 1980; Sawka et al., 1993; Willmott et al., 2016).

2.2 The Nature of Tennis

2.2.1 *Demands of tennis match play*

Tennis is a multi-dimensional sport with a number of performance determinants (Figure 2.1) (Fernandez-Fernandez, Ulbricht, & Ferrauti, 2014). Match-play, as characterised by several authors, involves bouts of whole-body intermittent sprint exercise (2-10 s) alternating with short recovery periods (10-20 s). However, longer recovery periods (60-120 s) are interspersed over an average match length of 1.5 h with some lasting ≥5 h (Fernandez-Fernandez, Sanz-Rivas, & Mendez-Villanueva, 2009; Kovacs, 2006, 2007). Tennis match-play generally evokes a mean heart rate of 70-80% HR_{max}, with peak values of 100%, analogous to 50-60% $\dot{V}O_{2max}$ with peaks of 80% $\dot{V}O_{2max}$ (Fernandez-Fernandez et al., 2009; Fernandez, Mendez-Villanueva, & Pluim, 2006). Perceived exertion has been reported at 3-8 (“moderate” to “very hard” intensity) on the Borg CR-10 scale (Borg, 1982) in elite male players, with a progressive increase throughout match play (Gomes et al., 2011).

Kovacs (2007) suggested that the physical skills and components of tennis can be grouped into 3 categories: anaerobic which includes speed, agility, strength, power and muscular endurance; aerobic which also includes muscular endurance, and aerobic endurance; and auxillary components of body awareness/dynamic balance, flexibility and reaction time/anticipation.

Whilst the above information provides an overview of the physical demands of tennis, there are several factors which can influence the match activity and physiological responses. Tennis is a reactive, unpredictable sport. The scoring system leads to intermittent repetition of exercise for durations of between one and five hours, with some reported cases longer than this depending on the format of the match *i.e.,* 3 or 5 sets (Kovacs, 2007).

2.2.2 *Anthropometry*

Players with a large range of body types and physiques have been shown to be successful at tennis over the years. Many players will be taller than the average population due to the obvious benefits that accompany increased stature, such as the ability to execute the serve, volleying and on-court reach. However, as stature increases, the ability to move and change direction might be compromised due to tennis being a sport involving getting the centre of mass close to the ground is often seen as a weakness area, therefore, must be balance between different physiques and the playing style that can be achieved (Parker-Simmons & Love, 2018).

In the 1980s and 1990s, tennis players with a lower BMI were winning the matches at the four Grand Slams (Australian Open, French Open, Wimbledon and US Open). However, in the 2000s, higher BMI were more likely to win at these tournaments. This change coincided with a general increase in BMI for all players; the 80s and 90s were around 22-23 kg·m^{-2} and the 2000s were 22.5-24 kg·m^{-2} with a change most apparent in the winners of the major tournaments. This transition can be seen in Gale-Watts & Nevill (2016) and has been suggested to be a product of tennis becoming more power based than endurance based. The transition might either be a consequence of the demands of tennis evolving, advancements in technology, evolvement in playing style, or most likely a combination of all these factors.

2.2.3 *Oxygen uptake*

Tennis players reportedly have a maximal oxygen consumption ($\dot{V}O_2max$) between 45 and 65 ml·kg^{-1}·min^{-1} (Bergeron et al., 1991; Girard & Millet, 2004; Kovacs, 2007; Kraemer et al., 2000). Generally, these values are higher in male players than female players (Urhausen et al. 1990; Reilly & Palmer 1995; König et al., 2001). These maximum values sit across both values reported for anaerobically trained (50.0 ± 7.8 ml·kg^{-1}·min^{-1}), and aerobically trained individuals (67.2 ± 8.5 ml·kg^{-1}·min^{-1}) demonstrating the mix of aerobic and anaerobic components (Green et al., 2003).

Oxygen uptake during tennis match play is expected to be around 23-29 ml·kg^{-1}·min^{-1} based on previous profiles of tennis (Ferrauti, Bergeron, et al., 2001; Mendez-Villanueva et al., 2007; Smekal et al., 2001), equating to around 50-60% of $\dot{V}O_2max$ for elite players (Fernández-Fernández et al., 2006; Girard & Millet, 2004; Torres-Luque et al., 2011). The percentage of maximal oxygen uptake would be higher for players of a lower standard due to lower $\dot{V}O_2max$ values, however they are unlikely to play at a similar intensity as elite players.

Playing style and the role in the match can affect oxygen uptake. Smekal et al., (2001) reported that oxygen uptake was no different whether serving or returning, however there was a difference between players who were described as offensive or defensive (30.8 ± 5.7 vs 27.5 ± 5.1 ml·kg^{-1}·min^{-1}, respectively); with offensive eliciting a higher uptake. This has also been suggested when thinking about game styles with a baseliner with a more defensive style expected to have a higher $\dot{V}O_2max$ than a serve and volleyer or similar offensive style as well as those who are more neutral in style (Bernardini et al., 1998).

There is no clear difference in oxygen uptake between the typically slower court of clay when compared to hard court or even grass (Fernández-Fernández et al., 2010; Murias et al., 2007). This was despite increases that were seen in HR, BLa and distance covered. Tennis involves many repeated lateral displacements and it is thought that these types of movements often lead to the highest $\dot{V}O_2$ responses (Williford et al., 1998).

Girard & Millet (2004) seem to be in agreement with this as they reported that oxygen consumption was indeed higher on clay courts than hard courts.

It has been demonstrated that as $\dot{V}O_2max$ levels increase and decrease, the following year's ranking level also follow suit, with a higher maximal oxygen uptake equating to a higher ranking on the professional tour (Banzer et al., 2008).

2.2.4 *Heart rate*

The mean observed HR values across a match in trained and elite players have been reported on a number of occasions and lie in the range of 140-160 beats·min^{-1} (Bergeron et al., 1991; Elliott, Dawson, & Pyke, 1985; Ferrauti, Bergeron, Pluim, & Weber, 2001; Girard, Jean-paul, & Millet, 2006; Gomes et al., 2011; Groppel & Roetert, 1992; Hornery, Farrow, Mujika, Young, & Pluim, 2007; König et al., 2001; Murias et al., 2007) with this range equating to around 70-80% of HR maximum for these players (Christmass, Richmond, Cable, Arthur, & Hartmann, 1998; Reilly & Palmer, 1995; Torres, Cabello, & Carrasco, 2004). A slightly lower HR (120-140 beats·min^{-1}) has been observed in the first set of match play in elite male tennis players (Gomes et al., 2011). A similar range, equating to a slightly higher percent HR max is also observed during match play in the older players (Fernández-Fernández et al., 2009). As tennis is intermittent and the HR everchanging, there are times during match play when HR might reach 190-200 beats·min^{-1} which is a useful way of demonstrating the varying demands placed on the cardiovascular system as different points in the match (Girard & Millet, 2004; Smekal et al., 2001; Torres et al., 2004). It is likely that HR is elevated above the mean range within points and then below the mean range during the rest periods. This demonstrates both the anaerobic nature (within points), and the aerobic nature (longevity and repeated actions) of tennis (Bergeron et al., 1991).

There is a possibility that HR is elevated during service games, with Fernandez-Fernandez et al. (2007) observing a HR of 166 beats·min^{-1}. However, it has been reported that no difference was apparent between service and return games, too (Smekal et al., 2001). Though, a number of other papers also agree that HR is increased when serving compared to returning games (Davey, Thorpe, & Willams, 2003; Elliott et al., 1985; Fernandez-Fernandez et al., 2007).

Whether court surface influences HR is yet to be agreed within the literature. It has been reported that HR was higher whilst playing on clay than hard court (Murias et al., 2007); in disagreement, a higher HR was observed whilst playing on hard compared to clay (Hornery, Farrow, Mujika, Young, et al., 2007); and also suggested that there is no difference due to changing surface (Fernandez-Fernandez et al., 2010).

Heart rate is also known to be affected by a plethora of other factors including circadian rhythm and the environmental conditions. Tennis is often played in warm or hot conditions (Kovacs, 2006), however, this will be discussed further in section 2.3 below.

2.2.5 *Blood lactate*

Blood lactate during tennis match play has been fairly well documented with values between 2 and 4 $mmol \cdot L^{-1}$ reported (Fernandez-Fernandez et al., 2007; Fernandez-Fernandez, Sanz-Rivas, Fernandez-Garcia, & Mendez-Villanueva, 2008; Mendez-Villanueva et al., 2007). This has remained relatively constant in the research over the previous 30 years. The early research suggested that tennis match play elicited slightly lower lactate values of around 2-3 $mmol \cdot L^{-1}$ (Bergeron et al., 1991; Girard & Millet, 2004b; Reilly & Palmer, 1994; Therminarias, Dansou, Chirpaz-Oddou, & Quirino, 1990; Therminarias, Dansou, Chirpaz, Eterradossi, & Favre-Juvin, 1995). Similarly to $\dot{V}O_2$ (in 2.2.3 above), peak lactate concentrations of 10 $mmol \cdot L^{-1}$ have been reported in tennis match play in less trained players (Therminarias et al., 1990). In trained players, peak concentrations of 4-5 $mmol \cdot L^{-1}$ (Christmass, Richmond, Cable, & Hartmann, 1995; Gomes, Coutts, Viveiros, & Aoki, 2011; Therminarias et al., 1995) and up to 8 $mmol \cdot L^{-1}$ in professional players (Mendez-Villanueva et al., 2007).

The influence that the match situation and playing style has on lactate is in a similar situation to the previous parameters discussed of HR and oxygen uptake; there is not agreement in the literature. It has been reported that lactate levels are higher when serving than receiving (Mendez-Villanueva et al., 2007), whereas others have observed no difference between game types (Fernandez-Fernandez et al., 2007; Smekal et al., 2001). What does seem to be in agreement is the fact that lactate levels are higher when playing on a clay surface when compared to hard courts (Girard & Millet, 2004; Murias et al., 2007), possibly due to the increased length of point that is expected when playing on clay (Fernandez-Fernandez et al., 2007; Mendez-Villanueva et al., 2007).

Training protocols which were monitored for physiological profiling demonstrated higher HR than seen in match play (160-180 $beats \cdot min^{-1}$ vs 140-160 $beats \cdot min^{-1}$, respectively), but with lactate values remaining between 2 and 4 $mmol \cdot L^{-1}$ as seen in match play (Reid et al., 2008).

2.2.6 *Match characteristics*

An analysis of elite match play was conducted on a sample of 197 players (102 male & 95 female) at the Australian Open between 2012 and 2014, including details of serve performance, return performance, groundstroke performance and movement characteristics (Reid, Morgan, & Whiteside, 2016), which is important for us to further understand the physical demands of match play. The study reported that both men and women hit, on average, just over 6 serves per game and it was more common for men to hit aces while it was more common for women to hit double faults. The peak and mean serve speeds of males were faster than females, with males more likely to hit an unreturned first serve. These factors likely have an influence on the observation that men win a higher percentage of points off both first and second serves than women.

When considering the return of serve, women play a relatively even split between forehand and backhand, whereas males are more likely to hit a backhand return. In agreement with the unreturned serve statistics, women are more likely to get the return in play on both the first and the second serve than men. Also, women are closer to the baseline when returning the first serve than men, though their contact point is lower, and their returns have a lower net clearance than male returns, possibly due to differences in spin placed on the ball or height of the players (Reid et al., 2016). Both males and females hit an average of 4 to 5 forehands and backhands per game with no difference between the contact height of around 1 m. The men hit their groundstrokes further up the court *i.e.,* closer to, or inside the baseline than women. Men also hit the ball with a higher net clearance and speed compared to women (Reid et al., 2016).

Over the course of a match, men covered more distance than women (2110 ± 839 vs 1232 ± 440 m, respectively). This is expected in a Grand Slam event due to the men playing best of 5 set matches and the women playing best of 3. The distance per set was comparable with men covering 572 ± 152 m and women covering 553 ± 172 m. A key difference was that the average running speed of males was faster than females; 3.68 ± 0.41 vs 3.43 ± 0.48 $m \cdot s^{-1}$, respectively. A commonality between sexes was that a higher distance was covered during points that were won than those that were lost.

The data of Pereira & colleagues (2015) demonstrates the multi-dimensional aspect of tennis with similar amounts of lateral and forward displacement. There will also be a level of vertical displacement as the legs generate power for each shot.

In a 2011 study which profiled the match play of elite male players prior to a Davis Cup match observed that over the course of 4 sets, the number of strokes per rally decreases as the match progresses. This coincided with increased physiological parameters, and therefore is likely to be due to an adjustment in work rate and tactics (Gomes et al., 2011).

2.3 Tennis in Hot Conditions

Tennis Grand Slam tournaments often occur during summer months. This exposes players to extreme environmental conditions, which, in turn, augments the risk of heat related illnesses such as heat exhaustion and heat stroke. Play was suspended during the 2014 Australian Open because ambient temperature exceeded 40 °C. These extremes were also observed at other tournaments with a temperature of 34 °C measured at Wimbledon 2015 and a record high 10 players retiring in the first round of the 2015 US Open in approximately 32 °C and 50% RH.

During tennis, the magnitude of heat stress appears significant; in 34 °C Wet-Bulb-Globe-Temperature (WBGT), core (T_c) and thigh temperatures of 39.4 °C and 37.5 °C, respectively were observed during match-play (Périard et al., 2014b). This is in accordance with previous findings of T_c during tennis in the heat: 38.9 °C in 32 ± 4.5 °C (Hornery, Farrow, Mujika, Young, et al., 2007) and 39.13 °C in ~31 °C WBGT (Tippet et al., 2011).

2.3.1 *Heat stress and performance*

Successful tennis performance requires speed, agility, muscular endurance and aerobic fitness alongside reaction and decision making; all of which are affected by cardiovascular and thermal strain induced by hot, humid conditions (Périard & Bergeron, 2014).

Whether a person becomes hyperthermic (T_c >38.5 ˚C) whilst exercising is dependent on the intensity on the exercise as well as the environmental condition. In humidities up to 50%, the intensity of the exercise is the main effector of body temperature. At a fixed intensity of ~30% $\dot{V}O_2max$ body temperature reached steady state in effective temperatures ranging 27.8 to 44 ˚C; exercise intensity was the primary effector of body temperature. Though when humidities increase above 50% the ambient temperature effects skin temperature, heart rate and skin wettedness which impedes the ability to dissipate heat and therefore also affecting core temperature (Gonzalez et al., 1978).

Tennis is intermittent in nature as described in section 2.1 above with repeated high intensity exercise interspersed with rest. When considering the metabolic response of tennis exercise, it is similar to continuous exercise (*e.g.* running and cycling) of a moderate intensity (Bergeron et al., 1991). The likelihood of someone becoming hyperthermic is thought to be strongly correlated with the exercise-to-rest ratio due to the increased metabolic heat production (Hornery et al., 2007; Périard et al., 2014b; Smekal et al., 2001), and a consistent maximum of 25 seconds of rest (Association of Tennis Professionals, 2020; Grand Slam Board, 2020; International Tennis Federation, 2020; Women's Tennis Association, 2020). The exercise-to-rest ratio is therefore only influenced by the length of the point. If the points become longer the rate of rise in core temperature increases and vice versa in a compensable environment, assuming that the evaporative potential is the same.

2.3.1.1 Aerobic performance

The effect of the heat has more regularly been observed on continuous exercise than intermittent exercise. Of importance within a tennis context is the idea of self-paced exercise. During self-paced cycling, power output decreased as time ensued in comparison to cooler conditions (Périard et al., 2011). A possible reason for this reduction in power is suggested to be the body the reflexively increasing skin blood flow in response to the core to skin temperature gradient becoming smaller, alongside an elevated heart rate (Coyle & González-Alonso, 2001). These two factors are thought to reduce central blood volume decreasing cardiac output. It has been suggested that this physiological response reduces $\dot{V}O_2max$; therefore, if absolute intensity remains the same, the relative intensity will increase (Périard & Racinais, 2015).

Some players core temperature response during temperatures ranging from 14.5 to 43.1 ˚C sees an initial elevation to around 38.5 ˚C then balances out and they manage to maintain an equilibrium. However, some players have been reported core temperatures of >39.4 ˚C (Bergeron, Waller, & Marinik, 2006; Bergeron, McLeod, & Coyle, 2007; Elliott et al., 1985; Hornery et al., 2007; Morante & Brotherhood, 2008; Morante & Brotherhood, 2007; Périard et al., 2014b; Therminarias, Dansou, Chirpaz-Oddou, Gharib, & Quirion, 1991). Of note, this elevated core temperature was associated with both increased physiological and perceptual strain (Périard et al., 2014b) which has been suggested to be a primary factor relating to the ability to maintain performance throughout a tennis match, including shot accuracy and shot speed (Hornery, Farrow, Mujika, & Young, 2007).

In a similar way to the work-to-rest ratio mentioned in section 2.3.1 above, the effective playing time is also considered to be related to thermal strain during tennis match play. Effective playing time is the amount of time that the ball is in play as a percentage of the total elapsed time. It has been observed that during match play in hot conditions the effective playing time was decreased in comparison to match play in cool conditions; along with the suggestion that a key influencing factor on the effective playing time is the thermal sensation (Fernandez et al., 2006; Hornery et al., 2007; Hornery et al., 2007; Torres-Luque et al., 2011). The effective playing time can be reduced in 2 ways; players might deliberately shorten the points through being more aggressive in an attempt to finish the point quickly (Morante & Brotherhood, 2008), or they might choose to take a longer rest between points (Périard et al., 2014b). Indeed, during the latter study, the players self-selected a rest length of 27.6 ± 2.8 seconds; longer than the maximum allowance of 25 seconds.

2.3.1.2 Sprint performance

Single sprint performance, such as peak power output or running sprint time, are thought to be improved by higher muscle temperature through the mechanisms of improved muscle contractility and enhanced conduction velocity (Gray, De Vito, Nimmo, Farina, & Ferguson, 2006; Racinais & Oksa, 2010). The increased temperature can be achieved through a traditional active warm-up, but also through passive heat exposure using heated trousers, blankets or warm-water immersion (Girard, Brocherie, & Bishop, 2015).

Repeated sprint ability (RSA) is a common method of testing tennis players as it is most similar to the intermittent nature of the sport (Fernández-Fernández et al., 2012). Increased thermal strain, through elevated core and skin temperatures, is thought to decrease voluntary muscle activation in large muscle groups and be associated with increased cardiovascular and metabolic loads; this occurs during tennis match play (Girard et al., 2015; Périard, Girard, et al., 2014). There is strong evidence to suggest that RSA declines in hot conditions compared with cooler conditions, when the rest lengths are <60 s which is comparable with tennis rest length of 25 seconds, though these decrements only seem to be apparent when core temperatures are considerably high (*i.e.* >39 ˚C) (Girard et al., 2015). Performance drop-off in RSA with less than 60 seconds of rest include a study using a cycling intermittent sprint protocol which demonstrated a decline in peak power over the course of the 40-minute protocol. In this study, there no was no more of a decline in the temperate group in comparison to the hot dry and hot humid groups, though, increased physiological strain was seen in the hot humid group. Though participants might have self-adjusted their pacing (Hayes, Castle, et al., 2014). Another example following a 40-min intermittent cycling protocol in the heat required participants to complete 5 x 15 s sprints on a cycle ergometer. They observed that peak and mean power in the first sprint was matched with the temperate trial, however, in the final 4 sprints the mean power in the hot group declined to a greater extent than the temperate group (Drust et al., 2005). Intermittent performance is impaired to a greater extent in the heat than in temperate conditions.

Tennis players change direction many times throughout the course of a match and produce forceful muscle action in the lower limbs to achieve the acceleration and deceleration required to do so. The ability to tolerate these impact forces and generate load through the stretch shortening cycle is impaired as matches continue (Girard et al., 2011). Possibly as a consequence of this, technical changes which cause a decline in performance measures such as accuracy and shot speed during long matches, particularly those where the players are closely matched for playing style or ability and this effect is more apparent in hot rather than cool conditions (Hornery, Farrow, Mujika, & Young, 2007). These technical changes are possibly due to players not being able to get to the ball as quickly which can lead to inaccurate stroke preparation and consequently, both reduced passing shot speed and accuracy as described above (Ferrauti, Pluim, et al., 2001).

Squat jump, counter movement jump, and leg stiffness were monitored throughout tennis match play; there was a decrease in all tests at the mid-match point and 24 hours post-match. However, there was no difference in the decline between hot and cool conditions; this was despite the increased level of heat strain observed in the hot conditions (Girard et al., 2014). Though, peripheral fatigue measured through strength in the knee extensors was more severe following tennis match play in the heat. This reduction in the knee extensor and plantar flexor neuromuscular system integrity was still observed 24 hours post-match in the hot condition and was attributed to a central fatigue mechanism (Périard, Girard, et al., 2014). Though, it was also suggested that recovery of the neuromuscular system should have occurred 24 hours after exercise, and the idea that perception of fatigue might cause the reduction in knee extensor strength rather than a physiological mechanism (Kraemer, Piorkowski, et al., 2000).

It appears that hot conditions do not exacerbate performance declines compared to temperate conditions, likely through the reduced effective playing time in the heat due to behavioural thermoregulation. Other research has suggested that increased core temperature, rather than local muscle temperature, might cause the impairment of voluntary muscle activation and maximal voluntary contraction (Thomas et al., 2006). However, there is also research suggesting neuromuscular fatigue might be peripheral in origin due to no change being observed in the reduction of maximal voluntary contraction following a 40-minute intermittent sprint protocol in hot humid conditions, despite a reduction in physiological strain following 2-weeks progressive heat acclimation (Hayes, Willmott, et al., 2014). The mechanisms underpinning the effect of heat on sprint performance and neuromuscular function are unclear.

2.3.2 *Sweat loss and fluid requirements*

Sweat loss during match play in hot conditions can become a problem if not addressed appropriately. The structure of a tennis match does allow for the regular consumption of fluid throughout a tennis match however, one must also consider the electrolyte and salts that are lost during match play and replace these, too. Sodium and chloride losses can still be extensive even, if a player is acclimatised to the heat (Bergeron, 2003; Bergeron, 1996). Methods of intake for salt might be through fluids or food items during match play and post-match play to allow complete rehydration (Bergeron, 2008; Mitchell, Phillips, Mercer, Baylies, & Pizza, 2000; Sanders, Noakes, & Dennis, 1999, 2001; Shirreffs & Maughan, 1998). The rate of salt loss is highly individual and players should undertake testing to estimate how much they need to consume (Bergeron, 1996, 2003, 2007, 2008).

Hydration status and temperature regulation can be negatively affected by an array of factors such as intensity of match play, the environmental conditions, fitness, genetics, acclimation state, and fluid intake; these will in turn affect tennis performance (Karpinski & Rosenbloom, 2017; Kovacs & Baker, 2014). Specifically, in the heat, sweat rate appears to increase concomitantly with environmental temperature and humidity, fitness and acclimation state (Ranchordas et al., 2013).

Sweat rates are expected to be around 1-2.5 $L \cdot hr^{-1}$ during competitive singles tennis match play (Bergeron, 2003), though sweat rates up to 3.5 $L \cdot hr^{-1}$ have been observed during play in very hot conditions (Ranchordas et al., 2013). More recent studies have corroborated with this estimate for tennis match play including sweat rates of 2.04 ± 0.44 and 1.51 ± 0.32 $L \cdot min^{-1}$ for match play on hard and clay courts, respectively (Hornery, Farrow, Mujika, Young, et al., 2007). It is worth noting that the hard-court match play was at a higher temperature than the clay court match play; 32 ± 4.5 ˚C, 38 ± 14% RH vs 25.4 ± 3.8 ˚C, 32 ± 5% RH, respectively. The notion of a relationship between air temperature and sweat rate during tennis match play has been suggested (Morante & Brotherhood, 2007; Ranchordas et al., 2013) and the increased heat stress is likely the cause of an increased sweat rate. Similar values were seen for 2 elite male players in 26-27.5 ˚C and 66-70% RH; a similar temperature to the clay court observations above.

Sweat rates of 1.5 and 1.36 L·hr^{-1} during singles match play; combined with 1970 and 2530 ml of fluid intake, led to a decrease in body mass of 3.5 and 2.6% respectively over the course of 197 minutes (4 sets) (Gomes et al., 2011). Dehydration (and body mass deficit) leads to a higher cardiovascular strain and further elevated core temperatures (Kovacs, 2008).

A crude measure of sweat loss can be achieved through body weight changes, where a reduction in body mass of 1 kg would signify a fluid loss of around 1 L. Performance decrements in aerobic capacity, cognition, mood, balance and readiness might become an issue when a body water deficit of 2% of body mass has been lost (Maughan, 2014).

Sweat loss and body mass deficits have been observed during match play on a number of occasions, some example being: USA Division 1 university standard player over three consecutive days of play (Bergeron et al., 1995); non-acclimatised players performing simulated match play in hot and cool conditions (Périard, Racinais, et al., 2014b, 2014a); professional male tennis players during official competitive matches (Hornery, Farrow, Mujika, Young, et al., 2007); and professional women playing in competitive matches in hot conditions (Tippet et al., 2011). Whilst all of these reported similar fluid losses to those reported above, it was observed that the body mass loss was not as severe as imagined based on the high sweat loss and length of the matches; often around 1%. This suggests that players might be well practised at rehydrating during match play, though this is not in complete agreement with some of the aforementioned observations, likely due to individualisation.

Even if body mass deficits are seemingly insignificant, tennis players should ensure that they incorporate hydrations strategies into practice sessions to become accustomed to the volumes of fluid that need to be consumed in different conditions, particularly in the heat. It is important that they don’t rely on thirst as a mechanism to maintain fluid balance alone and that they consume fluid prior to thirst. Players, especially on the professional tours often competing in hot environments, should prioritise maintaining fluid, mineral and glycogen balance (Kovacs & Baker, 2014).

Whilst fluid intake should be tailored to the individual through sweat analysis and fluid balance testing, there are general guidelines for the amount of fluid that players should be consuming. It has been suggested that players should consume 200 ml every change of ends in temperatures up to 27 ˚C, and 400 ml or more in temperatures above 27 ˚C to assist in maintaining fluid balance (Ranchordas et al., 2013).

2.3.3 *Thermal strain and exertional heat illness during tennis*

During tennis match play and training, a player's core temperature might be expected to progressively increase because of the metabolic heat production and continued heat storage. This is due to the aforementioned repeated nature of tennis and the constant repetition of intense activity interspersed with relatively short rest durations and is exacerbated when playing tennis in hot and or humid conditions, especially when uncompensable (Kraning & Gonzalez, 1991). Players reportedly getting exertional heatstroke either during match play or following a match is rare in all levels of the sport, more commonly reported is heat exhaustion; likely a consequence of long matches and a high intensity leading to deficits in energy availability and total body water leading to fatigue (Armstrong et al., 2007; Bergeron, 2013).

Thermal strain in adult tennis is sometimes considered to be more moderate than junior players (Bergeron, 2019), though with core temperature ranging from 38.5 – 39.4 ˚C in adult professional players, it is clear there are occasions where the heat strain is high. The means tend to be in the region of 38.5-39.0 ˚C and peaks >39.1 ˚C across male and female professional players during tournament match play (Hornery, Farrow, Mujika, Young, et al., 2007; Périard, Racinais, et al., 2014b; Tippet et al., 2011). A key observation from the study by Périard and colleagues (2014a) was that better pre-match hydration status lead to a lower core temperature during the early stages of simulated on-court match play; they achieved this through tailoring water volume and sodium for each individual.

Junior heat strain shows a similar pattern where expectedly, as the conditions become hotter, the level of heat strain also increases. Highly skilled male junior players were monitored whilst undertaking high intensity training drills in a WBGT of ~26.6 ˚C. During this study the participants were split across 2 groups, one only drinking water, and the other a carbohydrate-electrolyte drink. Both groups saw similar core temperatures in these moderate conditions; 38.2 ± 0.3 vs 38.0 ± 0.2˚C, respectively (Bergeron, Waller, & Marinik, 2006). A key observation to come out of this study was that the players who had core body temperatures of around 39 ˚C did not show any visible signs of heat illness because of this heat strain. Another study lead by the same researcher profiled male junior players during competitive match play in both singles and doubles. A higher mean core temperature of 38.7 ± 0.3 ˚C was observed during this study. Though, the environmental conditions were hotter with a mean WBGT of 29.6 ˚C. Interestingly, they reported that doubles can also elicit a high level of thermal strain in similar environmental conditions. All the observed matches were in the first round of the competitions where matches might have been slightly easier as the top seeds play the lower ranked players, suggesting that during the latter rounds, the level of heat strain might further increase (Bergeron, McLeod, & Coyle, 2007).

The literature used to suggest that young people were not as capable as dealing with hot conditions compared with adults, though it is now the consensus of the literature that adolescents are able to maintain cardiovascular capacity and the ability to thermoregulate if they ensure that they are hydrated (Inbar, Morris, Epstein, & Gass, 2004; Rivera-Brown, Rowland, Ramírez-Marrero, Santacana, & Vann, 2006; Rowland, Garrison, & Pober, 2007; Thomas Rowland, Hagenbuch, Pober, & Garrison, 2008). Some of the key issues surrounding the ability of pubertal tennis players to thermoregulate on court might be due to growth. For example, an increased muscle mass leads to a greater amount of metabolic heat production which would impact on heat storage. At the same time, as the sweat glands mature, a greater sweat rate is observed (Falk et al., 1992). Whilst this might counter any increased heat storage due to the changes in muscle mass, it might also lead to greater fluid and sodium losses which in turn could increase cardiovascular strain and decreases in cognitive function. It would seem appropriate to think that this notion of an increased level of strain would continue into adulthood.

2.3.4 *Consecutive same-day or successive-day match play*

A hot environment will undoubtedly make it more difficult for a player to maintain hydration during a tennis match. This places a focus on ensuring rehydration protocols and sodium loss replacement following a match. However, across all levels and ages it is not unusual for players to play more than one round or draw (*i.e.* singles and doubles) per day and also have successive days of competition if they win and progress through the rounds. Some players might find it particularly challenging to replenish body water and sodium deficits (Bergeron, 2003, 2007).

The negative impact of repeated exercise in hot conditions has been reported fairly extensively, affecting both physiological and perceptual strain in any repeated exercise bouts (Bergeron, Laird, Marinik, Brenner, & Waller, 2009; Brenner, Zamecnik, Shek, & Shephard, 1997; Kruk, Szczypaczewska, Opaszowski, Kaciuba-Uściłko, & Nazar, 1990; Ronsen, Haugen, Hallén, & Bahr, 2004; Sawka, Knowlton, & Critz, 1979; Yamada & Golding, 2004). This effect is still apparent if the exerciser were to recover their core body temperature and adequately rehydrate themselves back to resting levels. It is thought that this idea of a repeated bout effect is well known within the playing and coaching tennis community, with a belief that performance will decline in the second and any subsequent exposures, in agreement with the previously mentioned literature. However, it is reported that tournament organisers, referees and directors do not appreciate the impact of this and do not take it into consideration when scheduling tournaments etc. (Bergeron, 2019). This area warrants further research in the future, once the initial effects of the heat are fully understood within competitive tennis match play.

2.3.5 *Heat policies in tennis*

2.3.5.1 Association of Tennis Professionals (ATP)

The ATP has no heat policy in place. The only mention of heat in the rulebook is to state that as players are only allowed one medical time-out per distinct medical condition, multiple manifestations of heat illness will classify as one treatable medical condition; therefore, only one medical time-out would be permitted per match (Association of Tennis Professionals, 2021).

2.3.5.2 Women's Tennis Association (WTA)

The Women's Tennis Association (WTA) have an Extreme Weather Conditions policy stipulating modification of play when the conditions exceed 30.1 °C WBGT or 34 ˚C on the heat index (Figure 2.1). Players are allowed a 10-minute extended break between sets 2 and 3, should one player agree when offered by the umpire. If neither player requests the break, play continues. Players can leave the court to change during this break.

The policy also stipulates suspension of play in conditions of, or greater than 32.2°C WBGT or 40.1 ˚C on the heat index. This heat stress index incorporates air temperature, humidity, wind speed and radiation. Should a measurement of WBGT not be possible, a heat index can be calculated using ambient temperature and relative humidity. Details of this can be seen in Figure 2.1 below (Women's Tennis Association, 2021). The rule book also stipulates that in extreme heat conditions, fans and ice towels must be available for players to reduce body temperature and implement safety precautions.

It is not clear whether this policy applies to both singles and doubles, however the wording for accepting the extended break uses "player" (singular) which would suggest only in singles.

Air Temperature (Celsius/Fahrenheit)											
	21.1° 70°	23.9° 75°	26.7° 80°	29.4° 85°	32.2° 90°	35° 95°	37.8° 100°	40.6° 105°	43.3° 110°	46.1° 115°	48.9° 120°
Relative Humidity	**Apparent Temperature** (combined index of air temperature and relative humidity)										
0%	17.8° 64°	20.6° 69°	22.8° 73°	25.6° 78°	28.3° 83°	30.6° 87°	32.8° 91°	35° 95°	37.2° 99°	39.4° 103°	41.7° 107°
10%	18.3° 65°	21.1° 70°	23.9° 75°	26.7° 80°	29.4° 85°	32.2° 90°	35° 95°	37.8° 100°	40.6° 105°	43.9° 111°	46.7° 116°
20%	18.9° 66°	22.2° 72°	25° 77°	27.8° 82°	30.6° 87°	33.9° 93°	37.2° 99°	40.6° 105°	44.4° 112°	48.9° 120°	54.4° 130°
30%	19.4° 67°	22.8° 73°	25.6° 78°	28.9° 84°	32.2° 90°	35.6° 96°	40.1° 104.2°	45° 113°	50.6° 123°	57.2° 135°	64.4° 148°
40%	20° 68°	23.3° 74°	26.1° 79°	30° 86°	33.9° 93°	38.3° 101°	43.3° 110°	50.6° 123°	58.3° 137°	66.1° 151°	
50%	20.6° 69°	23.9° 75°	27.2° 81°	31.1° 88°	35.6° 96°	41.7° 107°	48.9° 120°	57.2° 135°	65.6° 150°		
60%	21.1° 70°	24.4° 76°	27.8° 82°	32.2° 90°	37.8° 100°	45.6° 114°	55.6° 132°	65° 149°			
70%	21.1° 70°	25° 77°	29.4° 85°	33.9° 93°	41.1° 106°	51.1° 124°	62.2° 144°				
80%	21.7° 71°	25.6° 78°	30° 86°	36.1° 97°	45° 113°	57.8° 136°					
90%	21.7° 71°	26.1° 79°	31.1° 88°	38.9° 102°	50° 122						
Extreme Heat Condition - Modification of Play											
Extreme Heat Condition - Suspension of Play											

Figure 2.1: The WTA (2021) heat policy matrix.

2.3.5.3 *International Tennis Federation (ITF)*

The International Tennis Federation (ITF) implements an Extreme Weather Conditions policy which is the same as the WTA in section 2.3.5.2. This policy is for both males and females competing in singles and doubles.

The ITF also stipulate that if a match has resumed following a suspension of play and one set has already been completed (in a best of 3 set match), the 10-min break will not be available, unless otherwise decided by the ITF supervisor (International Tennis Federation, 2021).

2.3.5.4 *Grand Slam Board*

There is no official heat policy in the rules for the Grand Slam tournaments (Grand Slam Board, 2021), however, the individual tournaments are allowed to govern a heat policy themselves, though these are not in official rulebooks and are unpublished. These will be detailed in the next four sections.

2.3.5.5 *Australian Open*

The Australian Open developed a new heat policy for the 2019 tournament with researchers from the Thermal Ergonomics Laboratory at the University of Sydney: The AO Heat Stress Scale (*Policies | Australian Open*, n.d.). This is a scale of 1-5 ranging from temperate playing conditions (1) to suspension of play (5), the graphic for the scale can be seen in Figure 1.1. The scale allows a 10-min extended break for women and juniors singles matches between the second and third sets, and a 15-min extended break for wheelchair singles players at level 4 on the scale. Men's singles players are allowed a 10-min break between the third and fourth sets.

The Australian Open have not published this policy or given the detail behind the rating system. However, it reportedly *"accounts for physiological variances between adults, wheelchair and junior athletes while also taking in account the four climate factors – air temperature, radiant heat or the strength of the sun, humidity and wind speed – which affect a player's ability to disperse heat from their body"* (*Australian Open Launches New Extreme Heat Policy*, n.d.).

2.3.5.6 Roland Garros

A heat policy has never been implemented at Roland Garros.

2.3.5.7 Wimbledon

Wimbledon implements a heat rule which allows all singles events (gentlemen's, ladies', juniors, wheelchair and qualifying) a 10-min extended break between the second and third set for best-of-three set matches, or between the third and fourth sets in a best-of-five set match when the heat stress index is ⩾30.1 ˚C WBGT (*Heat Rule - The Championships, Wimbledon 2020,* n.d.). However, the heat rule only applies for matches that have not yet been called to court.

2.3.5.8 US Open

The US Open implemented an extreme heat policy in 2018 for women's, men's and boys' and girls' singles matches (*US Open Implements Extreme Heat Policy*, n.d.). The extended break was allowed in line with Wimbledon in the previous section and the threshold for implementing this policy is 86.2 ˚F / 30.1 ˚C. This policy was initially on a case-by-case basis, though when it was implemented again in 2019, it was said that it will continue into future years. In 2019, the tournament also added air-conditioned cooling-off rooms, and electric fans in addition to the ice towels that players already used (*How the US Open Plans to Manage Oppressive Heat*, n.d.).

2.4 Strategies to Reduce Heat Strain in Tennis

There are numerous strategies which have the potential to reduce heat strain for tennis, these include autonomic behavioural responses and planned interventions focussed on one or more elements of thermal balance. Cooling methods with evidence for efficacy include external cooling through water immersion (Kay et al., 1999), ice packs (Castle et al., 2006), cold air exposure (Mitchell et al., 2003), external fans with/without a water spray (Lynch et al., 2018), ice vests (Duffield, Dawson, Bishop, Fitzsimons, & Lawrence, 2003), and internal cooling via ice slurry ingestion (Siegel et al., 2010). Players should be responsible for doing everything possible to prepare themselves for exercise in hot conditions, using some of the methods detailed above (Périard, Racinais, & Sawka, 2015; Périard et al., 2014a, 2016; Racinais et al., 2015).

However, tournaments must expect that as the conditions become hotter and/or more humid there will be a rise in the number of heat related incidences occurring (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018). These must be dealt with quickly and efficiently to ensure the safety of the players. Tournament officials must also consider the scheduling and make necessary changes according to the conditions.

Bergeron, (2019) details some factors to be considered which increase the risk of heat illness, and some current preventative measures that can be taken by both players and tournament officials. The risk factors are: a hot/humid climate with no or very little breeze and cloud cover; travelling players who are unlikely to be acclimatised to the environment; extensive competition or practice immediately prior to an event; those who inherently sweat considerably; long matches; multiple matches on the same day with significant increase in risk from match two onwards; and playing on a court with little or no shade. Bergeron (2019) also suggested a range of preventative measures to counter the deleterious effects of playing in hot conditions. For the players these are: ensuring adequate water and sodium intake pre-, during and post-match based on 120% of individualised on-court sweat losses; minimising the duration of warm up time and reducing needless heat exposure; and to consider the use of on-court and between match cooling strategies. The preventative measures that would be the responsibility of administrators or organisers are closely monitoring the players for signs and symptoms of heat illness, allowing adequate rest and recovery in between same-day matches, and having easily accessible and readily available personnel and facilities on-site for the treatment of heat illness. These risk factors and prevention measures are in addition to the responsibility of the player and the coach to ensure that the player is fully prepared and capable of playing in hot conditions.

This section will look at countermeasures in more detail, particularly heat alleviation strategies to be used during tennis match play in the heat.

2.4.1 *Fluid and sodium intake recommendations during match-play*

As previously mentioned, fluid intake should be tailored to the individual through sweat analysis and fluid balance testing. However, the general guidelines for the amount of fluid that players should be consuming are that players should consume 200 ml every change of ends in temperatures up to 27 ˚C, and 400 ml or more in temperatures above 27 ˚C to assist in maintaining fluid balance (Ranchordas et al., 2013). To encourage the players to consume the correct amount, the fluids should be appealing to them. This will hopefully lead to the adequate amount of consumption during each change of ends (Bergeron et al., 1995; Bergeron, Waller, & Marinik, 2006; Bergeron, 1996, 2003, 2014; Bergeron, McLeod, & Coyle, 2007). It is important that the players do not only drink to thirst if they want to sufficiently maintain levels of hydration and prevent any detrimental effects on tennis performance, as it might not always be enough; this is particularly apparent for any players who have a high sweating rate (Armstrong et al., 2016). Fluid consumption combined with sodium intake might lead to maintaining hydration status during match play more adequately, especially in players who sweat extensively or have a high concentration of sodium in the sweat or older junior and adult players (Bergeron et al., 1995; Bergeron, 1996, 2003, 2008). Though, a number of previous studies have observed that water alone may be just as effective at minimising a body mass deficit through fluid loss as a water and salt, or a carbohydrate-electrolyte drink. This was reported in young girls undertaking intermittent exercise in hot conditions (Wilk et al., 2007) and in junior tennis players with a high level of fitness completing on-court tennis drills in a hot environment (Bergeron et al., 2006). These observations were in contrast to a couple of studies who found salt intake alongside water was more beneficial for junior non-tennis players (Rivera-Brown et al., 1999; Wilk & Bar-Or, 1996). The important message is that at least water must be consumed and if possible, tailoring salt intake to each individual's sodium losses might lead to an increased ability to maintain hydration.

2.4.2 *Behavioural thermoregulation*

As well as the homeostatic methods of autonomic thermoregulation, including increased skin blood flow, onset of sweat response and increased sweat rate, in order to dissipate heat into the surrounding environment, players are considered to subconsciously attempt to ameliorate the effects of hyperthermia behaviourally, manifesting in greater spontaneous-chosen rest-periods between points (Hornery, Farrow, Mujika, Young, et al., 2007; Périard, Racinais, et al., 2014b) and playing more aggressively in an attempt to shorten point duration (Morante & Brotherhood, 2008b). These phenomena, whereby athletes voluntarily control exercise work rate in the heat in an attempt to attenuate a rise in T_c, is known as behavioural thermoregulation. The primary determinant of voluntary changes in work rate appears to be the Rate of Perceived Exertion (RPE), although this is is suggested to have a complex interaction with thermal perception, cardiovascular strain, ambient temperature, skin temperature and core temperature. This model can be found in Flouris & Schlader, (2015).

The longer rest periods taken when behaviourally thermoregulating, might be instrumental in attenuating fatigue during tennis match play in the heat; no differences were observed between mid-match and post-match repeated-sprint ability, leg stiffness and explosive power during tennis match play in hot and ambient conditions (Girard et al. 2014; Periard et al. 2014). This protocol did not have a control trial in the heat so it cannot be confirmed what effect the heat would have had on players if they had adhered to the ITF regulation of a 20 s between-point rest period. However, tennis performance (accuracy and skill) has been reported to decrease as an on-court protocol in 16.3°C 57.7% RH progressed (Davey, Thorpe, & Williams, 2002). Playing in hot, humid conditions would likely exacerbate this fatigue, as seen in other sports (Nassis et al., 2015).

2.4.3 *Heat alleviation strategies*

The drivers controlling self-selected exercise intensity in the heat are disputed. These include body heat storage (Tucker et al., 2006), core temperature (Nielsen et al., 1993), skin temperature and cardiovascular strain (Périard et al., 2011), perceptual drivers of thermal sensation and thermal comfort (Flouris & Schlader, 2015) and perceived exertion (Tucker, 2009). It is likely that a complex interaction between all of these elements actually drives performance, possibly also including brain temperature (Nybo et al., 2002). Acute and chronic heat alleviation strategies target one or more of these areas to improve safety or performance.

2.4.3.1 Chronic strategies

Chronic heat alleviation of heat acclimation or acclimatisation will likely have the highest impact on the player due to the many thermoregulatory, perceptual and performance physiology adaptations that occur following the repeated heat exposure through heat acclimation, as seen in Figure 2.2. This should be the first strategy utilised by players prior to competing in the heat. A good starting point for players is to acclimate as part of their pre-season training and then top up throughout the course of the season if necessary (Application of Evidence-Based Recommendations for Heat Acclimation:

Individual and Team Sport Perspectives, 2019). This can be achieved through 4-6 acclimation sessions or incorporating extra clothing or sweat restrictive measures (Willmott et al., 2018) into their skill training followed by passive heat exposure through hot baths or similar (Gibson et al., 2019; Ruddock et al., 2016; Zurawlew, 2018; Zurawlew et al., 2016, 2018). As few as four heat acclimation sessions over a ten-day period saw improvements in distance covered during the Loughborough intermittent shuttle test (LIST) and a reduction in core temperature compared to training and control groups. Pre- to post-training distances for the LIST were 7703 (1401) and 10215 (1313) m, 8723 (1313) and 8632 (1131) m, and 7359 (681) and 6837 (800) m for the acclimation, training and controls groups, respectively (Sunderland et al., 2008). This coincided with a decrease in core temperature throughout the trial. On the tennis court, this would likely allow players to maintain performance over the course of longer matches or maintain a higher intensity during matches in the heat. Acute strategies are suggested to supplement chronic strategies such as heat acclimation (Gibson et al., 2019), but also play their own role in alleviating heat strain. This thesis focusses on acute strategies therefore, heat acclimation and other chronic strategies will not be considered further.

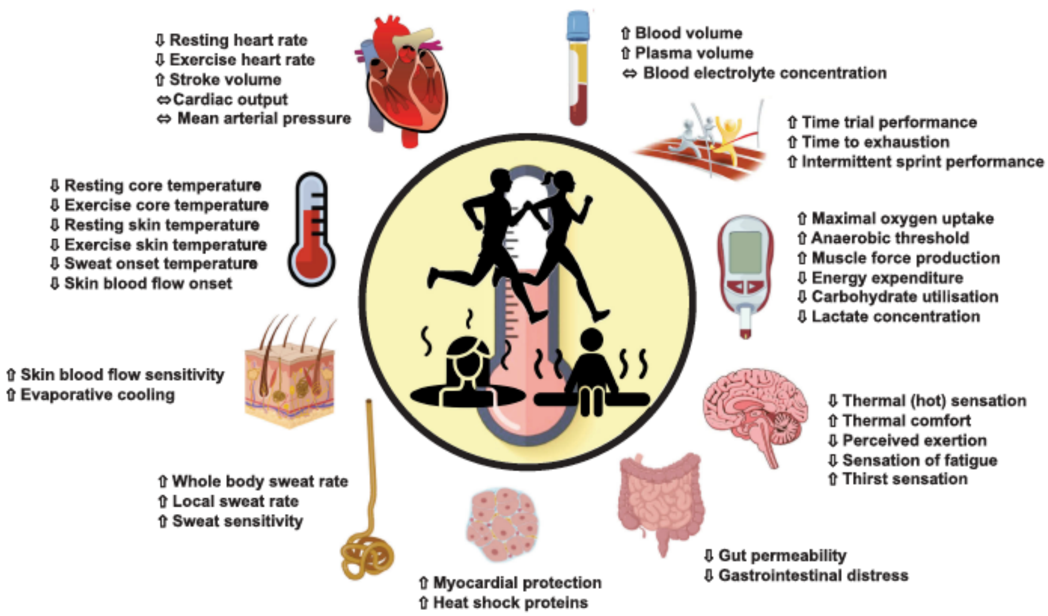

Figure 2.2: Summary of adaptations to thermoregulatory and performance physiology following exercise heat acclimation. Extracted, with permission, from Gibson et al., (2019)

2.4.3.2 Acute strategies

Acute strategies must target two key elements: a reduction in body temperature or enhancing heat loss, and decreasing the perception of the heat (Tyler, Sunderland, et al., 2015). Cooling is the most popular acute strategy with two methods of delivery: internal and external, though there are also some strategies which allow increased heat dissipation without actively cooling. Both cooling delivery methods aim to reduce the body temperature; with the external methods additionally affecting heat perception through peripheral thermoreceptors and the internal methods affecting perception through internal or central thermoreceptors. The different mechanisms of these approaches mean that combing the two approaches is likely to have an additive effect. The important factors that affect a strategy's efficacy are the temperature, the duration of use and the surface area coverage (Ruddock et al., 2017; Tyler, Sunderland, et al., 2015).

External strategies of cooling, such as ice towels, lead to a greater reduction in thermal discomfort (Best et al., 2018; Bongers et al., 2015). Strategies previously shown to negate the physiological and/or perceptual effect of the heat (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017) and ensure the safety of the players during tennis match play reduced core temperature and physiological strain, as well as likely enhancing performance capabilities likely through the perceptual improvements.

A review in 2016 considered factors including timing, feasibility of strategies based on the sport constraints *e.g.,* 90 s changeover breaks in tennis, equipment used, and cooling potential to suggest cooling strategies for a range of sports (W. M. Adams et al., 2016). For tennis, the recommendations were split into pre-match, mid-match, and post-match. As this thesis' focus is during match play, the pre- and post-match strategies will not be considered further. Hydration through cool drinks (15-21 ˚C) was the only optimal cooling modality with scientific evidence to support its use. Feasible modalities without any scientific basis for improving performance were ice towels, ice bags, cooling garments and slushy drinks (W. M. Adams et al., 2016). Several strategies were considered not feasible for tennis or the duration of the breaks: cold-water immersion, water dousing, misting fan, head cooling, hand cooling and an ice vest. Some of which have now been reported to be effective cooling strategies.

The current guidance for implementing acute heat alleviation strategies is that practitioners should have a "toolbox" of methods available in order to tailor to the individual needs (Gibson et al., 2019). A range of strategies will be considered further below.

2.4.3.3 Internal cooling

2.4.3.3.1 Cold drinks and ice slurry

Ingesting cold drinks or ice slurry before or during exercise can lead to reductions in core temperature. Ingestion pre-exercise lowers the starting core temperature (Ihsan et al., 2010; Snipe & Costa, 2018; Stanley et al., 2010; Zimmermann et al., 2017) and can decrease the rate at which core temperature increases following the onset of exercise (Hasegawa et al., 2006; Lee, Shirreffs, et al., 2008; Mündel et al., 2006). This reduction in rate and initial core temperature is due to the ingested bolus warming to reach equilibrium with the internal body temperature. The change in core temperature is dependent on the specific heat capacities of water and ice: 4.2 and 2.1 $kJ{\cdot}kg^{-1}{\cdot}°C^{-1}$, respectively, and the volume or mass ingested. Ice slurry reduces core temperature induces further heat transfer due to the enthalpy of fusion (334 $kJ{\cdot}kg^{-1}$) required for the state change of solid to liquid (Jay & Morris, 2018).

However, this internal cooling effect reduces the sudomotor response to exercise, either delaying the onset of sweat or decreasing the sweat rate decreasing the evaporative potential; a strong negative correlation is evident (Jay & Morris, 2018). Sweat evaporation is the most effective method of dissipation with a latent heat of vaporisation of 2430 $J{\cdot}g^{-1}$ (Parsons, 2014), therefore this reduction in evaporative potential is considered to be the cause of similar levels of heat gain when exercising at a fixed heat production intensity with and without internal cooling (Jay & Morris, 2018) or greater heat storage (Morris et al., 2016; Zimmermann et al., 2017). However, the true effectiveness of internal cooling is dependent on the environmental conditions, specifically the humidity, as this will affect the evaporative potential of sweat into the air. If the humidity is at a level that the evaporative efficiency does not meet the evaporative potential, then internal cooling will lead to a net heat loss. This level of humidity depends on the ambient temperature, the mode of exercise, which influences the airflow across the skin (*e.g.,* running *vs.* cycling) and the speed or intensity of the exercise, which influences metabolic heat production. Though tennis players move around the court, it a fairly small area and the airflow over the skin will be significantly lower than, for example, cycling; therefore, this threshold for a net cooling effect will be in drier and cooler conditions. This threshold would be further lowered if the players are competing at a high intensity, therefore a high metabolic heat production (Jay & Morris, 2018).

Another potential issue with ice slurry ingestion is the decreased body temperature reduces the gut permeability (Pires et al., 2017). This may have implications on gastrointestinal distress though this has been reported to not have an effect on systemic inflammatory cytokines, though the design of the study might have influenced these results due to the control trial water temperature not being thermoneutral (Snipe & Costa, 2018). Though, gastrointestinal distress has been reported in one other study (Ross et al., 2011). In addition, ice slurry ingestion may cause sphenopalatine ganglioneuralgia (brain freeze), though this side effect is reported to wear off quickly and it has been reported fewer times (Siegel et al., 2010, 2012) than not (Burdon et al., 2010; Ihsan et al., 2010; Ross et al., 2011; Stanley et al., 2010).

Irrespective of the core temperature net cooling effect, ice slurry consumption has a large effect on thermal comfort of athletes. Albeit a larger reduction in core temperature from cold-water immersion, ice slurry ingestion elicited a similar decrease in thermal comfort (Siegel et al., 2012). This apparent increased reduction in thermal comfort is thought to have positive effects on endurance performance in the heat (Stevens et al., 2018) and might also have a positive effect on decision-making and cognition. A potential mechanism for this is a reduction in brain temperature (Onitsuka et al., 2018) through the proximity of the mouth and oesophagus to the carotid arteries (Mariak et al., 1999) as deep brain temperature is thought to be slightly higher than that of the arterial blood and cerebral blood flow can transfer heat away from the brain (Sukstanskii & Yablonskiy, 2007).

The strategy is suggested for use within team sports, which have a similar intermittent nature to tennis match play, (Taylor et al., 2020) during the Tokyo 2020 Olympics. One previous study has investigated the effect of ice slurry ingestion on thermoregulatory and perceptual measure during a tennis specific lab protocol. Ice slurry ingestion reduced core temperature in the final third, and thermal comfort and forehead skin temperature in the second half of the protocol in comparison to a cold-water (4˚C) control (Naito et al., 2018). This result is extremely promising due to the comparison to a cold-water control rather than a thermoneutral, potentially underrepresenting the benefits of ice slurry for mitigating heat strain during tennis match play.

2.4.3.4 External cooling

2.4.3.4.1 Ice towels

Neck cooling, similar to the use of an ice towel around the neck has been evidenced to be effective in both endurance and intermittent exercise. It is possible that a threshold for thermal comfort may exist before a neck cooling method might be effective; distance covered in a 15-minute time trial in the heat was significantly more following a 75-minute pre-load when neck cooling but, no difference was observed when completing the time trial with no pre-load in the heat (Tyler et al., 2010). The study saw no reduction in rectal temperature, heart rate or RPE therefore, this effect was attributed to the improved thermal comfort. This conclusion was supported by a following study which reported a

13.5 ± 3.8% increase in the time to exhaustion in the heat. Participants ceased exercise at identical levels of perceptual scales (RPE, TS and FS), with higher rectal temperatures and heart rates (Tyler & Sunderland, 2011a). This relationship supports the use of such a cooling intervention for increased sports performance, however, it is not effective at reducing core temperature where heat illness is a potential issue.

Neck cooling can also have a marked improvement on repeated sprint performance in the heat. Repeated sprints were performed before, halfway and after a football specific treadmill protocol replicating a 90-minute football match in the heat. Peak power and mean power were significantly higher in the post-protocol sprints for the neck cooling trial compared to no neck cooling. In this trial there were no physiological differences between conditions and differing from the previous studies, there was no reduction in thermal sensation. Rather, a localised cooling effect was observed with a lowered neck skin temperature and neck thermal sensation and RPE was lower throughout the football protocol whilst wearing the collar, too (Sunderland et al., 2015). Neck cooling with an ice bag also increased the accuracy of young national table tennis players when used for one minute prior to the replication of 3 'games' of table tennis in temperate conditions. Showing promise for application to tennis performance (Desai & Bottoms, 2017).

Recent research reported the ice towel method is the preferred method of choice on the tennis tour. Through communication with a WTA representative, players are advised to have an ice towel around the neck simultaneously with cold wet towels on the head and the lap (Lynch et al., 2018; Schranner et al., 2017). The ice towel strategy has efficacy in both hot humid conditions and hot dry conditions along with the newly suggested strategy of using a damp sponge to wet the skin and the use of a fan (FAN_{wet}) (Lynch et al., 2018; Schranner et al., 2017). Both interventions lead to reductions in rectal temperature (T_{re}), heart rate (HR) and thermal sensation (TS) compared against cold-water (10˚C) as their control condition.

2.4.3.4.2 Ice vest

Ice vests are external cooling garments, jackets or vests which aid cooling through conduction. They vary in make-up but tend to have pockets of gel or water which can be frozen or cooled prior to use. An example of a vest can be seen in Figure 2.3 below and a tennis player using one during practice at the US Open in Figure 2.4 below.

The construction of an ice vest being made of pouches of cooling sections allows them to be flexible and wearable pre-, during or post-exercise depending on the mode. However, this means that a higher proportion of the body is covered (~25%) than is being actively cooled (5-10%) (Cuttell et al., 2016; Luomala et al., 2012). Though a large proportion of the area covered is not being actively cooled which might affect the evaporative potential of the person, wearing an ice vest lowers thermoregulatory strain and allows participants to feel more comfortable (Arngrímsson et al., 2004; Webster et al., 2005). No effect on rectal temperature after using an ice vest for 40 minutes of pre-cooling in hot and humid conditions (34.3 ± 1.1 ˚C; 41.2 ± 3.0% rh); no change in cycling time trial was evident either compared with control (-16 ± 36 s, -0.7%, $P = 0.35$) (Quod et al., 2008). An ice vest as part of aggressive pre-cooling method combining cold towels, forearm immersion, ice vest and cooling shorts led to a significantly faster running speed at both 2 and 4 $mmol \cdot L^{-1}$. Though, no difference was observed in running economy or $\dot{V}O_2max$ (James et al., 2015).

Figure 2.3: An example of ice vest

Ice vests were better than ice slushy for half time cooling during a team-sport simulated intermittent protocol (Brade et al., 2014). Ice vest use with cold towels on the head and lap, similar to the ice towel approach used by Schranner et al. (2017) and Lynch et al. (2018), implemented as pre-cooling before an on-court tennis conditioning session showed a moderate-large effect ($d = 0.7$-1.0; $P > 0.05$) on total an high intensity distance covered whilst significantly lowering thermal sensation (Duffield et al., 2011). A 60-minutes ice vest pre-cool and 15-minute half-time pre-cool during a 90-minute soccer specific protocol in the heat led to a reduced initial muscle temperature, a lower core temperature to the end of the protocol, higher self-selected running speeds in a performance test and an improved level of mental concentration (Clarke et al., 2011). Similar results were seen in another soccer specific protocol with both the 20-minute pre-cooling trial and the 20-minute pre-cool and 15-minute mid-cool trials, though the pre- and mid-cool trial elicited longer lasting reductions in thermal strain (Price et al., 2009).

Further supporting evidence reported higher mean power output during the second half of a cycling intermittent sprint protocol following the use of an ice vest for 15 minutes at half time. There was no change in rectal temperature but, thermal sensation, comfort and RPE were significantly lower during the second half compared with no ice vest at half time (Chaen et al., 2019).

When worn continuously throughout a soccer-specific trial lasting 90 minutes in hot and humid conditions, an ice vest slowed the rate of rectal temperature increase, skin temperature, RPE and thermal sensation in the second 45 minutes, though no change was seen in the performance variable of peak sprint speed (Parris & Tyler, 2018). Though, rules and regulations may prevent the wearing of an ice vest during some sports or competitions. Another factor to consider is the added weight of the vest, reported to be 0.5-4.5 kg (Arngrímsson et al., 2004; Eijsvogels et al., 2014). An increased load causes a concomitant increase in the energy cost of running and walking and significantly decrease the distance completed in a 12-minute running test (Cureton et al., 1978). Therefore, it is reasonable to presume there would be a similar increase in the energy cost of tennis match play which would likely outweigh any benefit of wearing the ice vest continuously; though, this has not been directly assessed. Another consideration for use during tennis match play is the time it takes to get a vest on and off at each change of ends, likely filling much of the break and making it impractical.

Figure 2.4: A tennis player wearing an ice vest during training at the US Open

2.4.3.4.3 Fans

Airflow is often neglected or lower than would exist during competition when undertaking research (Junge et al., 2016) which would reduce the cooling effect of the environment (S. A. Morrison et al., 2014; Saunders et al., 2005). This may lead to misleading research conclusions that suggest cooling strategies are beneficial when they might not have an additive effect on the airflow which would already be apparent during competition (S. A. Morrison et al., 2014).

Increasing airflow increases the convective and evaporative heat loss, through enhanced evaporative potential leading to reductions in physiological strain of core temperature, skin temperature, heart rate and sweat rate (W. C. Adams et al., 1992; Mora-Rodríguez et al., 2007; Otani et al., 2017; Schranner et al., 2017). Dependent on wind or airflow speed, this is more likely to have a positive effect in a mildly humid environment rather than a dry environment where the sweat evaporation efficiency is high. Increasing airflow with a fan during the change of end breaks during a tennis-specific intermittent protocol in 45 ˚C 10% rh led to a similar rise in core temperature compared to a control condition (Lynch et al., 2018); though it was found beneficial in hot and humid conditions using the same protocol with participants exercising for longer before exhaustion (Schranner et al., 2017). Increasing airflow also reduces RPE and thermal sensation during exercise in the heat (S. A. Morrison et al., 2014; Otani et al., 2017; Schranner et al., 2017).

2.4.3.4.4 Water spray and fan

Water spray is often applied to the face area or head. A study which compared the effect of CWI and water spray against a control of no cooling reported faster 5 km times in the heat for both cooling methods in trained male runners. The procedure was 3 water sprays (22 ˚C) per kilometre during the time trial; 15 sprays in total. This would have been around every 4-5 minutes (Stevens et al., 2017). Runners had a 50 cm fan placed 1 m in front of them set at 4 $m \cdot s^{-1}$ which simulated the airflow of outdoor running (Saunders et al., 2005). The spray lowered forehead skin temperature and thermal sensation but had no effect on core temperature (Stevens et al., 2017).

A similar method of combining a water spray with a fan was used to pre-cool participants for 20 minutes prior to a run to exhaustion at maximal aerobic power in 38 ˚C, 40% rh (Mitchell et al., 2003). Participants wore only shorts, socks and shoes, and stood in front of a large industrial fan set to 4 $m \cdot s^{-1}$ whilst having 100 ml of water sprayed as a fine mist every 2 minutes which covered the whole skin surface area. They rotated 180˚ to ensure full body cooling. Oesophageal temperature was significantly reduced prior to exercise compared with control and the pre-cooling trial had a reduced rate of heat gain whilst exercising. Though, time to exhaustion was lower with pre-cooling than without; this might have been due to lowered cardiorespiratory function or a reduced $\dot{V}O_2max$ being associated with lowered oesophageal temperatures (Bergh & Ekblom, 1979). This combined with the intensity of exercise being at maximal aerobic power might explain this reduction (Mitchell et al., 2003).

The combination of a fan with a water spray is as effective as ice towels (ice towel around neck and cold damp towels on head and lap) at slowing the rise in core temperature and reducing thermal sensation during a tennis treadmill protocol in both hot dry and hot humid conditions (Lynch et al., 2018; Schranner et al., 2017). This intervention was implemented at every change of ends break using a 45 cm fan at a speed of 6.4 $m \cdot s^{-1}$, placed 1.5 m in front of the participants. Rather than a spray, participants moistened their face, neck, arms and thighs with a damp sponge; this would be a similar wetting effect on the skin as a spray.

2.4.3.4.5 Cold-water immersion

Cold-water immersion (CWI) is generally used as a pre-cooling or post-cooling rather than a mid-cooling technique, likely due to the practicalities of the method. The body can be fully or partially immersed in water ranging from 2-26 ˚C. Heat is dissipated directly into the water and the maintenance of blood flow from the core to the periphery and back again will maintain heat dissipation. If the water is too cold, vasoconstriction will lead to less blood flow in the periphery which will slow the rate of heat loss. Due to this, it has been suggested that warmer temperatures are as effective at reducing core temperature as cooler temperatures (26 *vs.* 14 ˚C) (Caldwell et al., 2018). The benefits of using warmer water are that the person would still see an improved thermal comfort but without the coldness feeling unpleasant (Tyler, Reeve, et al., 2015). Another way to increase comfort for the participant is to immerse less of the body (Sendowski et al., 1997).

CWI reduces the physiological thermal and perceptual strain in both distance and intermittent exercise (Goosey-Tolfrey et al., 2008; Marsh & Sleivert, 1999; Stevens et al., 2017). It also causes a reduction in muscle temperature leading to reductions in maximal power, force and velocity, therefore, it is important that the active muscles are not cooled to avoid any negative effects on performance (Racinais et al., 2009).

CWI is effective at reducing core temperature (Ross et al., 2013) which might be vital if players are close to thresholds of heat illness. However, CWI can decrease nerve conduction and muscle contraction velocities (Racinais & Oksa, 2010) which, from a playing perspective, might mean players see a drop off in performance until the muscles rewarm. When CWI was implemented for 15 minutes intermittently (1 min in, 2 min out) at various temperatures (10, 15 and 20 ˚C) or continuously at 20 ˚C between two 30-minute bouts of cycling, the total work done in the second bout was not different to the first bout; total work was significantly reduced following active recovery alone. Following the mid-break cooling, physiological and perceptual thermal strain were also significantly lower (Vaile et al., 2008). Cold water immersion was deemed to be effective at reducing core temperature in athletes with exercise induced hyperthermia. When core temperature started at >38.6 ˚C and both torso and limbs were immersed, a rate of 0.08 $˚C·min^{-1}$, the authors also considered CWI to be most effective when used for 10 min or less (Y. Zhang et al., 2015). This data suggests that CWI might be beneficial during tennis match play, particularly during the 10-minute extended break when this is offered due to the environmental conditions; core temperature could be reduced by up to 0.8 ˚C in this period.

2.4.3.4.6 Water pouring

Some research suggests that water dousing in a single dose might not be effective at reducing physiological markers such as core temperature (W. M. Adams et al., 2016). However, other data presented at a conference, suggests that water dousing 4 times throughout a sport-specific intermittent treadmill protocol in 33 ˚C and 50% rh might delay the rise in rectal temperature, decrease heart rate and improve repeated sprint performance in comparison to no dousing whilst both euhydrated and dehydrated (Benjamin et al., 2020). Used for a longer duration, cold-water poured continuously, such as a shower or a hose for 60 minutes as a pre-cooling method reduced core temperature by 0.3 ˚C, though this increased to 0.6 ˚C after a further 15 minutes of rest prior to exercise commencement (Drust et al., 2000). However, it has the potential to enhance evaporative heat loss during hot, dry conditions, whilst during hot humid conditions it might offer short term comfort but lead to clothes becoming sodden (Morris & Jay, 2016). Dousing might have a significant physiological benefit (Benjamin et al., 2020) and it is likely to have a perceptual benefit (Morris & Jay, 2016). Further enhancements in heat dissipation would be expected if used alongside increasing airflow with a fan; dousing might be similar to wetting the skin with a sponge (Lynch et al., 2018; Schranner et al., 2017). Though, during tennis match play it is likely that players would not like the feeling of being drenched and the added weight of the water might also increase the exercise demand (Cureton et al., 1978), though there is no evidence for this and the additional weight might have a negligible effect, if any, on performance.

2.4.3.5 Combining external and internal cooling

An approach combining various methods of cooling is considered to be superior to each individually (Gibson et al., 2019). The environment or sport-specific rules, regulations and time-constraints will often dictate the approach to acute cooling. An example of combined cooling for a racquet-based sport could be cold-water immersion or ice slurry ingestion prior to going on court, a warmup wearing an ice vest and neck cooling collar (if this does not inhibit movement) prior to preparing for competition. Depending on the location and the available facilities, it is likely that an ice slurry might be a more practical solution; this would mean a combined internal and external cooling approach.

There is little research into the combined effects of internal and external cooling on physiology and performance. Ross et al. (2011) compared external pre-cooling of 10-min CWI followed by a cooling jacket for 20-min to a combined approach of ice slurry (14 $g \cdot kg^{-1}$) whilst also applying ice towels; both compared to a control of cold-water. The external cooling only reduced core temperature more than combined cooling, which itself reduced core temperature more than the control. The combined cooling led to an increase in power and a reduction in completion time of a cycling time trial in hot and humid conditions. The effect of the combined approach was considered to range from trivial to large whilst the external only effect was unclear. A combined pre-cooling approach (ice slushy and cooling jacket) was also investigated prior to a simulated team-sport circuit in hot and dry conditions (Brade et al., 2014). The protocol involved four 20-min quarters with 5-min quarter breaks and a 10-min half-time break. Following pre-cooling, core temperature was reduced, though the completion time for the first quarter was slower; no differences were apparent for the remainder of the protocol. Finally, a combined pre-cooling approach when combined with an internal per-cooling strategy led to lower thermal comfort and increased mean power output during a 60-min cycle at a fixed intensity (RPE = 14), though no difference in mean core temperature was observed. (Schulze et al., 2015).

Simultaneous internal and external cooling is not conclusively beneficial when used as a pre-cooling intervention. Schulze et al. (2015) suggested that performance in the heat be affected as much by thermal comfort as it is thermal state. Therefore, any per-cooling intervention investigated should maximise both of these elements.

2.4.3.6 Alternative heat alleviation strategies

2.4.3.6.1 Increased between-point rest

Periard et al. (2014) observed players taking a mean of 9.6 s longer between-point rest length with 27.6 ± 2.8 s rest when playing in hot conditions (36.8 ± 1.5˚C 36.1 ± 11.3% RH) compared with 18.0 ± 4.2 s in temperate conditions (21.8 ± 0.1˚C 72.3 ± 3.2% RH) when allowed to self-select their rest periods. The rest length chosen by the players in this study is longer than the updated Grand Slam rules (Grand Slam Board, 2020) which are now in line with the other ruling bodies (Association of Tennis Professionals, 2020; International Tennis Federation, 2020; Women's Tennis Association, 2020). With the recent introduction of the shot clock, umpires are being stricter with issuing time violations when players go over this limit. Choosing to take a longer rest between points in an example of behaviourally attempting to thermoregulate as players feel too hot and has also been observed by others (Hornery, Farrow, Mujika, Young, et al., 2007; Morante & Brotherhood, 2008b). Restarting play before players feel ready will likely have implications for performance; it might lead to other thermoregulatory behaviours previously observed in tennis such as attempting to shorten points by hitting the ball harder with the hope it is unreturned (Morante & Brotherhood, 2008b).

2.4.3.6.2 Extended break

There is little research on the use of an extended break within tennis, however various studies have evidenced either the physiological and/or perceptual benefit of cooling during a half time break within intermittent sports which might present a similar situation (Chaen et al., 2019; Chalmers et al., 2019; Duffield et al., 2003; Price et al., 2009; Soo et al., 2019). An extended break (10-minute) reduced core temperatures by 0.25 ± 0.20 ˚C during match play in the heat as part of a sanctioned WTA tournament (Tippet et al., 2011). This study combined both players who took the 10-minute extended break and those who were not offered this break but had a bathroom break. The behaviours in both situations were similar with a towel dry and a change of clothes. Whilst the extended break demonstrated a larger core temperature decrease (0.30 ± 0.14 ˚C vs 0.17 ± 0.27 ˚C), a bathroom break is an effective strategy that players can use should the conditions be hot but not high enough for this rule to be implemented.

2.4.3.6.3 Seeking shade

Seeking respite from solar radiation, which might reduce radiative heat gain by as much as 100 W (Nielsen et al., 1988), may offer players an opportunity to dissipate heat at a more effective rate in comparison to heat gain. Solar radiation replicating a clear sky (1072 ± 91 $W \cdot m^{-2}$) decreased self-selected exercise intensity at a fixed RPE, though similar intensities were apparent between thin cloud (592±32 $W \cdot m^{-2}$) and thick cloud (306±52 $W \cdot m^{-2}$) conditions (Otani et al., 2019), suggesting that seeking shade is most important when skies are clear or when solar radiation is similar to these simulated conditions.

2.4.3.6.4 Clothing choices

Clothing choices can enhance a player's ability to dissipate heat and/or the effectiveness of cooling strategies. A popular strategy is to wear white clothing (see Table 7.8), which will curtail the absorption of heat from solar radiation, though might allow more radiation to penetrate the clothing. Fewer respondents suggested they consider the clothing material. Colour and material of clothing affect heat balance: black clothing can enhance dry heat loss through an increased surface temperature; however, physiological strain has been reported to be significantly reduced whilst wearing white polyester compared to black cotton (Nielsen, 1990), though it has also been suggested that a cotton/wool blend is most effective at reducing core temperature in windy conditions (Kwon et al., 1998). It is likely that clothing material does not make a large difference to thermoregulation (Gavin, 2003) with little difference being observed between cotton and polyester (Gavin et al., 2001).

2.4.4 *Timing of cooling*

2.4.4.1 Pre-cooling

Pre-cooling has been evidenced to improve intermittent sprint performance in hot conditions (Brade, Dawson, & Wallman, 2014; Duffield & Marino, 2007), however, has also decreased performance (Skein et al., 2012), perhaps the result of excessively reduced muscle temperatures impairing force production capacity (Racinais et al., 2015). Despite inconclusive data, pre-cooling is suggested to benefit intermittent sprint performance in hot conditions (Tyler, Sunderland, et al., 2015). Pre-cooling the active muscles prior to a single sprint performance has been evidenced to reduce peak power output (Crowley et al., 1991; Sleivert et al., 2001), however, localised cooling (thigh ice packs) led to a 4% improvement in peak power output in a cycling intermittent sprint protocol (Castle et al., 2006). Pre-cooling has more benefit when the ensuing exercise is prolonged and causes a higher thermal strain (Tyler, Sunderland, et al., 2015).

Cooling increases the heat storage capacity and increase the comfort of exercise in the heat. Aggressive external cooling pre-exercise can cause immediate vasoconstriction of the peripheral blood vessels. When exercise begins, this can cause a delayed drop in core temperature as the increased peripheral blood flow is cooled and returned to the core (Bogerd et al., 2010; Duffield et al., 2010; Hasegawa et al., 2006; Kay et al., 1999; Quod et al., 2008).

The physiological and perceptual benefits of pre-cooling are often nullified during exercise leading to similar thermal strain as controls (James et al., 2017; Quod et al., 2008; Tyler, Sunderland, et al., 2015) though sometimes these reductions in core temperature can last up to 90 minutes (Cotter et al., 2001; Mitchell et al., 2003; Quod et al., 2008). Pre-cooling can also lead to a faster increase in thermal perception when exercising which, can make participants feel more uncomfortable in the heat (Gibson et al., 2019; James et al., 2015) and highlights the importance of trialling strategies prior to use (Gibson et al., 2019; Taylor et al., 2020). The focus of this thesis is cooling during tennis match play therefore, pre-cooling will not be considered further.

2.4.4.2 Per-cooling

Due to the nullification of physiological and perceptual benefits of pre-cooling during following exercise (James et al., 2017; Quod et al., 2008; Tyler, Sunderland, et al., 2015) and a faster increase in thermal perception making participants feel more uncomfortable in the heat (Gibson et al., 2019; James et al., 2015), methods to prolong the benefits have been sought; hence, per-cooling (cooling during exercise) intermittently and continuously are beginning to be explored.

Implementing strategies during match play, known as mid-cooling or per-cooling (Taylor et al., 2020), is beneficial to exercise performance and capacity in the heat (Bongers et al., 2015; Ruddock et al., 2017; Tyler, Sunderland, et al., 2015). The research as to whether per-cooling should be used in addition to pre-cooling is currently equivocal with some evidence of an additional effect (Best et al., 2018), and other evidence of per-cooling being as effective and pre- and per-cooling combined (Schulze et al., 2015). The latter study compared an internal and external pre-cool (15 $g \cdot kg^{-1}$ ice slurry and iced towels) with ad libitum ice slurry ingestion against the ad libitum ice slurry ingestion only during a 60-min cycle at a fixed RPE of 14. Neither strategy elicited differences in mean rectal temperature, though thermal comfort was likely and very likely lower and mean power output was possibly and likely higher for per-cooling and pre- & per-cooling, respectively. This suggests that a per-cooling internal only strategy elicits similar physiological, perceptual and performance improvements to a combined pre-cooling approach and subsequent internal per-cooling.

Continuous torso cooling using an ice vest under protective clothing that creates an uncompensable environment reduces core and skin temperatures, and improves exercise capacity by around 12% (Kenny et al., 2011). Often, environments within sporting are compensable though this evidences the benefit of continuous cooling in such an environment, if needed. Torso cooling also improves cycling capacity in a compensable environment, though this is through a reduction in thermal perception as no differences were seen in physiological measures of core temperature, skin temperature or heart rate (Cuttell et al., 2016; Luomala et al., 2012). Similarly, head and neck cooling does not reduce physiological strain while it does reduce perceptual strain (Ando et al., 2015; Bulbulian et al., 1999; Cuttell et al., 2016; Lee et al., 2014; Sunderland et al., 2015; Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b). Performance improvements have been evidenced when continuously cooling, some statistically significant increases in running performance and capacity (Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b), and some showing a likely effect (Cuttell et al., 2016; Lee et al., 2014). The implications that head or neck cooling dissociates core temperature from thermal perception are that players or athletes are at an increased risk of heat-related illness (Gibson et al., 2019; Wilson et al., 2002).

Intermittent cooling, occurring at breaks in play throughout exercise, has not been extensively researched. Early research suggests it decreases thermal perception and RPE (Duffield et al., 2003). This reduction would likely reduce the need to behaviourally thermoregulate (Flouris & Schlader, 2015), and might have implications for the reduction in perceptual strain and maintenance of performance throughout tennis match play. A couple of studies assessed the effectiveness of cooling interventions during simulated tennis match-play under conditions similar to the US Open (Schranner et al., 2017) and the Australian Open (Lynch et al., 2018). The former concluded that wetting the skin and sitting in front of a fan was as effective at reducing physiological and perceptual strain as ice towels in hot, humid conditions; the latter suggested a similar result in hot, dry conditions. The studies followed the current guidelines, attained through personal communication with the WTA, consisting of a wet towel filled with crushed ice around the neck, with ice towels over the head and knees.

Internal per-cooling has a limited evidence base. Ice slurry ingestion during exercise increases cycling exercise capacity by 13% through a reduction in physiological strain (Mündel et al., 2006) and around a 2.5% increase in mean power output through a reduction in perceptual strain (Schulze et al., 2015). Internal per-cooling does not always reduce the physiological strain (Burdon et al., 2013; Lee, Maughan, et al., 2008; Morris et al., 2016), which might be in part because of the previously mentioned increase in intensity due to improved thermal comfort. Internal pre-cooling reduces core temperature and perceptual strain during a tennis-specific exercise protocol (Naito et al., 2018).

Though, more research is needed to corroborate this due to the current equivocal stand on whether it has a physiological or perceptual benefit, or both.

2.5 Exercise Protocols for Tennis Specific Exercise

Gaining the data needed to advance our knowledge of how the body responds to tennis match play in various environments is difficult due to the invasive nature of many of the parameters that need to be measured, such as core and skin temperature. Though, there have recently been a few technological advances that might make things easier in the future (Buller et al., 2019; Byrne & Lim, 2007; Epstein et al., 2015; MacRae et al., 2018). Albeit these advancements, players are reluctant to make any changes whatsoever to their match play routines during official competition – somewhat understandable with the external rewards at stake - which make collecting real-world live data difficult. Because of this, researchers have opted to use simulated match protocols both on- and off-court to try and gain a better understanding of the physiological responses to tennis match play in hot conditions and nay exertional heat strain associated. Various field-based tennis-specific protocols have been published to assess aerobic capacity (Fargeas-Gluck & Léger, 2012; Ferrauti et al., 2011; Girard et al., 2006; Smekal et al., 2000), though measuring aerobic capacity is not a good measure of tennis match play performance and therefore, not suitable for assessing the effectiveness of interventions. A simulated match play protocol using a ball machine which entails serving and hitting balls as though playing an opponent has been published which elicits similar physiological responses as 'actual' match play (Davey et al., 2003). On-court tennis match play has also been used to assess the effects of the heat (Périard, Racinais, et al., 2014b). The protocol involved playing tennis as normal with the effective playing time (ball in play) calculated to allow comparisons between conditions or interventions. However, as these protocols are on-court, it is logistically difficult to implement interventions in an 'artificial' hot humid environment. The latter protocol more closely resemble tennis match play, the unpredictability of match play makes experimental trials difficult as the lack of control might prevent a confident interpretation of an intervention, even with using effective playing time. A laboratory treadmill protocol published during this programme of research has been used to assess cooling strategies during simulated tennis match play in the heat (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017), however, even after accounting for treadmill acceleration and deceleration, the rest length is shorter than the 20 s stipulated by the Grand Slam Board (2017) and even shorter than the now stipulation of 25 s (Grand Slam Board, 2021). Thus, this protocol is not representative of tennis match play as the rest length might not be enough to implement interventions.

2.6 Summary

Whilst there is obvious evidence of thermal strain through observing players on court during match play in hot conditions, and some data of retirements and cases of heat illness beginning to come into the public domain (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018), there is still much to be learned about the prevalence and extent of increased core body temperatures and associated heat illness. Alongside this, practical recommendations for counteracting measures across the different temperatures and humidities seen on the tennis tour have not been described during competitive match play at an elite level.

3 General Methods

This chapter describes the methods that are commonly used throughout this thesis. All testing was conducted in the BASES accredited Collegiate Hall Laboratories. Where alternative methods were used for specific chapters, these are detailed within the methods section of that chapter. Data collection was combined for the temperate element of chapter 4 and all conditions in chapter 5, therefore for these parts, the participants, methods and equipment were the same.

3.1 Health And Safety

All studies that make up this thesis were individually approved by the Sport Research Ethics Committee, a sub-committee of the Sheffield Hallam Research Ethics Committee and were conducted in accordance with the Declaration of Helsinki 1964, as revised in 2013 (World Medical Association, 2013). Applications can be seen in section 10.3. Written informed consent was sought from all participants and recent medical history was assessed through a medical questionnaire prior to starting each study. In line with the laboratory standard operating procedures and as stated in the relevant risk assessments, all biological waste and hazardous materials were handled and disposed of accordingly.

Testing sessions were ceased if any of the following was apparent:

- The investigator decided cessation was needed due to equipment issues, or if the participant was displaying signs of illness or discomfort *e.g.* dypsnea, nausea, vomiting, faintness or dizziness, chest pain, generic pain/discomfort
- The participant asked for test cessation; no reason was needed for this
- Rectal core temperature exceeded 39.7˚C as agreed through the ethics process (Willmott et al., 2015)

Where participants were removed from a testing session due to T_{re} increasing above 39.7˚C, they were actively cooled through fans, cold fluid ingestion and water immersion. They were monitored until T_{re} was within 0.5˚C of the baseline measure.

3.2 Participants

3.2.1 *Recruitment*

Due to the focus of this thesis being tennis specific performance, all participants were tennis players who trained at least twice per week and competed in local or British University and Colleges Sport leagues. They were recruited through the Sheffield Hallam

University Tennis Club and local clubs affiliated to the Sheffield and District Lawn Tennis Association. Participants were healthy males, aged between 18 and 40.

Prior to attending the laboratory, an information sheet was provided with all the detail of requirements, risks and benefits of the study; this included explicitly stating their right to withdraw without penalty and reason at any stage.

Participants were excluded if they displayed any pre-existing medical conditions that indicated they should not be participating in maximal exercise. Any participants with a history of blood carried infections *e.g.* hepatitis and HIV, diabetes, or any previous cardiac, haematological, renal or respiratory disease were also excluded. Due to the use of rectal thermometry and blood sampling, participants were excluded if they had known conditions such a fissures, haemorrhoids or anal bleeding, as well as any history of nausea, dizziness or light headedness as a result of needles or medical probing equipment.

3.3 Pre-Trial Diet and Exercise Standardisation

Due to the number of sessions involved in the studies in this thesis, all sessions were separated by a minimum of 48 hours. It has previously been suggested that 7 days is sufficient to ensure that no adaptations from repeated heat exposure occur (Barnett & Maughan, 1993). However, due to availability of participants and the number of trials required in each study, a minimum of 48 hours was set for all studies in this thesis. Trials in all studies were randomised to counterbalance any effect in the case that fewer than 7 days could be achieved between trials. Each participant's trials were conducted at the same time of day in order to account for any fluctuations due to circadian rhythm and variation (Thomas Reilly & Waterhouse, 2009; Winget et al., 1985).

Participants were encouraged to maintain their physical activity and dietary patterns throughout all experimental studies. It was communicated to them through the participant information and verbally that they should make a note of their diet for 24 hours prior to each session so they could match as close as practically possible the same diet before subsequent trials. From 24 hours prior to each session, participants were asked to maintain hydration through drinking water regularly. They were asked to consume 500 ml of water in the 2 hours before each trial beginning to ensure hydration on arrival to the lab. Guidelines were also given to participants that prior to all lab visits they should not: eat for 2 hours, undertake strenuous activity for 48 hours, consume alcohol for 24 hours and consume caffeine for 12 hours.

It was advised that they should avoid any situation of prolonged heat exposure during the course of the study and certainly in the preceding 48 hours before a trial *e.g.* sauna, steam room, baths.

3.4 Anthropometric Assessment

3.4.1 *Stature*

Stature was measured using a fixed stadiometer (Harpenden, UK). Participants stood vertically with their back to the stadiometer, facing the experimenter. The stadiometer arm was lowered until it rested on the most superior aspect of the head, ensuring this was not hair.

3.4.2 *Body mass*

Body mass was measured using the body mass using weighing scales (Adam GFK 150H, Adam Equipment Co. Ltd., Milton Keynes, UK) and recorded to 0.01 kg. The scales were calibrated prior to each study in accordance with the manufacturer's guidelines. Pre- and post- all experimental trials, participants were required to measure nude body mass. This was completed behind a privacy screen and self-reported to the experimenter to 0.01 kg.

3.4.3 *Body surface area*

From the data recorded of stature and body mass, body surface area (BSA) was subsequently calculated using Equation 3.1 below.

Equation 3.1: Calculation of body surface area (DuBois & DuBois, 1916)

$$BSA = 0.007184 \times BM^{0.425} \times H^{0.725}$$

BM = body mass; H = stature in metres

3.4.4 *Body fat percentage*

Body fat percentage was measured using bioelectrical impedance (InBody 770 Body Composition Analyzer, InBody, USA). Participants were required to wear minimal clothing; the machine contacts were wiped down prior to use and euhydration was assessed prior to testing (see 3.7 below) to ensure consistency between all participants.

3.5 Pre-Experimental Testing Session and Familiarisation

3.5.1 *Incremental exercise test*

An incremental exercise test was used as part of the preliminary testing to measure the gas exchange threshold (GET) of ventilatory threshold (T_{vent}) and maximum oxygen consumption ($\dot{V}O_2max$). Eighty percent of the GET was used to determine the warm-up speed for the experimental trials and $\dot{V}O_2max$ was profiled as a measure of the participants' aerobic fitness.

The incremental exercise test was completed on a treadmill ergometer (h/p/cosmos Saturn 250/75r, h/p/cosmos sports & medical GmbH, Germany). Participants began at 8 $km \cdot hr^{-1}$ and the speed increased by 1 $km \cdot hr^{-1}$ every minute until volitional exhaustion. The treadmill speed increased incrementally throughout, controlled by h/p/cosmos para graphics 2.6.14 (h/p/cosmos sports & medical GmbH, Germany). Throughout the test participants' expired air was analysed using the methods as described in the Oxygen consumption ($\dot{V}O_2$) section below.

3.5.2 *$\dot{V}O_2max$ determination*

$\dot{V}O_2max$ was determined as the highest 30s moving average of oxygen consumption recorded during the incremental exercise test.

In accordance with the recommendations of BASES (2007) and Edvardsen, Hem, & Anderssen (2014), a $\dot{V}O_{2max}$, not $\dot{V}O_{2peak}$, was accepted when three out of the following four criteria were met; blood lactate concentration >9 $mMol.L_{-1}$, HR within 10 beats of age predicted maximum, respiratory exchange ratio >1.1, and RPE at or above 19 RPE.

3.5.3 *Gas exchange threshold*

The GET was determined using the multiple parallel methods as suggested by Beaver, Wasserman & Whipp (1986). Oxygen consumption was plotted against carbon dioxide production and the change in regression line was identified. If there was any level of uncertainty, the V slope method was also employed – plotting minute ventilation against oxygen consumption.

3.5.4 *Familiarisation*

Following the pre-experimental trial including anthropometric measurements and the incremental exercise test, participants completed the first 5 games of the Tennis-Specific Treadmill Protocol (TSTP) (see 3.11 below) in situ where the experimental trials would take place. This familiarised them with the environmental conditions, the intermittent nature of the protocol and the acceleration speeds. Simultaneously, participants were familiarised with the perceptual measures (see section 3.10 below): Rating of Perceived Exertion [RPE] (Borg, 1982); Thermal Sensation [TSS] (Toner et al., 1986); and Thermal Comfort [TC] (Dobnikar et al., 2009). The familiarisation length was lengthened in chapters 5 and 6. Participants ran the first set of the TSTP in the heat (~36 ˚C, 50% rh), to ensure they were accustomed to the intermittent nature of the protocol, acceleration speeds and hot, humid conditions.

3.5.5 *Warm-up speeds*

The warm-up speeds were calculated for each participant as 80% of the speed at which the gas exchange threshold (GET) occurred. GET was estimated by plotting $\dot{V}CO_2$ against $\dot{V}O_2$ to identify the deflection point (Beaver et al., 1986). This individualised running speed was used to ensure the warm-ups were consistent for each participant in all conditions. This approach was the same for all studies in this thesis.

3.6 Environmental Conditions

3.6.1 *Ambient temperature*

During preliminary testing (anthropometry and graded exercise tests), and for all preparation prior to entering the heat chamber for experimental protocols, conditions were maintained using air conditioning between 20-22˚C.

3.6.2 *Experimental temperature and humidity*

All experimental sessions in both temperate and hot conditions were performed in a purpose-built environmental chamber (Watford Refrigeration & Air Conditioning Ltd., Hertfordshire, UK). The chamber had a range of -10 to 50˚C and humidity ranging from 20 to 95%. No fans or radiant heat lamps were used in addition to this. Environmental conditions were monitored throughout all trials at regular intervals and are reported in the experimental chapters within this thesis.

3.7 Hydration Assessment

To ensure that all participants were euhydrated and eligible to undertake the exercise testing, hydration status was assessed at the beginning of every trial through urine osmolality using a handheld micro osmometer (Advanced Instruments Inc., Massachusetts, USA). The osmometer was calibrated before each use using distilled water (osmolality 0 $mOsm \cdot kg^{-1}$). Urine was placed on to the osmometer lens (approximately 1 ml), where the sample was assessed using water freezing point depression. A threshold of ≤ 700 mOsm·kg^{-1} was set (Sawka et al., 2007). If a participant was over this threshold, they consumed 500 ml of water and waited until they next needed to void their bladder in order to be reassessed. If a participant was still not able to reach euhydration, their session was rescheduled.

3.8 Thermoregulatory Measures

3.8.1 *Rectal temperature*

Core temperature (T_{re}) was monitored through the method of rectal thermometry for all studies in this thesis. It was monitored in order to ensure safety as well as assess the efficacy of any interventions during the experimental chapters. Whilst rectal thermometry is invasive, it is considered to be one of the criterion measures of core temperature (Ganio et al., 2009). The other criterion method is pill telemetry, which provides a less invasive whilst valid and reliable measure of core temperature (Byrne & Lim, 2007). However, there are high costs involved with this method and the potential of bias from cooling methods in the experimental chapters, such as ice slurry, depending on the inter-individual differences of gut transit time (Lee, 2011). Consequently, a reusable rectal thermometer (Eltek U-type VL-U-VL5-0, Eltek Ltd., Cambridge, UK) connected and logged through a data logger (Squirrel 1000 series, Grant Instruments, Cambridge, UK) was used throughout this thesis. Rectal thermometers were self-inserted 10 cm past the anal sphincter and wrapped in sheaths and zinc oxide tape to ensure they remained in place.

3.8.2 *Skin temperature*

Skin temperature ($\overline{T}_{sk}$) was recorded using thermistors (iButton DS1922L, Measurement Systems Ltd, Newbury, UK) placed on the skin in four different sites. These sites were the chest (midpoint of the pectoralis major), the upper arm (midpoint of the triceps brachii lateral head), the upper leg (midpoint of the rectus femoris) and the lower leg (gastrocnemius lateral head). Each site was prepared prior to thermistor attachment by shaving any hair coverage and cleaning with an alcohol wipe to remove any oils that might affect the attachment of the adhesive. iButtons were attached using kinesiology tape (KT Health, LLC, Utah, USA) and in the case of the later 3 were secured using zinc oxide tape or leukofix tape (Leukoplast, BSN medical GmbH, Hamburg, Germany). The temperature measures at each of the four sites were then used to calculate mean skin temperature as seen in

Equation 3.2 below.

Equation 3.2: Mean skin temperature (Ramanathan, 1964)

$$\bar{T}_{sk} = 0.3(T_{chest} + T_{tricep}) + 0.2\ (T_{thigh} + T_{calf})$$

3.8.3 *Sweat rate*

Towel-dried nude body mass (NBM) was measured and recorded to the nearest gram pre- and immediately post- all experimental trials to assess fluid loss. These values were not corrected for respiratory and metabolic weight losses due to the assumption that these were similar in all trials due to the matched work and environmental conditions in all trials. NBM along with the amount of fluid that had been consumed during 'change of ends' and any urine output during the trials were then inputted into Equation 3.3 as seen below.

Equation 3.3: Sweat rate

$$SR\ (L \cdot hr^{-1}) = \frac{((Post\ NBM - Pre\ NBM) + (Fluid\ consumed - Urine))}{Exercise\ time\ x\ 60}$$

3.9 Physiological Measures

3.9.1 *Heart rate*

During all trials described in chapters 4, 5 and 6, heart rate was measured using a Polar HR monitor (Polar Electro Oy, Kempele, Finland). A Polar H7 chest strap was affixed to the participants during trials in chapter 4 and a Polar H10 chest strap was affixed to participants in chapters 5 and 6. The strap was dampened with water prior to wearing to aid conductivity. Heart rate was recorded every 5 s throughout trials using a Polar RS400 watch; when oxygen consumption was also being recorded, HR was also recorded through the Cortex Metalyzer 3B (Cortex Biophysik GmbH, Leipzig, Germany).

3.9.2 *Mean heart rate*

Mean heart rate was calculated using the above recorded HR data in chapters 4, 5 and 6 during games 3, 5, 7 and 9 of every set, throughout the TSTP. Any missed data points due to telemetry issues were removed prior to calculation. These dropouts occurred infrequently in chapter 4 with the occasional few seconds of data being missed. However, due to longer dropouts in following studies, mean heart rate was not used as a variable after chapter 4.

3.9.3 *Oxygen consumption ($\dot{V}O_2$)*

Oxygen consumption was measured and recorded using the Cortex Metalyzer 3B breath-by-breath online gas analysis system (Cortex Biophysik GmbH, Leipzig, Germany) during chapters 4-6. After an initial 30-minute warm up period in the heat chamber and environment in which the testing would take place, a 3-point calibration was run using the Metasoft software (Cortex Biophysik GmbH, Leipzig, Germany) before every session to ensure no drift in values would have occurred. First, barometric pressure was inputted from a reading on a portable barometer (Greisinger GPB 3300, Gresinger electronic GmbH, Regenstauf, Germany). Second, the Metalyzer sampled ambient air (fraction of inspired (Fi), FiO2 = 0.2093, $FiCO_2$ = 0.0003) in the same environmental conditions as the testing (~36˚C 50% RH), followed by a calibration gas (Cortex Biophysik Gmbh, Leipzig, Germany) with known gas concentrations (FiO_2 = 0.15, $FiCO_2$ = 0.05). Finally, volume was calibrated using a 3-litre syringe (Hans Rudolph, Germany) to simulate inspiration and expiration. The syringe was attached to the Metalyzer's volume transducer and required 5 cycles within the flow rate limits of 2-4 $L \cdot s^{-1}$.

Online gas analysis systems are not the gold standard Douglas bag method, may have higher intra- and inter-day variation than Douglas bags (Carter & Jeukendrup 2002), and manufacturers do not publish the exact algorithms used in order to calculate the outputs (Hodges et al., 2005). However, online systems have been shown to be both reliable (Meyer et al. 2001) and valid (G. Atkinson et al., 2005; Macfarlane, 2001; Macfarlane & Wong, 2012). During the testing in chapters 4-6, the online system offered a useful solution due to steady state not being reached in either the max test or the TSTP. The online system allowed the data to be averaged over a period of time, which might offer increased accuracy if a Douglas bag collection was interrupted by cessation of the test.

3.9.4 *Blood lactate*

Lactate was measured after game 3, 5, 7 and 9 in chapter 4 whilst assessing reliability. Following this, the number of samples was reduced to only be after games 5 and 9 as the data in the reliability study showed a high variability and little chance to observe a meaningful change as a result of an intervention. Blood lactate samples were collected through fingertip capillary blood sample in capillary tubes which were mixed with haemolysing solution before being analysed (Biosen C-Line, EKF Diagnostics, Cardiff, UK).

3.10 Perceptual Measures

3.10.1 *Rating of perceived exertion*

To assess participants' subjective perception of effort throughout trials was achieved through the use of Borg's rating of perceived exertion (RPE) scale (Borg, 1982). The scale, as seen in Figure 3.1 below, ranged from 6 (no exertion at all), through 13 (somewhat hard) to 20 (maximal exertion) on a 15-point scale. RPE has previously been demonstrated to be strongly correlated with the metabolic and cardiac parameters of blood lactate and heart rate (Scherr et al., 2013). During the initial consultation and at the start of every following trial, participants were provided with standardised instructions as to how to report overall feelings of exertion; the summary of these was always displayed in front of them, as seen in Figure 3.1. In order to further help participants understand the scale, the end values of 6 and 20 were 'anchored' to previous experiences matching those levels of RPE prior to any testing taking place (Mauger et al., 2013).

RATING OF PERCEIVED EXERTION

How heavy and strenuous does the exercise feel?

Consider strain and fatigue in your muscles AND feelings of breathlessness or aches in the chest.

6	No exertion at all
7	
8	Extremely light
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 3.1: Rating of perceived exertion scale (Borg, 1982)

3.10.2 *Thermal sensation*

Thermal sensation (TS) was measured using the thermal sensation scale, as described and validated by Toner, Drolet, & Pandolf (1986). As seen in Figure 3.2 below, it is a 17-point scale ranging from 0.0 (“unbearably cold”) to 8.0 (“unbearably hot”). The participant was presented with the scale and asked the question: “how cold or hot do you feel now?” (Ganio et al., 2009).

THERMAL SENSATION SCALE

(Toner 1986)

0.0	**Unbearably cold**
0.5	
1.0	**Very cold**
1.5	
2.0	**Cold**
2.5	
3.0	**Cool**
3.5	
4.0	**Neutral (Comfortable)**
4.5	
5.0	**Warm**
5.5	
6.0	**Hot**
6.5	
7.0	**Very hot**
7.5	
8.0	**Unbearably hot**

How cold or hot are you now?

Figure 3.2: Thermal sensation scale (Toner et al., 1986)

3.10.3 *Thermal comfort*

Thermal comfort (TC) was measured using the thermal sensation scale ranging from 1 = *comfortable* to 5 = *very uncomfortable* (as seen in Figure 3.3 below) throughout all experimental trials. TC was always taken simultaneously to RPE and TS.

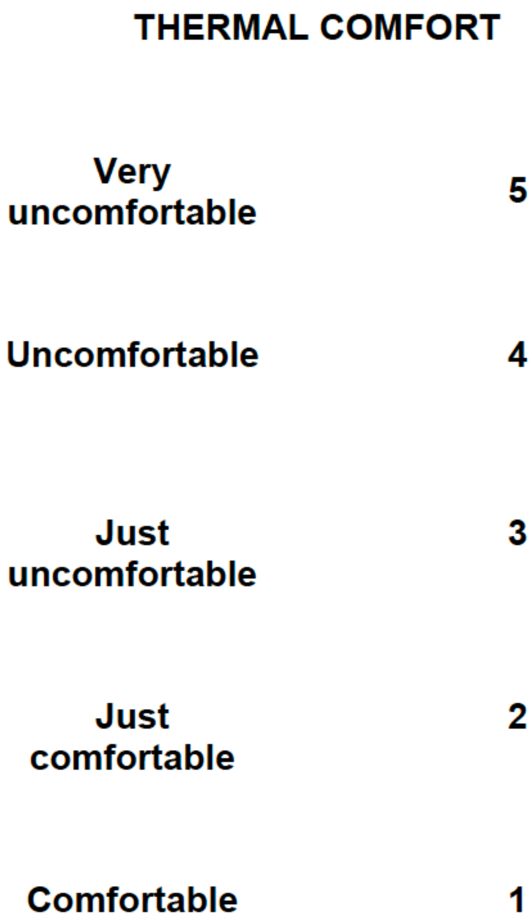

Figure 3.3: Thermal comfort scale (Dobnikar et al., 2009; Guéritée & Tipton, 2015; H. Zhang et al., 2004)

3.11 Tennis-Specific Treadmill Protocol

The TSTP was designed using various elements of tennis match play. Firstly, the reported average point length of 8.2 s for a whole-court player (Kovacs, 2006). Secondly, an average running speed of 13.29 $km \cdot hr^{-1}$ in men's tennis at the Australian Open (Reid et al., 2016). Thirdly, an average of 6 points per game (Filipcic & Filipcic, 2006; Reid et al., 2016). Fourthly, an average of ~90 min per match (Kovacs, 2007). And finally, previously reported $\dot{V}O_2$ during match play of 23-29 $ml \cdot kg^{-1} \cdot min^{-1}$ (Fernández-Fernández et al., 2006), confirmed post-study with an overall mean ± SD of 24 ± 2 $ml \cdot kg^{-1} \cdot min^{-1}$ and 26 ± 2 $ml \cdot kg^{-1} \cdot min^{-1}$ in temperate and hot, humid conditions, respectively.

Table 3.1: Tennis time-motion and match play characteristics

	Published	TSTP
Mean speed (men)[1]	13.25 km·hr^{-1}	13.29 km·hr^{-1}
Mean match length[2]	90 min	92.15 min
Mean point length (whole-court)[2]	8.20 s	8.17 s
Effective playing time[2]	20 - 30%	24%
Range of point length (hard court)[3]	6 - 12.2 s	6 - 13 s
Mean points per game[1,4]	6	6
Points under 10 s[4]	76%	83%
Mean time between games with no change of ends[4]	30 s	30 s

[1]Reid, Morgan & Whiteside (2016); [2]Kovacs (2006); [3]Kovacs (2007); [4]Filipčič & Filipčič (2006)

The resulting TSTP, as seen in

Figure 3.4 below, incorporated "points" ranging from 10-20 km·hr^{-1} and 6-13 s; resulting in weighted means of 8.17 s and 13.29 km·hr^{-1} for point duration and speed, respectively. Each "game" consisted of 6 "points", each "set" consisted of 9 "games" and there were 3 "sets" in total. The time characteristics of between-point (20 s), change of ends (90 s) and between-set rest periods (120 s) were set in accordance with the regulations of the International Tennis Federation (Grand Slam Board, 2017); all rest periods included 6 s deceleration and 6 s acceleration. The protocol was automated from start to finish (h/p/cosmos para graphics 2.6.14, h/p/cosmos sports & medical GmbH, Germany), lasting a total time of 92 min 9 s.

3.11.1 *Protocol completion*

Protocol completion was calculated by dividing the duration completed by the total duration of the protocol (HOT20 = 97.15 min; HOT30 = 119.65 min) in each condition as seen in Equation 3.4 below.

Equation 3.4: Protocol completion

$$Protocol\ completion\ (\%) = \left(\frac{Duration\ completed\ (min)}{Total\ duration\ (min)}\right) x\ 100$$

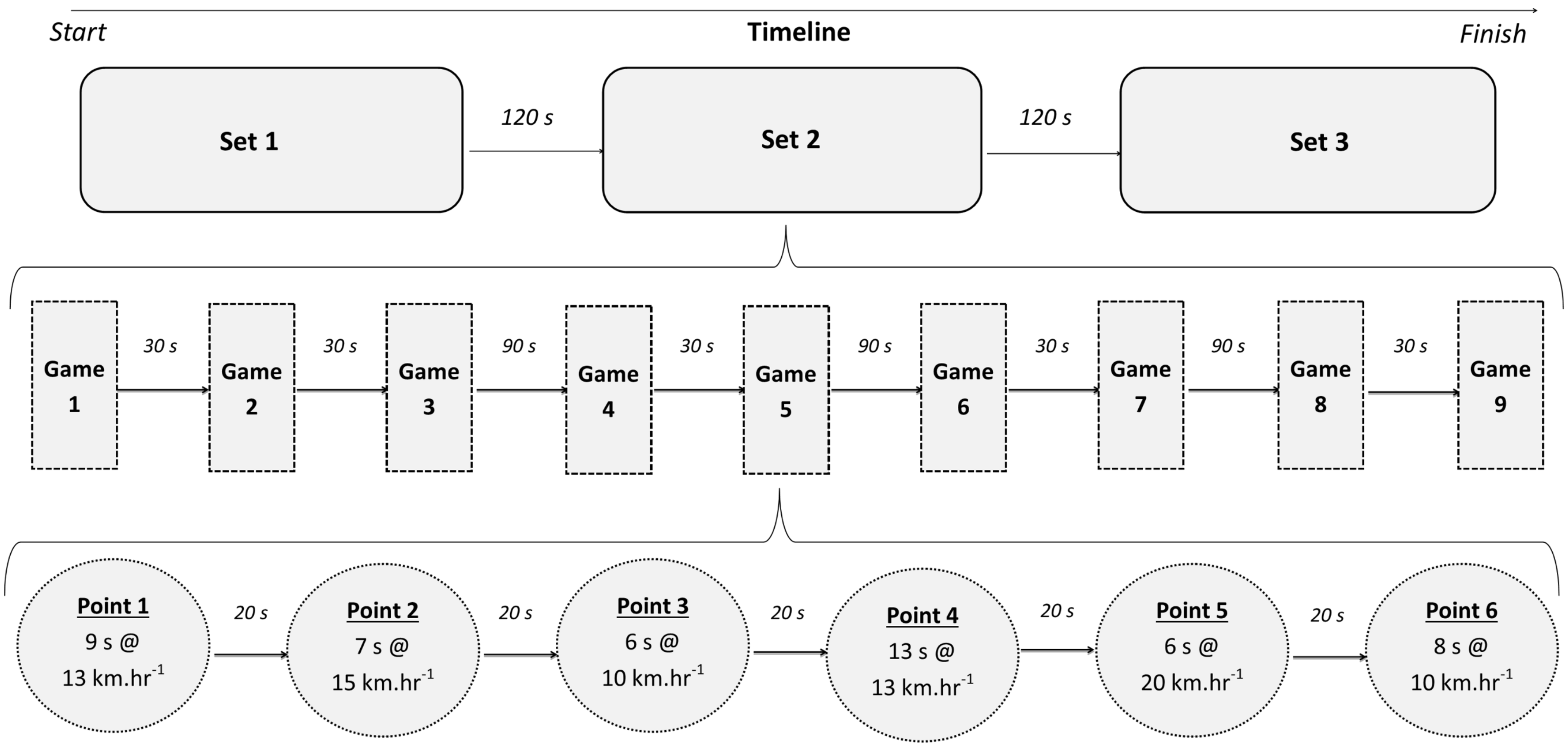

Figure 3.4: A visual representation of the tennis-specific treadmill protocol

3.12 Statistical Methods

3.12.1 *Power analysis*

A sample size of 12 participants was aimed for in all studies. To estimate an appropriate sample size, a power analysis was undertaken using the software G*Power3. Effect sizes relating to primary dependant variables were obtained based upon published data reporting mean and standard deviation. Using an alpha level of 0.05 and power at 0.8, effect sizes were obtained from peak core temperature (d_z = 1.29) and mean heart rate (d_z = 1.63) from an on-court study comparing hot and temperate environments (Périard, Racinais, et al., 2014b). An effect size from change in core temperature (d_z = 1.33) was also inputted in a study using ice towels in hot, humid conditions (Schranner et al., 2017). This analysis indicated that a minimum of 6 participants would be required to detect differences between trials. Based on the estimated sample size needed and adding several participants to account for dropouts and non-completions, 12 participants were estimated as suitable to identify a difference, should there be one.

3.12.2 *Normality and sphericity of data*

3.12.2.1 Normality

Data were first checked for skewness and kurtosis with the limits of -1.96 and +1.96 indicating normal distribution. If the values were within these limits the data was then assessed through the Kolmogorov-Smirnov test and the Shapiro-Wilk test. These tests are robust to the violations of any assumptions in the following analysis of variance (ANOVA) (Field, 2013).

3.12.2.2 Sphericity of data

Mauchly's test of sphericity was used to assess the variance of differences between conditions prior to an ANOVA. If the test result was not significant (P <.05) then the data was assumed to be spherical and the parametric route of ANOVA was then followed. If the test was significant (P < .05), then it was deemed there were differences between conditions and sphericity was not met. The Greenhouse-Geisser method was then applied to adjust the degrees of freedom and sphericity assumed if the data were then not significant (P > .05).

3.12.3 *Statistical significance level*

A significance level was set within this thesis to describe the probability that an analysis of data is at least as surprising as the observed sample results would be generated under a model of random chance (Vincent, 1999). The *P*-value is defined as the probability, under the assumption of hypothesis, of obtaining a result equal to or more extreme than what was observed.

The threshold *P*-value for the studies within this thesis was set at 5%, giving 95% confidence that when *P* is calculated correctly, it will control the type I error to be no greater than α level of 0.05.

3.12.4 *Effect sizes*

3.12.4.1 Hedges' g_{av}

Results throughout this thesis were also interpreted using Hedges' g_{av} effect size. Cohen's d_{av} is based on a sample estimate and is therefore positively biased. To account for a low sample size, Hedges' correction was applied and Hedges' g_{av} selected as the most appropriate effect size as suggested by Lakens (2013). Equation 3.5, as seen below, was implemented in accordance with the supplementary spreadsheet.

Equation 3.5: Hedges' g_{av} (Lakens, 2013)

$$g_{av} = \left(\frac{M_{diff}}{\left(\frac{SD_1 + SD_2}{2}\right)}\right) \times \left(1 - \left(\frac{3}{4 \times (N-1) - 1}\right)\right)$$

M_{diff} = Mean difference; SD = standard deviation; N = sample size

3.12.4.2 Partial eta squared

Effect sizes for ANOVAs in this thesis are expressed as partial eta squared (η_p^2) as calculated by SPSS. The equation for partial eta squared can be seen in Equation 3.6 below.

Equation 3.6: Partial eta squared (Cohen, 1973)

$$\eta_p{}^2 = \frac{SS_{between}}{SS_{between} + SS_{error}}$$

$SS_{between}$ = sum of squares of the effect. SS_{error} = sum of squares of the error associated with the effect.

3.12.5 *Post hoc analysis*

Bonferroni corrections were applied for all post hoc analysis of ANOVAs in order to identify where any differences occurred in multiple comparisons. The Bonferroni correction is a conservative estimation of difference and adjusts the *P* value accordingly (Field, 2013). The application controls the familywise error rate, which in turn, reduces the likelihood of type I error; it remains a robust method when sphericity is violated (Field, 2013).

4 Validity and Reliability of the Tennis-Specific Treadmill Protocol in Temperate and Hot, Humid Conditions

4.1 Introduction

Tennis match play is characterised by bouts of whole-body sprint exercise (2 to 10 s) coupled with short recovery periods (10 to 20 s), and longer recovery periods (60 to 120 s). The mean-average duration for a match is 1.5 h, however, matches have been known to last ≥5 h (Fernandez-Fernandez, Sanz-Rivas, & Mendez-Villanueva, 2009; Kovacs, 2006, 2007). Players cover a mean of 1300 to 3600 $m.hr^{-1}$ during match play, moving an average of 3 m per shot, including 3-4 changes of direction, hitting the ball 4-5 times per point and covering a distance of 8-15 m (Fernandez-Fernandez et al., 2009; Kovacs, 2007). Tennis evokes a mean HR of 70-80% HR_{max}, with peak heart rate reaching 100%, analogous to 50-60% $\dot{V}O_2max$ with peaks of 80% $\dot{V}O_2max$ (Fernandez-Fernandez et al., 2009; Fernandez, Mendez-Villanueva, & Pluim, 2006).

Previously reported peak environmental conditions during Grand Slam tournaments have been 36 ˚C 50% Relative Humidity (RH) at the US Open and 45 ˚C 10% RH at the Australian Open. These environments increase perceptual, thermal, and physiological demand as the body attempts to attenuate heat gain and augment heat loss; core temperatures during match play have been reported up to 39.4 ˚C (Bergeron et al., 2006; Morante & Brotherhood, 2008b; Périard et al., 2014; Tippet, Stofan, Lacambra, & Horswill, 2011), compared with ~38.5 ˚C in a temperate environment (Périard, Racinais, et al., 2014b). This heat gain might influence the result of a match or tournament through 1) adopting more aggressive tactics (Morante & Brotherhood, 2008b); 2) a decrease in the number of winners and an increase in the number of errors (Smith, Reid, Kovalchik, Wood, et al., 2018); 3) heat-related incidents during a match leading to retirement, or post-match recovery hindrance (Smith, Reid, Kovalchik, Woods, et al., 2018). Where the impact of environmental conditions is thought to influence safety and performance the effectiveness of appropriate countermeasures needs to be known. Decisions regarding such strategies are reliant on the observation and analysis of thermoregulatory, physiological, and perceptual responses. Moreover, these responses should be observed in a controlled environment using a valid and reliable protocol. By calculating the measurement error of dependant variables through repeated measurements, a confident interpretation whether a change in a dependant variable is due to the intervention, or biological variation and measurement error, can be achieved (Ruddock et al., 2014).

Knowledge of test-retest reliability is also important for calculating sample sizes for future studies (Greg Atkinson & Nevill, 1998; Currell & Jeukendrup, 2008; Hopkins, 2000, 2004).

Laboratory-based exercise protocols to assess physiological responses to intermittent exercise have been designed (Aldous et al., 2014; Bishop et al., 2001; Bishop & Maxwell, 2009; Davey, 2006; Hayes et al., 2013; Wragg et al., 2000). However, these assess physiological responses to intermittent activity rather than physiological responses to tennis-specific activity and duration. These data, detailing physiological and metabolic responses, therefore, do not suitably reflect the work-rate pattern observed during match play, nor the total duration.

A tennis-specific treadmill protocol has been used previously in an environmental chamber (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017). The protocol is ecologically valid due to the match characteristics and time-motion data it is based on, such as: points per game, point length, sit down breaks *etc.* However, it was published after this programme of research had begun. Regardless, no reliability data has been published which is needed to interpret data when assessing the effectiveness of interventions.

The aim of this study was to assess the validity and reliability of a tennis-specific laboratory-based protocol representing match play work and activity profiles.

4.2 Methods

4.2.1 *Participants*

Seventeen moderately trained male tennis players who play at least twice per week and compete in local or British Universities and Colleges Sport leagues volunteered for this study (see details below in Table 4.1). Five participants completed the TEMP study only, six participants completed the HH study only, and six participants completed both TEMP and HH studies. All participants were non-smokers, free from any known cardiorespiratory disorders.

Table 4.1: Participant characteristics

Characteristic	TEMP	HH
Number of participants[#]	11	12
Age (years)	23 ± 5	25 ± 6
Stature (m)	1.79 ± 0.07	1.80 ± 0.06
Body mass (kg)	76.1 ± 11.0	76.8 ± 9.7
Body fat (%)	13.4 ± 5.5	14.6 ± 5.6
Body surface area (m^2)*	1.9 ± 0.2	2.0 ± 0.1
Gas exchange threshold ($km \cdot hr^{-1}$)	12.2 ± 1.9	12.4 ± 1.4
Maximal aerobic capacity ($ml \cdot kg^{-1} \cdot min^{-1}$)	51 ± 5	49 ± 4

* Estimated using an equation (DuBois & DuBois, 1916)

[#] 6 participants completed both arms of this study, 5 participants completed TEMP only 6 participants completed HH only

4.2.2 *The Tennis-Specific Treadmill Protocol (TSTP)*

The protocol used during this testing was the TSTP, as seen in Figure 3.4. The design of which is detailed in section 3.11 of this thesis.

4.2.3 *Experimental design*

The TEMP and HH studies were conducted separately with identical design. Each required participants to visit the lab on 3 separate occasions. A preliminary session, followed by two experimental trials, separated by at least 48 h, in either temperate (TEMP; 20.2 ± 0.2°C; 48 ± 4% relative humidity (RH); 15.6 ± 0.4°C Wet Bulb Globe Temperature (WBGT) or hot, humid (HH; 35.9 ± 0.3°C; 50 ± 2% RH; 29.5 ± 0.3 WBGT) conditions. The environmental conditions of HH were selected to replicate peak conditions previously observed at the US Open (Schranner et al., 2017). Both experimental trials were conducted at the same time of day to negate any effect of circadian rhythm (Winget et al., 1985). The study was approved by the institution's ethics committee and conducted in accordance with the guidelines of the revised Declaration of Helsinki 2013.

4.2.4 *Preliminary measurements*

Anthropometric and physiological characteristics were identified during the preliminary session. Participants were also familiarised to the TSTP in the respective environmental conditions. Warm up speeds were then calculated based on this assessment. This was as detailed in section 3.5.5.

4.2.5 *Experimental protocol*

Participants were asked to refrain from eating for 2 hours, undertaking strenuous activity for 48 hours, consuming alcohol for 24 hours and consuming caffeine for 12 hours, prior to testing. They were instructed to drink 500 ml of water a few hours before the trial to ensure euhydration, defined as a urine osmolality result of <700 mOsm$\cdot$kg^{-1} (Sawka et al., 2007), measured on a Pocket Pal-Osmo (Vitech Scientific, Ltd.). If this threshold was not met (zero incidences), participants were given water and waited 30 mins before rechecking hydration status. Urine colour (U_{col}) was also assessed alongside osmolality (Armstrong, 2000).

Participants self-inserted the rectal probe (Eltek U-type VL-U-VL5-0, Eltek Ltd., Cambridge, UK) 10 cm past the anal sphincter to measure core temperature (T_{re}); exercise was terminated if $T_{re} \geqslant 39.7$°C (Willmott et al., 2015) or volitional exhaustion occurred; both had 1 occurrence. Nude Body Mass (NBM) (Adam GFK 150H, Adam Equipment Co. Ltd., Milton Keynes, UK) was noted before and after all trials and used to calculate Sweat Rate (SR). Skin temperature ($\overline{T}_{sk}$) was recorded using skin thermochrons or thermistors (TEMP: iButtons, Measurement Systems Ltd., Berkshire, UK; HH: Eltek U-type EUS-U-VS5-0, Eltek Ltd., Cambridge, UK) attached to the mid belly of the pectoralis major (T_{chest}), triceps brachii ($T_{upperarm}$), rectus femoris ($T_{upperleg}$) and gastrocnemius ($T_{lowerleg}$); all on the right side of the body. Rectal and skin thermistors were recorded throughout the protocol by a data logger (Grant Squirrel 1000 series, Grant Instruments, Cambridge, UK). A HR belt (Polar H7, Polar Electro, Finland); recorded throughout on a watch (Polar RS400, Polar Electro, Finland). [BLa] was assessed through fingertip capillary blood sample (Biosen C-Line, EKF Diagnostics, Cardiff, UK).

Following a 5 min stabilisation period, resting measures were recorded, before entering the environmental chamber (Watford Refrigeration & Air Conditioning Ltd., Hertfordshire, UK); conditions were monitored using a heat stress meter (HT30, Extech

Instruments, USA). Participants then underwent a 5 min seated acclimatisation period with perceptual measures taken afterwards. Following this, a 5 min warm up at a speed equivalent to 80% of their GET and a further 2 min rest (on the treadmill) prior to the commencement of the TSTP; perceptual, HR, T_{re} and $\overline{T}_{sk}$ measures were recorded post-warm up.

During the TSTP, T_{re}, $\overline{T}_{sk}$, HR and perceptual scales were observed at the end of games 3, 5, 7 and 9, prior to sitting down; mean HR was an average over the duration of the aforementioned games and $\dot{V}O_2$ was an average of game 7 in each set. At "change of ends" when the participant was seated, a lactate sample was taken, and they consumed 150 ml water (TEMP: 18.36 ± 0.49˚C; HH: 19.31 ± 0.17˚C); apart from after game 1, where participants remained on the treadmill but still drank 150 ml water. "Time" was called with 30 s left of the rest period to allow the participants to get back on the treadmill ready for the start of the next game.

4.2.6 *Statistical Analyses*

A battery of statistical analyses assessed the test-retest reliability of the TSTP following the guidelines of Atkinson & Nevill (1998). Bland-Altman plots were generated to investigate any systematic and random error trends. Heteroscedasticity was evaluated by plotting a regression line through the data points on the Bland-Altman plots; the criteria was set at $r < \pm 0.20$. A paired t-test was run to assess for any systematic bias between trials; significance set at $P > 0.05$. Following this relative reliability was investigated using Intraclass Correlation Coefficients (ICC) and Pearson's moment correlation coefficient (r). Absolute reliability was assessed through 95% limits of agreement (LoA), typical error of the measurement (TEM) - calculated from the SD of the mean difference between the two TSTP trials, divided by √2 (Hopkins, 2000) - then expressed as a percentage of the respective mean to form a coefficient of variation (CV), and standard error of the mean (SEM). Hedges' g_{av} was used as a measure of effect size and data were evaluated according to Hopkins (2004).

ICC for T_{re}, $\overline{T}_{sk}$, EoG HR, Mean HR, RPE, TS and TC was average measures (k = 12) two-way mixed effect absolute agreement; Peak T_{re}, ΔT_{re}, Peak $\overline{T}_{sk}$, $\Delta\overline{T}_{sk}$, SR and $\dot{V}O_2$ was single measure two-way mixed effect absolute agreement.

Data were assessed for normality using the Kolmogorov-Smirnov test; significance set at $P > 0.05$. If data were significant the Shapiro Wilk statistic was observed with the same significance. If data violated normality, a Wilcoxon signed rank test assessed between-trial differences.

All data were analysed using a standard statistical package (SPSS 24.0). Statistical significance was accepted at the level of $P \leq 0.05$ and data reported as mean ± standard deviation.

4.3 Results

4.3.1 *Physical characteristics*

All participants arrived at the laboratory in a similar physiological state for both trials, in both conditions. In TEMP, there were no differences between resting HR (64 ± 9 and 61 ± 10 beats·min^{-1}; $t_{(10)} = 1.922$; P =.084; g_{av} = .02), resting T_{re} (37.36 ± 0.30 and 37.37 ± 0.24°C; $t_{(10)} = 1.922$; P =.084; g_{av} = .19), U_{osm} (302 ± 173 and 383 ± 251; $t_{(10)} = 1.922$; P =.084; g_{av} = .33) or pre-trial NBM (76.68 ± 9.79 and 76.59 ± 10.16 kg; $t_{(10)} = 1.922$; P =.084; g_{av} = .003).

In HH, there were no differences between resting HR (62 ± 8 and 62 ± 10 beats·min^{-1}; $t_{(11)} = 1.835$; P = .094; g_{av} = .24), resting T_{re} (37.32 ± 0.3 and 37.38 ± 0.27°C; $t_{(11)} = -0.166$; P = .871; g_{av} = .03), U_{osm} (401 ± 276 and 319 ± 175; $t_{(11)} = -1.002$; P=.338; g_{av} = .35) or pre-trial NBM (75.86 ± 11.06 and 75.83 ± 10.59 kg; $t_{(7)} = 0.043$; P = .967; g_{av} = .01).

4.3.2 *Temperate conditions*

4.3.2.1 Thermoregulatory

The mean systematic bias was low in T_{re} and peak T_{re} (0.04-0.09 ˚C), and SR (-0.022 L·min^{-1}). Bias in $\overline{T}_{sk}$ was low in TSTP, S1 and S3 (0.00-0.13 ˚C) but higher in S2 (0.29 ˚C). Other variables generally had a larger bias (0.06-1.40). Many of these differences were statistically significant ($P < 0.05$) and had small or moderate effect sizes. Random error for rectal temperature variables was reasonable with 95% LoA ranging 0.24-0.58 ˚C; as was SR (0.121 L·min^{-1}). Skin temperature variables had more random error (1.52-4.92 ˚C). T_{re} demonstrated the best agreement with an excellent ICC for the TSTP, good to excellent for S1 and S2, and fair to excellent for S3. Other variables showed worse levels of agreement on varying scales. This trend was also apparent for Pearson's r. Rectal temperature variables and SR had the lowest typical error. $\overline{T}_{sk}$ and Peak $\overline{T}_{sk}$ had higher TE whilst the highest was $\Delta\overline{T}_{sk}$. The same pattern was observed for SEM and SWC.

4.3.2.2 Cardiopulmonary

EoG HR and mean HR demonstrate very low systematic bias (0-2 beats·min^{-1}), no significance of difference between trials (*P>0.05)* and all trivial effect sizes (<0.20). $\dot{V}O_2$

showed systematic bias of 0.1-0.6 ml·kg^{-1}·min^{-1}. No significant differences were observed between trials, and a small effect size (0.21) was observed in S1. Limits of agreement (95%) were narrow for HR variables (10-14 beats·min^{-1}) and wider for $\dot{V}O_2$ (1.84-2.72 ml·kg^{-1}·min^{-1}). Heteroscedasticity can be seen below in Table 4.3. Heart rate variables all show excellent agreement with confidence intervals ranging 0.865-0.990. TSTP and S3 $\dot{V}O_2$ demonstrated good to excellent agreement, with S1 and S2 having fair to excellent agreement. Pearson's *r* for all cardiopulmonary variables ranged 0.856-0.964. Typical error was small for EoG HR (5 beats·min^{-1}), mean HR (4 beats·min^{-1}), and $\dot{V}O_2$ (0.66-0.98 ml·kg^{-1}·min^{-1}).

4.3.2.3 Perceptual

All perceptual variables had small systematic bias (0.0-0.6), however, trials were significantly different for all variables and timepoints apart from RPE in S1 and S2. Some small effect sizes were apparent, and a moderate effect size as seen below in Table 4.4. Limits of agreement showed a 95% confidence of 2-3 for RPE, and 1 for both TS and TC. Many timepoints were heteroscedastic. Most perceptual variables and timepoints demonstrated excellent agreement through ICC. RPE S2 was good to excellent; as was TS S2 and S3; TS S1 was poor to excellent. Pearson's *r* reinforced this agreement (0.732-0.922). Typical error was excellent for RPE (1), TS (0) and TC (0). Between- and within-participant differences were similar throughout the trial in all variables.

Table 4.2: Mean ± SD data for both trials and a battery of reliability statistics for the thermoregulatory variables in temperate conditions

Variable		**Trial 1**	**Trial 2**	**Homo-scedastic**	**ΔMean** ***(± 95% CI)***	***P***	**95% LoA RE (±)**	***r***	**ICC** ***(95% CI)***	**SEM**	**TEM**	**TEM (CV%)**	**Hedges' g_{av}**	**SWC**
T_{re} (°C)	TSTP	37.89 ± 0.31	37.84 ± 0.28	✓	0.05 *(0.02, 0.08)*	.000	0.35	.817	0.891 *(0.846, 0.923)*	0.55	0.13	0.4	0.16	0.06
	S1	37.90 ± 0.25	37.86 ± 0.24	✓	0.04 *(-0.01, 0.09)*	.120	0.34	.750	0.853 *(0.731, 0.919)*	0.45	0.12	0.4	0.17	0.05
	S2	38.02 ± 0.18	37.95 ± 0.20	✓	0.07 *(0.03, 0.11)*	.002	0.26	.747	0.822 *(0.618, 0.911)*	0.32	0.09	0.2	0.36	0.04
	S3	38.02 ± 0.16	37.93 ± 0.21	×	0.09 *(0.05, 0.13)*	.000	0.26	.771	0.808 *(0.510, 0.911)*	0.30	0.09	0.2	0.45	0.04
Peak T_{re} (°C)	TSTP	38.10 ± 0.19	38.01 ± 0.19	✓	0.09 *(0.01, 0.17)*	.031	0.24	.805	0.735 *(0.199, 0.925)*	0.23	0.08	0.2	0.47	0.04
	S1	38.03 ± 0.21	37.96 ± 0.21	✓	0.07 *(-0.02, 0.17)*	.112	0.27	.776	0.745 *(0.311, 0.924)*	0.27	0.10	0.3	0.32	0.04
	S2	38.05 ± 0.19	37.99 ± 0.19	✓	0.07 *(-0.03, 0.16)*	.142	0.28	.722	0.694 *(0.231, 0.906)*	0.26	0.10	0.3	0.33	0.04
	S3	38.05 ± 0.17	37.96 ± 0.21	×	0.09 *(0.01, 0.17)*	.031	0.24	.830	0.739 *(0.204, 0.926)*	0.23	0.08	0.2	0.43	0.04
ΔT_{re} (°C)	TSTP	0.61 ± 0.29	0.50 ± 0.24	×	0.11 *(0.07, 0.16)*	.000	0.49	.551	0.496 *(0.308, 0.636)*	0.35	0.18	32	0.43	0.05
	S1	0.58 ± 0.21	0.48 ± 0.20	✓	0.43 *(0.03, 0.17)*	.004	0.43	.422	0.380 *(0.102, 0.605)*	0.28	0.15	29	0.49	0.04
	S2	0.73 ± 0.22	0.60 ± 0.21	✓	0.13 *(0.05, 0.21)*	.007	0.50	.324	0.280 *(0.007, 0.521)*	0.30	0.18	28	0.58	0.04
	S3	0.73 ± 0.28	0.58 ± 0.21	×	0.15 *(0.06, 0.24)*	.007	0.58	.291	0.242 *(-0.025, 0.487)*	1.08	0.21	34	0.58	0.05
$\overline{T}_{sk}$ (°C)	TSTP	30.79 ± 1.19	30.87 ± 1.20	✓	-0.08 *(-0.26, 0.10)*	.371	2.23	.546	0.707 *(0.598, 0.787)*	2.10	0.80	2.6	-0.07	0.24
	S1	30.64 ± 0.97	30.78 ± 0.90	✓	-0.13 *(-0.37, 0.10)*	.259	1.52	.656	0.789 *(0.616, 0.885)*	1.69	0.19	1.8	-0.14	0.19
	S2	31.29 ± 0.91	31.00 ± 1.14	×	0.29 *(0.00, 0.57)*	.047	1.84	.602	0.726 *(0.500, 0.850)*	1.79	0.66	2.1	0.28	0.20
	S3	31.14 ± 1.02	31.14 ± 1.46	×	0.00 *(-0.37, 0.38)*	.983	2.43	.544	0.682 *(0.413, 0.827)*	2.20	0.88	2.8	0.00	0.25
Peak $\overline{T}_{sk}$ (°C)	TSTP	31.60 ± 0.90	31.84 ± 1.32	×	-0.24 *(-1.12, 0.65)*	.566	2.58	.350	0.339 *(-0.325, 0.769)*	1.62	0.93	2.9	-0.19	0.22
	S1	31.13 ± 0.83	31.19 ± 0.88	✓	-0.06 *(-0.58, 0.47)*	.808	1.53	.580	0.600 *(0.008, 0.876)*	1.24	0.55	1.7	-0.06	0.17
	S2	31.47 ± 0.95	31.23 ± 1.21	×	0.24 *(-0.41, 0.89)*	.820	1.90	.622	0.611 *(0.065, 0.877)*	1.55	0.69	2.2	0.20	0.22
	S3	31.27 ± 1.03	31.54 ± 1.71	×	-0.27 *(-1.31, 0.77)*	.579	3.03	.456	0.419 *(-0.233, 0.804)*	2.03	1.09	3.5	-0.17	0.27
$\Delta\overline{T}_{sk}$ (°C)	TSTP	1.75 ± 1.99	0.65 ± 1.64	✓	1.11 *(0.75, 1.46)*	.000	4.20	.314	0.262 *(0.081, 0.421)*	2.49	1.51	126	0.60	0.36
	S1	1.48 ± 1.45	0.50 ± 1.30	✓	0.98 *(0.43, 1.52)*	.001	3.49	.166	0.134 *(-0.107, 0.382)*	1.91	1.26	127	0.70	0.28
	S2	2.12 ± 2.15	0.72 ± 1.67	×	1.40 *(0.75, 2.05)*	.001	4.18	.398	0.308 *(0.011, 0.555)*	2.56	1.51	105	0.71	0.38
	S3	1.97 ± 2.32	0.86 ± 1.98	✓	1.11 *(0.35, 1.88)*	.014	4.92	.327	0.289 *(0.016, 0.529)*	2.98	1.78	125	0.51	0.43

SR ($L \cdot min^{-1}$)	TSTP	0.571 ± 0.089	0.592 ± 0.094	✓	-0.022 *(-0.063, 0.020)*	.274	0.121	.776	0.770 *(0.375, 0.931)*	0.128	0.044	7.5	-0.22	0.018

n = 11; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; P: t test or non-parametric sig.; LoA RE: limits of agreement random error; r: Pearson moment correlation coefficient; ICC: intra-class correlation; T_{re} & $\overline{T}_{sk}$: average measures (k = 12) two-way mixed effect absolute agreement; Peak T_{re}, ΔT_{re}, Peak $\overline{T}_{sk}$, $\Delta\overline{T}_{sk}$ & SR: single measure two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; ΔT_{re}: change in core temperature; T_{re}: core temperature; $\Delta\overline{T}_{sk}$: change in skin temperature; $\overline{T}_{sk}$: skin temperature; SR: sweat rate

Table 4.3: Mean ± SD data for both trials and a battery of reliability statistics for the physiological variables in temperate conditions

Variable		**Trial 1**	**Trial 2**	**Homo-scedastic**	**ΔMean *(± 95% CI)***	***P***	**95% LoA RE (±)**	***r***	**ICC *(95% CI)***	**SEM**	**TEM**	**TEM (CV%)**	**Hedges' g_{av}**	**SWC**
EoG HR	TSTP	142 ± 16	141 ± 16	✓	1 *(0, 2)*	.065	13	.912	0.953 *(0.934, 0.966)*	31	5	3.3	0.07	3
(beats$\cdot$min^{-1})	S1	144 ± 14	143 ± 15	✓	1 *(-1,3)*	.241	13	.895	0.944 *(0.898, 0.970)*	28	5	3.4	0.07	3
	S2	141 ± 17	140 ± 16	✓	1 *(-1,3)*	.315	14	.908	0.951 *(0.911, 0.973)*	32	5	3.6	0.06	3
	S3	141 ± 19	139 ± 18	✓	2 *(0, 4)*	.275	13	.936	0.964 *(0.935, 0.981)*	36	5	3.4	0.08	4
Mean HR	TSTP	131 ± 18	130 ± 16	✓	0 *(-1, 1)*	.922	11	.944	0.905 *(0.865, 0.933)*	19	4	3.1	0.02	3
(beats$\cdot$min^{-1})	S1	133 ± 16	132 ± 15	✓	0 *(-2, 2)*	.774	12	.922	0.961 (0.927, 0.979)	31	4	3.3	-0.01	3
	S2	130 ± 18	130 ± 16	×	0 *(-2, 2)*	.893	12	.941	0.968 *(0.941, 0.983)*	35	4	3.4	0.01	3
	S3	131 ± 19	129 ± 18	×	1 *(-1, 3)*	.330	10	.964	0.981 *(0.964, 0.990)*	37	4	2.8	0.05	4
$\dot{V}O_2$ (ml$\cdot$kg$^{-1}\cdot$min^{-1})	TSTP	24.62 ± 2.20	24.27 ± 2.60	×	0.35 *(-0.09, 0.78)*	.153	2.41	.882	0.864 *(0.743, 0.931)*	3.33	0.87	3.6	0.14	0.48
	S1	24.58 ±1.95	24.05 ± 2.67	×	0.54 *(-0.39, 1.47)*	.228	2.72	.866	0.815 *(0.474, 0.946)*	5.06	0.98	4.0	0.21	0.46
	S2	24.46 ± 2.26	24.52 ± 2.55	×	-0.06 *(-0.94, 0.83)*	.889	2.59	.856	0.861 *(0.560, 0.961)*	3.54	0.93	3.8	-0.02	0.48
	S3	24.81 ± 2.56	24.24 ± 2.81	×	0.56 *(-0.07, 1.20)*	.074	1.84	.943	0.924 *(0.711, 0.980)*	3.41	0.66	2.7	0.19	0.54

n = 11; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; *P*: t test or non-parametric sig.; LoA RE: limits of agreement random error; *r*: Pearson moment correlation coefficient; ICC: intra-class correlation; EoG HR & Mean HR: average measures (k = 12) two-way mixed effect absolute agreement; $\dot{V}O_2$: single measure two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; EoG HR: end of game heart rate; Mean HR: average game heart rate; $\dot{V}O_2$: rate of oxygen consumption

Table 4.4: Mean ± SD data for both trials and a battery of reliability statistics for the perceptual variables in temperate conditions

Variable		**Trial 1**	**Trial 2**	**Homo-scedastic**	**ΔMean** **(± *95% CI)***	***P***	**95% LoA RE (±)**	***r***	**ICC *(95% CI)***	**SEM**	**TE**	**TE (CV%)**	**Hedges' g_{av}**	**SWC**
RPE	TSTP	10 ± 3	10 ± 2	×	0.3 *(0.1, 0.4)*	.004	2	.907	0.945 *(0.924, 0.960)*	5	1	7.9	0.1	0.5
	S1	10 ± 2	10 ± 2	×	0.4 *(-0.0, 0.8)*	.092	3	.732	0.830 *(0.688, 0.907)*	3	1	9.7	0.2	0.4
	S2	11 ± 2	11 ± 1	×	0.0 *(-0.4, 0.4)*	.888	2	.809	0.866 *(0.754, 0.927)*	3	1	7.5	0.0	0.3
	S3	12 ± 2	11 ± 2	×	0.6 *(0.2, 0.9)*	.004	2	.885	0.913 *(0.794, 0.958)*	3	1	6.3	0.27	0.4
TS	TSTP	5 ± 1	4 ± 1	×	0.2 *(0.2, 0.3)*	.000	1	.866	0.902 *(0.797, 0.944)*	1	0	6.1	0.29	0.2
	S1	5 ± 1	4 ± 0	×	0.4 *(0.3, 0.5)*	.000	1	.765	0.761 *(0.130, 0.907)*	1	0	5.9	0.67	0.1
	S2	5 ± 1	5 ± 1	×	0.2 *(0.1, 0.3)*	.001	1	.869	0.899 *(0.740, 0.953)*	1	0	5.3	0.31	0.1
	S3	5 ± 1	5 ± 1	✓	0.3 *(0.2, 0.4)*	.000	1	.891	0.912 *(0.682, 0.964)*	1	0	4.8	0.35	0.1
TC	TSTP	2 ± 1	1 ± 1	✓	0.1 *(0.1, 0.2)*	.000	1	.897	0.940 *(0.912, 0.958)*	1	0	17	0.14	0.2
	S1	2 ± 1	1 ± 1	✓	0.1 *(-0.0, 0.2)*	.180	1	.895	0.944 *(0.897, 0.969)*	1	0	16	0.09	0.1
	S2	2 ± 1	1 ± 1	×	0.2 *(0.1, 0.4)*	.002	1	.885	0.918 *(0.805, 0.961)*	1	0	18	0.26	0.2
	S3	2 ± 1	2 ± 1	✓	0.2 *(0.1, 0.3)*	.008	1	.922	0.952 *(0.899, 0.975)*	2	0	15	0.17	0.2

n = 11; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; *P*: t test or non-parametric sig.; LoA RE: limits of agreement random error; *r*: Pearson moment correlation coefficient; ICC: intra-class correlation, average measures (*k* = 12) two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; RPE: Rating of Perceived Exertion; TS: Thermal Sensation; TC: Thermal Comfort

4.3.3 *Hot, humid conditions*

4.3.3.1 Thermoregulatory

T_{re}, Peak T_{re}, ΔT_{re}, $\overline{T}_{sk}$, Peak $\overline{T}_{sk}$ & SR all have low systematic bias (0.01-0.11 ˚C); $\Delta\overline{T}_{sk}$ has a larger systematic bias (0.26-0.41 ˚C). Only $\Delta\overline{T}_{sk}$ is significantly different between trials, and all but a few have a trivial Hedges' g_{av} effect size. The same is apparent for random error identified through 95% LoA, where $\Delta\overline{T}_{sk}$ has a larger confidence interval than the other variables. Heteroscedasticity is present in a number of variables and timepoints as seen below in Table 4.5. Agreement between conditions is excellent in all thermoregulatory variables (ICC > 0.750). The ICC lower confidence intervals for Peak $\overline{T}_{sk}$ are poor for S1 and S3 (0.312 and 0.336, respectively), good in S2 (0.666) and fair for the TSTP (0.525). However, Pearson's moment correlation coefficient is 0.809-0.975 for all time points. Typical error is low for all variables apart from $\Delta\overline{T}_{sk}$ (>0.29 ˚C compared to 0.62-0.68 ˚C, respectively). Between- and within-participant differences increase throughout the protocol, observed through SWC and SEM, respectively increasing for most variables from S1 to S3.

4.3.3.2 Cardiopulmonary

EoG HR and mean HR demonstrate very low systematic bias (0-2 beats·min^{-1}), no significance of difference between trials (*P>0.05)* and all trivial effect sizes (>0.20). $\dot{V}O_2$ showed systematic bias of 0.3-0.5 ml·kg^{-1}·min^{-1}. A significant difference was observed between trials in S3, and a small effect size (0.2-0.6) was observed in TSTP and S2. Limits of agreement (95%) show random error of 10-20 beats·min^{-1} for HR variables and 0.7-3.1 ml·kg^{-1}·min^{-1} and only $\dot{V}O_2$ in S1 showing heteroscedasticity. HR demonstrates excellent agreement with all ICCs >0.918 (>0.854), and *r* 0.850-0.968. $\dot{V}O_2$ was a little less agreeable. ICCs TSTP, S1 and S3 were fair to excellent, however, S2 was poor to excellent. A similar pattern occurred with *r* reported as 0.791-0.986 and 0.457, for the aforementioned timepoints respectively. Typical error ranged from 4-7 beats·min^{-1} for HR and 0.24-1.11 ml·kg^{-1}·min^{-1} for $\dot{V}O_2$. Between-participant differences remained similar throughout the protocol for HR and $\dot{V}O_2$ with similar SWC throughout. Within-participant differences increased throughout for HR but decreased throughout for $\dot{V}O_2$.

4.3.3.3 Perceptual

Systematic bias was within an acceptable limit for RPE (0.6-1.4), TS (0.3-0.4) and TC (0.4-0.5), however, trials were significantly different ($P < 0.01$) at all time points, in all variables; small effect sizes were also observed (0.23-0.56). Random error was relative to the number of points on the scale with 95% LoA of 2-3 for RPE and 1 for both TS and TC. Homoscedasticity can be seen below in Table 4.7. All variables demonstrated excellent agreement (ICC >0.75). Confidence intervals of overall TSTP for RPE and TC were excellent, and TS was good to excellent. Set time points had lower confidence intervals ranging from poor to excellent. Pearson's *r* evidenced good agreement (0.705-0.941). Typical error was excellent with all variables and timepoints ≤ 1. Between- and within-participant differences were similar throughout the trial in all variables.

Table 4.5: Mean ± SD data for both trials and a battery of reliability statistics for the thermoregulatory variables in hot, humid conditions

Variable		Trial 1	Trial 2	Homo-scedastic	ΔMean *(± 95% CI)*	*P*	95% LoA RE (±)	*r*	ICC *(95% CI)*	SEM	TE	TE (CV%)	Hedges' g_{av}	SWC
T_{re} (°C)	TSTP	38.24 ± 0.58	38.22 ± 0.57	✓	-0.01 *(-0.03, 0.02)*	.592	0.34	.954	0.976 *(0.968, 0.983)*	1.11	0.12	0.3	-0.01	0.12
	S1	37.97 ± 0.31	37.98 ± 0.34	✓	-0.02 *(-0.07, 0.04)*	.534	0.37	.839	0.911 *(0.841, 0.950)*	0.63	0.13	0.3	-0.05	0.06
	S2	38.50 ± 0.35	38.49 ± 0.41	×	-0.02 *(-0.07, 0.04)*	.658	0.35	.901	0.943 *(0.898, 0.969)*	0.75	0.13	0.3	-0.04	0.08
	S3	38.72 ± 0.45	38.68 ± 0.43	✓	0.01 *(-0.05, 0.06)*	.663	0.32	.929	0.964 *(0.933, 0.981)*	0.85	0.11	0.3	0.01	0.09
Peak T_{re} (°C)	TSTP	38.82 ± 0.48	38.86 ± 0.48	✓	-0.04 *(-0.19, 0.11)*	.563	0.46	.884	0.890 *(0.668, 0.967)*	0.70	0.16	0.4	-0.08	0.10
	S1	38.20 ± 0.29	38.23 ± 0.35	×	-0.02 *(-0.15, 0.10)*	.681	0.38	.836	0.832 *(0.516, 0.949)*	0.47	0.14	0.4	-0.07	0.06
	S2	38.61 ± 0.37	38.63 ± 0.47	×	-0.03 *(-0.13, 0.08)*	.609	0.33	.947	0.924 *(0.763, 0.978)*	0.62	0.12	0.3	-0.06	0.08
	S3	38.79 ± 0.50	38.80 ± 0.46	✓	-0.01 *(-0.14, 0.13)*	.943	0.41	.909	0.913 *(0.709, 0.976)*	0.70	0.15	0.4	-0.01	0.10
ΔT_{re} (°C)	TSTP	0.95 ± 0.53	0.94 ± 0.53	✓	-0.01 *(-0.04, 0.02)*	.940	0.36	.938	0.938 *(0.915, 0.955)*	0.74	0.13	14	-0.01	0.11
	S1	0.61 ± 0.25	0.63 ± 0.32	×	-0.02 *(-0.07, 0.04)*	.841	0.36	.819	0.800 *(0.670, 0.883)*	0.41	0.13	21	-0.06	0.06
	S2	1.13 ± 0.35	1.13 ± 0.40	×	-0.01 *(-0.07, 0.05)*	.930	0.41	.849	0.845 *(0.737, 0.911)*	0.54	0.15	13	-0.02	0.08
	S3	1.37 ± 0.48	1.33 ± 0.43	×	0.01 *(-0.05, 0.06)*	.777	0.34	.928	0.925 *(0.867, 0.960)*	0.64	0.12	9.2	0.02	0.09
$\overline{T}_{sk}$ (°C)	TSTP	35.91 ± 0.60	35.95 ± 0.51	×	-0.04 *(-0.12, 0.03)*	.233	0.72	.794	0.981 *(0.972, 0.987)*	2.66	0.26	0.7	-0.08	0.11
	S1	36.21 ± 0.42	36.13 ± 0.43	✓	0.08 *(-0.03, 0.20)*	.194	0.63	.714	0.828 *(0.652, 0.916)*	0.86	0.23	0.6	0.19	0.09
	S2	35.91 ± 0.53	35.98 ± 0.42	×	-0.07 *(-0.16, 0.02)*	.470	0.49	.888	0.923 *(0.852, 0.927)*	0.90	0.18	0.5	-0.14	0.09
	S3	35.81 ± 0.67	35.83 ± 0.60	✓	-0.06 *(-0.21, 0.10)*	.537	0.81	.793	0.884 *(0.756, 0.944)*	1.21	0.29	0.8	-0.09	0.13
Peak $\overline{T}_{sk}$ (°C)	TSTP	36.42 ± 0.42	36.33 ± 0.41	✓	0.09 *(-0.08, 0.27)*	.261	0.41	.875	0.867 *(0.525, 0.971)*	0.57	0.15	0.4	0.19	0.08
	S1	36.37 ± 0.37	36.26 ± 0.40	✓	0.11 *(-0.09, 0.31)*	.230	0.47	.809	0.789 *(0.312, 0.953)*	0.52	0.17	0.5	0.26	0.08
	S2	36.04 ± 0.54	36.11 ± 0.38	×	-0.06 *(-0.23, 0.09)*	.363	0.38	.975	0.915 *(0.666, 0.982)*	0.66	0.14	0.4	-0.13	0.09
	S3	35.89 ± 0.69	35.99 ± 0.50	×	-0.11 *(-0.43, 0.21)*	.443	0.75	.842	0.808 *(0.336, 0.958)*	0.87	0.27	0.8	-0.16	0.12
$\Delta\overline{T}_{sk}$ (°C)	TSTP	5.13 ± 1.93	5.46 ± 1.82	✓	-0.37 *(-0.55, -0.19)*	.002	1.78	.884	0.866 *(0.779, 0.916)*	2.48	0.64	12	-0.20	0.37
	S1	5.43 ± 1.99	5.69 ± 1.85	✓	-0.26 *(-0.58, 0.06)*	.105	1.72	.898	0.891 *(0.787, 0.945)*	2.66	0.62	11	-0.13	0.38
	S2	5.12 ± 1.90	5.54 ± 1.83	✓	-0.41 *(-0.76, -0.07)*	.640	1.87	.869	0.851 *(0.694, 0.927)*	2.47	0.68	13	-0.22	0.37
	S3	5.02 ± 1.91	5.22 ± 1.90	✓	-0.34 *(-0.67, 0.00)*	.213	1.76	.888	0.877 *(0.748, 0.940)*	2.56	0.64	12	-0.17	0.38

SR ($L \cdot min^{-1}$)	TSTP	1.363 ± 0.283	1.342 ± 0.352	×	0.021 *(-0.068, 0.110)*	.685	0.274	.926	0.913 *(0.636, 0.982)*	0.47	0.099	7.3	0.06	0.064

T_{re}, Peak T_{re} & ΔT_{re}, n = 12; $\overline{T}_{sk}$, Peak $\overline{T}_{sk}$, $\Delta\overline{T}_{sk}$ & SR, n = 8; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; P: t test or non-parametric sig.; LoA RE: limits of agreement random error; r: Pearson moment correlation coefficient; ICC: intra-class correlation; T_{re} & $\overline{T}_{sk}$: average measures (k = 12) two-way mixed effect absolute agreement; Peak T_{re}, ΔT_{re}, Peak $\overline{T}_{sk}$, $\Delta\overline{T}_{sk}$ & SR: single measure two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; ΔT_{re}: change in core temperature; T_{re}: core temperature; $\Delta\overline{T}_{sk}$: change in skin temperature; $\overline{T}_{sk}$: skin temperature; SR: sweat rate

Table 4.6: Mean ± SD data for both trials and a battery of reliability statistics for the physiological variables in hot, humid conditions

Variable		**Trial 1**	**Trial 2**	**Homo-scedastic**	**ΔMean** ***(± 95% CI)***	***P***	**95% LoA RE (±)**	***r***	**ICC** ***(95% CI)***	**SEM**	**TEM**	**TEM (CV%)**	**Hedges' g_{av}**	**SWC**
EoG HR	TSTP	151 ± 20	150 ± 20	✓	1 *(-1, 2)*	.275	15	.929	0.963 *(0.963, 0.974)*	39	5	3.5	0.03	4
($beats \cdot min^{-1}$)	S1	148 ± 18	146 ± 19	✓	2 *(-1, 5)*	.781	20	.850	0.918 *(0.854, 0.954)*	35	7	4.9	0.09	4
	S2	154 ± 19	154 ± 19	✓	-1 *(-2, 1)*	.428	11	.956	0.978 *(0.960, 0.988)*	39	4	2.6	-0.03	4
	S3	157 ± 21	156 ± 21	✓	1 *(0, 3)*	.169	10	.968	0.983 *(0.968, 0.991)*	41	4	2.4	0.06	4
Mean HR	TSTP	146 ± 19	146 ± 19	✓	0 *(-1, 1)*	.486	12	.949	0.974 *(0.963, 0.981)*	38	4	2.9	0.02	4
($beats \cdot min^{-1}$)	S1	141 ± 17	141 ± 18	✓	0 *(-2, 2)*	.580	13	.929	0.963 *(0.934, 0.979)*	35	5	3.4	-0.01	4
	S2	148 ± 18	147 ± 18	✓	0 *(-2, 2)*	.702	12	.949	0.974 *(0.953, 0.986)*	37	4	2.8	-0.01	4
	S3	150 ± 21	150 ± 20	✓	1 *(0, 3)*	.159	11	.964	0.981 *(0.965, 0.990)*	40	4	2.6	0.06	4
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	TSTP	25.85 ± 1.70	25.49 ± 1.88	✓	0.38 *(-0.03, 0.80)*	.070	2.30	.791	0.776 *(0.590, 0.883)*	2.48	0.83	3.1	0.21	0.36
	S1	25.95 ± 1.76	25.66 ± 2.27	×	0.29 *(-0.53, 1.12)*	.780	2.55	.821	0.801 *(0.456, 0.938)*	2.91	0.92	3.3	0.13	0.40
	S2	25.63 ± 1.55	25.25 ± 1.40	✓	0.47 *(-0.58, 1.52)*	.343	3.06	.457	0.454 *(-0.144, 0.814)*	2.12	1.11	3.2	0.29	0.29
	S3	25.99 ± 1.92	25.54 ± 1.99	✓	0.40 *(0.16, 0.64)*	.004	0.65	.986	0.968 (0.568, 0.994)	1.86	0.24	2.7	0.19	0.39

n = 12; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; *P*: t test or non-parametric sig.; LoA RE: limits of agreement random error; *r*: Pearson moment correlation coefficient; ICC: intra-class correlation, EoG HR & Mean HR: average measures (*k* = 12) two-way mixed effect absolute agreement; $\dot{V}O_2$: single measure two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; EoG HR: end of game heart rate; Mean HR: average game heart rate; $\dot{V}O_2$: rate of oxygen consumption

Table 4.7: Mean ± SD data for both trials and a battery of reliability statistics for the perceptual variables in hot, humid conditions

Variable		**Trial 1**	**Trial 2**	**Homo-scedastic**	**ΔMean** ***(± 95% CI)***	***P***	**95% LoA RE (±)**	***r***	**ICC** ***(95% CI)***	**SEM**	**TE**	**TE (CV%)**	**Hedges' g_{av}**	**SWC**
RPE	TSTP	12 ± 4	11 ± 3	×	0.9 *(0.6, 1.0)*	.000	3	.941	0.950 *(0.876, 0.974)*	6	1	7.9	0.23	0.7
	S1	12 ± 2	11 ± 2	✓	0.6 *(0.2, 0.9)*	.004	2	.820	0.883 *(0.757, 0.940)*	4	1	7.5	0.28	0.4
	S2	14 ± 3	13 ± 2	×	1.4 *(1.0, 1.8)*	.000	3	.877	0.844 *(0.200, 0.946)*	3	1	7.1	0.54	0.5
	S3	15 ± 3	14 ± 3	×	1.1 *(0.8, 1.5)*	.000	3	.909	0.912 *(0.558, 0.969)*	4	1	6.2	0.39	0.6
TS	TSTP	6 ± 1	6 ± 1	×	0.3 *(0.2, 0.4)*	.000	1	.882	0.911 *(0.807, 0.951)*	2	0	6.6	0.28	0.2
	S1	6 ± 1	6 ± 1	×	0.3 *(0.1, 0.4)*	.000	1	.769	0.817 *(0.585, 0.910)*	1	0	6.1	0.40	0.1
	S2	7 ± 1	6 ± 1	×	0.4 *(0.2, 0.5)*	.000	1	.835	0.848 *(0.539, 0.935)*	1	0	5.7	0.43	0.2
	S3	7 ± 1	6 ± 1	✓	0.4 *(0.3, 0.6)*	.000	1	.880	0.892 *(0.502, 0.961)*	1	0	5.0	0.43	0.2
TC	TSTP	3 ± 1	2 ± 1	✓	0.4 *(0.3, 0.5)*	.000	1	.838	0.883 *(0.731, 0.938)*	2	0	19	0.34	0.2
	S1	2 ± 1	2 ± 1	✓	0.5 *(0.3, 0.7)*	.000	1	.705	0.759 *(0.352, 0.891)*	1	0	21	0.56	0.2
	S2	3 ± 1	2 ± 1	✓	0.5 *(0.3, 0.7)*	.000	1	.803	0.849 *(0.574, 0.933)*	2	1	19	0.41	0.2
	S3	3 ± 1	3 ± 1	✓	0.4 *(0.2, 0.6)*	.000	1	.899	0.924 *(0.755, 0.968)*	2	0	13	0.30	0.3

n = 12; TSTP: tennis-specific treadmill protocol; S1: set 1; S2: set 2; S3: set 3; CI: confidence interval; *P*: t test or non-parametric sig.; LoA RE: limits of agreement random error; *r*: Pearson moment correlation coefficient; ICC: intra-class correlation, average measures (k = 12) two-way mixed effect absolute agreement; SEM: standard error of the measurement; TE: typical error of the measurement; CV: coefficient of variation; RPE: Rating of Perceived Exertion; TS: Thermal Sensation; TC: Thermal Comfort

4.4 Discussion

The aim of this study was to assess the reliability and validity of a novel tennis-specific laboratory-based protocol representing match play work rates and activity profiles. The TSTP has good test-retest reliability for thermoregulatory, physiological and perceptual measures in both temperate and hot, humid environments, with the majority of variables being either reliable (ICC > 0.8; CV < 10%) or highly reliable (ICC > 0.9; CV < 5%) in accordance with defined criterion for reliability (Greg Atkinson & Nevill, 1998; Currell & Jeukendrup, 2008). The TSTP also elicits physiological responses comparable to previously published match play data. Considering all the variables analysed in this study, the TSTP is considered a valid and reliable tool to assess physiological responses in moderately trained tennis players.

4.4.1 *Reliability*

Atkinson & Nevill (1998) suggest reliability studies should have n > 20, however, recruiting participants to achieve this sample size can be difficult with studies such as this that require a specific population using a design that is demanding on participants and includes some invasive procedures. Other studies in the literature have used similar sample sizes previously and reported acceptable reliability statistics (Aldous et al., 2014; James, Richardson, Watt, & Maxwell, 2014; Mee, Doust, & Maxwell, 2015; Relf, Willmott, Flint, Beale, & Maxwell, 2019; Willmott et al., 2015).

4.4.1.1.1 Thermoregulatory

The reliability of rectal temperature in temperate conditions is similar or better than the reliability data during a field hockey specific treadmill protocol using elite female hockey players (Macleod & Sunderland, 2012). They reported a mean difference of -0.08 (-0.01, 0.17) ˚C, LoA of 0.6 ˚C, r = 0.85, ICC = 0.84, SEM = 0.84 ˚C and a CV of 0.6% in environmental conditions of 16.37 ˚C 53% RH. Thermoregulatory responses to the TSTP are likely to be similar with players of different standards. Comparable reliability data in temperate conditions are limited, that T_{re} is more reliable than $\overline{T}_{sk}$. A possible explanation for this is that the environmental chamber samples ambient temperature from a temperature probe located in the ceiling, close to the heating/cooling fans and has a relatively large set-point range before automatic temperature adjustments are made. This makes precise temperature control difficult. and leads to variable airflow temperature (sometimes hot, sometimes cool) which might have affected the participant's skin temperature. However, whilst the ICC seems to indicate this protocol is less reliable, all variables apart from ΔT_{re} and $\Delta \overline{T}_{sk}$ evidence high reliability in CV.

4.4.1.1.2 Cardiopulmonary

Similar comparisons can be made with EoG HR and the aforementioned study with mostly consistent reliability statistics: mean difference 1 (-1, 4) beats·min^{-1}; $r = 0.97$; ICC = 0.98; SEM = 5.72 beats·min^{-1}; LoA = 11 beats·min^{-1} and a CV of 3.5% (Macleod & Sunderland, 2012). This study demonstrated a much higher SEM (31 beats·min^{-1}); which could be due to the participants standard of fitness being more variable. An intermittent ball-sport protocol again had similar findings: mean difference -3.1 (-6.77, 0.57) beats·min^{-1}; TE 3.6 beats·min^{-1}; CV 2.1% (Williams et al., 2010).

Mean HR was aligned with a previously designed soccer match simulation reporting a CV of 2.6% (Russell et al., 2011), and a non-motorised treadmill protocol for team sports with an ICC of 0.933 and a CV of 1.71 (Sirotic & Coutts, 2008).

$\dot{V}O_2$ was more reliable in the TSTP than the team-sport simulation (ICC: 0.598 and CV: 5.28%) though oxygen uptake was measured throughout the simulation with no report on the data processing, so understanding the increased reliability for the TSTP is difficult (Sirotic & Coutts, 2008).

4.4.1.1.3 Perceptual

Reliability statistics for RPE during a ball-sport protocol on a non-motorised treadmill (mean difference: -0.2 (-1.21, 0.88); TE: 1.3; CV: 10.4%) are similar to those found during the TSTP (Williams et al., 2010). It is uncommon to measure thermal perceptual scales in a temperate environment which limits comparisons. In Table 4.4 above that both TS and TC were highly reliable when interpreting ICC, while only TS was reliable for CV. TC is a scale from 1-5; a larger CV (%) will be observed when the measured values are low in magnitude and a small sample size is used, limiting interpretation (Greg Atkinson & Nevill, 1998). Therefore, the absolute measure of TE is likely a more meaningful indicator of reliability when analysing smaller data (Relf et al., 2019; Willmott, Gibson, James, Hayes, & Maxwell, 2018). The TE for TC is low (<0.5) suggesting good reliability.

4.4.1.2 Hot Humid

4.4.1.2.1 Thermoregulatory

Comparisons for the reliability statistics for peak core temperature (T_{re}) are limited with intermittent protocols. However, similar levels of reliability were observed in the TSTP and a 30-minute running heat tolerance test (RHTT) (LoA: 0.37 ˚C; ICC: 0.93; TE 0.13 ˚C; CV: 0.34%) at 40 ˚C and 40% RH (Mee et al., 2015) and a heat acclimation state test (HAST) (mean difference: 0.04 (-0.11, 0.19) ˚C; LoA: 0.53 ˚C; *r*: 0.78; ICC: 0.80; SEM: 0.53 ˚C; TE: 0.19 ˚C; CV: 0.5%; *d*: 0.10) in 44.7 ˚C 18.1% RH (Willmott et al., 2015), suggesting that the TSTP is also reliable.

The TSTP is more reliable than the HAST (mean difference: 0.05 (-0.10, 0.20) ˚C; LoA: 0.47 ˚C; *r:* 0.71; ICC: 0.74; SEM: 0.50 ˚C; TE 0.17 ˚C; CV 24%; *d*: 0.15) when considering ΔT_{re}. The HAST involves continuous cycling exercise in three 30-minute blocks of increasing intensity so is not a direct comparison to the TSTP, although, the HAST exposes participants to exercise in hot conditions over 90 minutes.

A similar observation is evident for peak $\overline{T}_{sk}$ which had similar reliability (LoA: 0.39; ICC: 0.95; TE: 0.14 ˚C; CV: 0.37%) to the RHTT (Mee et al., 2015). Though, the same is not apparent for $\Delta\overline{T}_{sk}$ when compared to other reliability data. James et al. (2014) assessed the reliability of skin thermistors during a graded exercise test in 31.9 ˚C 61% RH (mean difference: 0.18 (-0.46, 0.09) ˚C; LoA: 0.86; ICC: 0.62; TE: 0.31 ˚C; CV; 0.88) reporting a lower mean difference between trials. The protocol in the study was a 5-km time trial on a motorised treadmill with trained runners, which is significantly shorter than the TSTP and a constant rather than intermittent profile of exercise which might explain the higher mean difference observed during the TSTP.

Whole body sweat rate (SR) is comparable to and better than the RHTT (LoA: 0.359 $L \cdot min^{-1}$; ICC: 0.95; TE 0.162 $L \cdot min^{-1}$; CV: 9%) and Relf et al. (2019) during a 30 minute walk at 4 METs (5.6 ± 0.5 $km \cdot hr^{-1}$) in 35˚C 50% RH (ICC 0.94; TE 0.04 $L \cdot min^{-1}$; CV 10.2%; *d*: 0.49).

4.4.1.2.2 Cardiopulmonary

Both HR variables are highly reliable in hot, humid conditions (ICC>0.9 & CV<5%). These results are comparable to the mean HR (ICC: 0.97; TE: 3 $beats \cdot min^{-1}$; CV: 2%) and peak HR (ICC: 0.99; TE: 2 $beats \cdot min^{-1}$; CV: 1%) observed in a repeatability assessment of the RHTT (Mee et al., 2015). $\dot{V}O_2$ was still considered reliable, though ICC was below the 0.8 threshold, the CV was highly reliable below 5% and low TE was observed. A squash-specific on-court aerobic fitness test demonstrated a TE of 1.4 $ml \cdot kg^{-1} \cdot min^{-1}$ for $\dot{V}O_2max$ which was higher than the 0.83 $ml \cdot kg^{-1} \cdot min^{-1}$ in the present study;

however, these both equated to a CV of 3.1%. This demonstrates a similar result for submaximal $\dot{V}O_2$ in this study to maximal $\dot{V}O_2$ values in a squash-specific test (James et al., 2019). These data evidence a similar reliability in the present study to previously published literature for cardiopulmonary variables.

4.4.1.2.3 Perceptual

All perceptual variables were reliable during the TSTP (Table 4.7). The CV for TC was again above the threshold of 10%, however, as before this is due to low magnitude and reliability might then be determined using TE which is deemed to be reliable.

4.4.1.2.4 Validity

Assessing the validity of a tennis-specific protocol is difficult without using a repeated measures design comparing laboratory-based simulation to actual match play (Aldous et al., 2014). Moreover, tennis has a high level of unpredictability, including strategy, weather, opponent tactics all influencing physiology and perception (Kovacs, 2006), with no fixed length for points or matches. Therefore, the aim of the TSTP was to encompass reported tennis match play characteristics and time-motion within a laboratory environment.

The activity pattern of the TSTP is representative of the time-motion and match characteristics of a tennis match which have been previously reported (Filipcic & Filipcic, 2006; Kovacs, 2006, 2007; Reid et al., 2016). Though, there are activities and movements that could not be included, such as change of direction, upper activity, and sprints, due to a motorised treadmill in a controlled laboratory environment. Albeit the absence of these activities, the oxygen uptake throughout the TSTP in this study (24 ± 2 ml·kg^{-1}·min^{-1} in TEMP and 26 ± 2 ml·kg^{-1}·min^{-1} in HH) were comparable to 23-29 ml·kg^{-1}·min^{-1} reported by Fernández-Fernández et al., (2006).

The maximal aerobic capacity of the participants in this study is similar to previously reported values (47.5 - 53.2 ml·kg^{-1}·min^{-1}) of top club (Thomas Reilly & Palmer, 1995; Vodak et al., 1980) and college standard (Kraemer et al., 2003), and some national senior players (Ferrauti, Bergeron, et al., 2001). However other reports show this study's participants to have slightly lower maximal aerobic capacity than state level (M. A. Christmass et al., 1998; Girard & Millet, 2004), national (Smekal et al., 2001) and international (Fernández-Fernández et al., 2006; Mendez-Villanueva et al., 2007) standard players (54.2 – 58.2 ml·kg^{-1}·min^{1}).

During match play, $\dot{V}O_2$ as a percentage of maximum is around 50% regardless of standard (Fernández-Fernández et al., 2006). This was replicated in the current study with similar values observed and a slight increase in $\dot{V}O_2$ in HH compared with TEMP.

The TSTP elicited core temperatures which were lower than the literature. Reported values from actual match play have shown means ranging 38.65-38.9 ˚C in hot (>29 ˚C) conditions (Bergeron, McLeod, & Coyle, 2007; Hornery, Farrow, Mujika, Young, & Pluim, 2007; Morante & Brotherhood, 2007; Tippet et al., 2011) and 38.4-38.7 ˚C in temperate (20-25 ˚C) conditions (Hornery et al., 2007; Morante & Brotherhood, 2007; Périard et al., 2014). Morante & Brotherhood's (Morante & Brotherhood, 2007) data suggest there is no difference in core temperature between standard of player so, the recreational players used in this study were not a likely explanation for the lower core temperatures. Though most research has not reported initial core temperature, some players started around 0.5 ˚C higher than in the present study (Bergeron et al., 2007), however, the peak core temperature was similar to HH in this study. Previous studies using simulated match play protocols have observed peak core temperature values of 38.8-39.5 ˚C (Lynch et al., 2018; Schranner et al., 2017). Based on the rate of rise throughout the TSTP of 0.013 $˚C \cdot min^{-1}$, another 30 minutes might have further increased core temperature by 0.4˚C to around 39.24 ˚C. Therefore, the higher core temperatures observed previously in hot conditions might be due to a longer match time (Hornery, Farrow, Mujika, Young, et al., 2007; Périard, Racinais, et al., 2014b; Tippet et al., 2011) or protocol (Lynch et al., 2018; Schranner et al., 2017), all lasting around 120 minutes, compared to 92 minutes in this study. Further to this, where they were played at professional tournaments, Hornery et al. (Hornery, Farrow, Mujika, Young, et al., 2007) reported court temperatures around 8-9 ˚C higher than air temperatures on hard courts, this increases the radiant heat stress which might account for the increased core temperature values observed.

The mean HR values observed in this study, for both TEMP (131 ± 18) and HH (146 ± 19), are close to previously documented results of 140-160 and 94-164 $beats \cdot min^{-1}$ during singles and doubles competition, respectively. These reported values equate to around 70-80% HRmax (Fernández-Fernández et al., 2009); similar to the %HRmax in this study of 66% in TEMP and 73% in HH.

RPE can range from 11 (light) to 14 (somewhat hard/hard) with peaks of 17 (very hard) (Fernández-Fernández et al., 2008; Mendez-Villanueva et al., 2007). This is higher than observed in this study for TEMP (10 ± 3), though HH was similar (12 ± 4). Mendez-Villaneuva et al. (2007) analysed matches in a similar ambient temperature (20 ± 1 ˚C) but, higher relative humidity (76 ± 6%) compared with TEMP. The rally and rest time ranges were 0.6-53.7 s and 3.7-40.2 s, respectively demonstrating the variability of on-court match play. The measured RPE would have been influenced by the preceding intensity of exercise which would not have been consistent on-court, as it was during the TSTP.

4.5 Conclusion

This protocol is comparable to both previously recorded internal (physiological) and external (time-motion and match characteristics) match play data, though these data are from a range of participants (*i.e.* age and standard) which do not directly compare to the participants in this study. The protocol also demonstrates good reliability. Therefore, meaningful physiological, perceptual, and thermoregulatory inferences can be made using the TSTP in both temperate and hot, humid environments in response to interventions. As suggested by Aldous et al. (2014), such a protocol could also be used in the rehabilitation of players due to both the lack of movement across multiple planes and explosive actions. Using the protocol for this purpose might allow institutes and practitioners to develop strategies for competition and governing bodies such as the ITF, WTA, ATP and Grand Slam Board to assess policies e.g. heat policies.

5 The Effect of Increasing Between-Point Rest Length on Thermoregulation During Tennis-Specific Treadmill Exercise

5.1 Introduction

Depending on the severity of the environmental conditions, tennis players core temperatures can vary from 38.3 to 39.4 ˚C (Bergeron et al., 2006; Morante & Brotherhood, 2008a; Périard, Racinais, et al., 2014b; Tippet et al., 2011). As core temperature rises above 39 ˚C, the risk of heat illness and performance is increased (Armstrong et al., 2007; Sawka et al., 1992). Core temperature is driven by the balance of heat gain through metabolic heat production and heat loss through convective, conductive, radiant and evaporative mechanisms (Nielsen et al., 1988). This balance is represented by the exercise-to-rest ratio where heat gain increases during points and heat loss increases during rest, demonstrating the importance of rest length in tennis. The Grand Slam Board increased the maximum length of rest allowed between points in 2018, from 20 to 25 seconds, bringing it in line with the ATP and WTA tours.

Periard et al. (2014) allowed players to self-select the rest between points and documented a mean increase of 9.6 s in rest duration with 27.6 ± 2.8 s rest in hot conditions (36.8 ± 1.5˚C 36.1 ± 11.3% RH) compared with 18.0 ± 4.2 s in temperate conditions (21.8 ± 0.1˚C 72.3 ± 3.2% RH); self-selecting a longer rest length when playing in the heat than the updated Grand Slam stipulation of 25 s. The introduction of the shot clock, which counts down the rest length and was first used in a Grand Slam at the US Open in 2018, prevents the umpire's discretion when issuing time violations to players who exceed this limit. Choosing to take a longer rest between points in an example of behavioural thermoregulation, as players feel too hot and has also been observed by others (Hornery, Farrow, Mujika, Young, et al., 2007; Morante & Brotherhood, 2008b). Another example of behavioural thermoregulation is that players change their tactics during match play, by hitting harder and/or closer to the lines in an attempt to shorten the points (Morante & Brotherhood, 2008b). These behavioural adjustments are an attempt to reduce the risk of retirement, illness, or injury and can negatively influence performance.

Currently, the heat policy in tennis is not universal across all governing bodies (see section 2.3.5) with the ATP (2021) offering no heat policy whatsoever. The policies currently implemented include modification of play at ⩾30.1 ˚C WBGT and suspension of play at ⩾32.2 ˚C WBGT. The modification of play threshold invokes cooling devices having to be made available (WTA, 2021) and a 10-min extended break if a match exceeds 2 sets in a best-of-three set match or 3 sets in a best-of-five set match (see section 2.3.5). The effect of a 10-minute extended break has been assessed in professional female players performing in an ambient temperature of 30.3 ± 2.3 ˚C. Players started the break (between set 2 and 3) with a core temperature of 38.92 ˚C and through sitting in an air-conditioned room or shade combined with towelling down and changing clothes, core temperature decreased by 0.25 ± 0.20 ˚C to 38.67 ˚C (Tippet et al., 2011). A similar reduction of 0.21 ˚C was observed after an extending half time (20 vs 15 minutes) during a simulated football protocol, which also reduced exercising heart rate by 8 beats·min^{-1} and session RPE by 0.9, though no differences in skin temperature or thermal sensation were apparent (Chalmers et al., 2019). A similar strategy reduced playing time by 2 to 3 min and extending the half-time break by the same duration, as well as a 2-min break at the mid-point in each half during a youth football tournament in the heat (Elias et al., 1991). Introducing this strategy led to fewer reported cases of heat illness during the remainder of the tournament (Elias et al., 1991). Interspersed rest also increases the duration of exercise prior to exhaustion in the severe exercise domain (~70-80% $\dot{V}O_2max$) in a temperate environment (Jones & Vanhatalo, 2017), a similar intensity to peaks reported in tennis (Fernandez-Fernandez et al., 2009; Fernandez, Mendez-Villanueva, & Pluim, 2006).

Provided the environment is compensable, extended breaks or additional rest periods during exercise reduce thermal strain and demonstrate an improvement in exercise capacity, achieved through greater heat dissipation and a simultaneous reduction in metabolic heat production. The extended break is effective at reducing thermal strain in tennis (Tippet et al., 2011), however, if a similar response is apparent from extending the between-point rest length to match the reported self-selected rest length (Périard, Racinais, et al., 2014b), this might provide a practical alternative strategy for policy makers and tournament organisers which would likely be welcomed by players competing in the heat.

The aim of this study was to assess the physiological and perceptual response to increasing between-point rest length, in comparison to a temperate environment, during simulated tennis match play in hot humid conditions.

5.2 Methods

5.2.1 *Participants*

Nine male tennis players volunteered for this study (mean ± standard deviation [SD] age 23 ± 6 years, height 1.79 ± 0.79 m, body mass 77.0 ± 12.1 kg, percentage body fat (PBF) 14.3 ± 5.5 %, body surface area (BSA) 1.96 ± 0.19 m^2, gas exchange threshold (GET) 12.7 ± 1.7 $km \cdot hr^{-1}$ and maximal aerobic capacity ($\dot{V}O_{2max}$) 49 ± 4 $ml \cdot kg^{-1} \cdot min^{-1}$). Participants were moderately trained ($\dot{V}O_{2max}$ > 43 $ml \cdot kg^{-1} \cdot min^{-1}$), train at least twice per week, play tennis competitively (in local, university or college leagues), non-smokers, free from any known cardiorespiratory disorders and had not been exposed to hot conditions for 6 weeks prior to testing. All experimental procedures were approved by the institution's ethics committee and conducted in accordance with the guidelines of the Declaration of Helsinki (World Medical Association, 2013).

5.2.2 *Experimental design*

After undertaking a preliminary testing and familiarisation session, participants returned to the lab to complete a tennis-specific treadmill protocol (TSTP) under three conditions:

- **TEMP**; 20.2 ± 0.2°C, 49.7 ± 1.8% Relative Humidity [RH], 15.5 ± 0.3 Wet Bulb Globe Temperature [WBGT] with 20 s between-point rest
- **HOT20**; 36.1 ± 0.2°C, 49.9 ± 0.7% RH, 29.6 ± 0.3 WBGT with 20 s between-point rest
- **HOT30**; 36.0 ± 0.1°C 50.0 ± 1.6% RH, 29.6 ± 0.3 WBGT with 30 s between-point rest

Experimental trials were completed in a randomised order and separated by at least 48 h to avoid any heat adaptation.

5.2.3 *The Tennis-Specific Treadmill Protocol (TSTP)*

The protocol used during this testing was the TSTP, as seen in Figure 3.4. The design of which is detailed in section 3.11 of this thesis. The between-point rest was adjusted to be either 20 or 30 s as per the conditions listed in 5.2.2 above.

5.2.4 *Preliminary measurements*

Anthropometric and physiological characteristics were identified, as well as, ensuring participants were familiarised to the TSTP in the hot, humid conditions. Warm up speeds were then calculated based on this assessment. This was as detailed in section 3.5.5.

5.2.5 *Experimental procedures*

Experimental sessions were all completed in an environmental chamber (Watford Refrigeration & Air Conditioning Ltd., Hertfordshire, UK). Participants undertook sessions at the same time of day to account for circadian rhythmic changes and were asked to refrain from eating for 2 hours, undertaking strenuous activity for 48 hours, consuming alcohol for 24 hours and consuming caffeine for 12 hours, prior to testing. All participants were instructed to drink 500 ml of water a few hours prior to the trial to ensure arrival in a euhydrated state indicated by a urine osmolality > 700 $mOsm \cdot kg^{-1}$ (Sawka et al., 2007), measured on a Pocket Pal-Osmo (Advanced Instruments, Horsham, UK). If this threshold was not met (one incidence), participants were given water before waiting 30 mins to reassess hydration status. Urine colour (U_{col}) was also assessed alongside osmolality (Armstrong, 2000).

Upon arrival at the laboratory, participants voided their bladder for the assessment of hydration status. Once euhydration was confirmed, a rectal probe (Eltek U-type VL-U-VL5-0, Eltek Ltd., Cambridge, UK) was self-inserted, 10 cm past the anal sphincter, to record rectal temperature (T_{re}), before nude body mass (NBM) and clothed body mass (CBM) (Adam GFK 150H, Adam Equipment Co. Ltd., Milton Keynes, UK) were recorded. Following hair removal, skin thermistors (iButton DS1922L, Measurement Systems Ltd, Newbury, UK) were attached to the mid belly of the pectoralis major, triceps brachii, rectus femoris and gastrocnemius on the right side of the body using KT tape (KT Health, LLC, Utah, USA) and zinc oxide tape (Leukoplast, BSN medical GmbH, Hamburg, Germany); these logged every 5 s and were downloaded post-trial allowing the calculation of mean skin temperature ($\overline{T}_{sk}$). The rectal thermistor was recorded at a frequency of 5 s on a Squirrel 1000 data logger (Grant Instruments, Cambridge, UK) and downloaded post-trial. A HR belt was fitted (Polar H10, Polar Electro, Finland); and linked to a recording watch with a frequency of 5 s (Polar RS400, Polar Electro, Finland). Finally, a resting [BLa] was collected through fingertip capillary blood sampling and analysed (Biosen C-Line, EKF Diagnostics, Cardiff, UK). Once the participant had been prepared, resting physiological and perceptual measures were noted at room temperature, prior to entering the environmental chamber.

The experimental protocol consisted of a five-minute seated acclimatisation period, a 5-minute warm up at a speed equivalent to 80% of the GET, and completion of the TSTP. Environmental conditions were monitored on entry to the chamber, prior to the TSTP and at the end of each of the 3 sets, using a heat stress meter (HT30, Extech Instruments, USA). Post-warm up, HR, T_{re}, $\overline{T}_{sk}$ and perceptual scales were noted. Heart rate, T_{re}, $\overline{T}_{sk}$ and perceptual variables (RPE, TS and TC) were recorded at the end of games 3, 5, 7 and 9, with [BLa] collected during the “change of ends” sit down. Mean HR was calculated using the data recorded every 5 seconds in the same games. During game 7 in each set expired air was collected for later analysis of $\dot{V}O_2$. After every odd game, participants were required to drink 150 ml of water (TEMP: 18.4 ± 0.3 °C; HOT20: 29.7 ± 1.7 °C; HOT30: 30.1 ± 0.8 °C) whilst sitting down; between games 1 and 2 in each set, the participant drank water but remained on the treadmill. This replicated change of ends in a tennis match. "Time" was called with 30 s left of the rest period to allow the participants to get back on the treadmill ready for the start of the next game. If participants needed to urinate, they did so between sets in the environmental chamber, after data had been collected; volume of urine was then accounted for in the sweat rate (SR) calculation.

Following the completion of the TSTP, NBM and CBM were recorded again to calculate sweat rate (SR). The trial was terminated early if participant's T_{re} reached 39.7 °C (Willmott et al., 2015) or volitional exhaustion occurred. Participant’s T_{re} was then lowered through cooling measures and participants monitored until they were within 0.5 °C of their resting value.

5.2.6 *Data Processing*

The data processing for skin temperature (Equation 3.2), sweat rate (Equation 3.3), and protocol completion (Equation 3.4) is detailed in chapter 3.

5.2.7 *Statistical analysis*

Data were assessed for normality using the Kolmogorov-Smirnov test; significance set at $P > 0.05$. If data were significant the Shapiro Wilk statistic was observed with the same significance. If data violated normality, a Wilcoxon signed rank test or a Friedman’s two-way Analysis of Variance (ANOVA) by ranks assessed between-trial differences. Prior to parametric ANOVA, data were assessed using Mauchly's test for sphericity; if this was violated ($P < .05$), the Greenhouse-Geisser correction was used.

Hydration status, NBM, resting T_{re} and SR were analysed using a one-way repeated measures ANOVA. Percentage protocol completion was analysed by a paired samples *t*-test. All other physiological and perceptual variables were analysed using two-way repeated measures ANOVAs (condition x time); all had 3 levels of condition. The levels of time differed between variables and were as follows: T_{re}, $\overline{T}_{sk}$, end of game HR, RPE, TS and TC (5 levels: rest, post-warm up, set 1, set 2 and set 3); mean HR and $\dot{V}O_2$ (3 levels: set 1, set 2 and set 3); and ΔT_{re} and $\Delta\overline{T}_{sk}$ (4 levels: post-warm up, set 1, set 2 and set 3). Where main and/or interaction effects were evident, Bonferroni corrected paired samples t-tests were performed to identify where differences occurred.

All data were analysed using a standard statistical package (SPSS 24.0) with statistical significance being accepted at the level of $P < 0.05$. Data were reported as the mean ± standard deviation (SD) of every measurement taken during the time frame referred to, for all participants *e.g.,* Set 1 would consist of a mean of all participants over 4 time points (post-games 3, 5, 7 and 9).

5.3 Results

5.3.1 *Preliminary Measures*

There were no significant differences between conditions for hydration status ($F_{(2,16)} = 1.015$, $P = .385$, $\eta_p^2 = 0.113$), pre-trial nude body mass ($F_{(2,16)} = 0.196$, $P = .824$, $\eta_p^2 = 0.024$) or resting T_{re} ($F_{(2,16)} = 0.937$, $P = .412$, $\eta_p^2 = 0.105$).

5.3.2 *Protocol Completion*

All participants completed the TSTP in TEMP. In both hot trials, 2 participants did not complete the TSTP, due to T_c reaching 39.7 °C. One participant was stopped at the end of set 3, game 3 (76% completed) and set 3, game 6 (86%) in HOT20 and HOT30, respectively. The other participant was stopped at the end of set 3, game 4 (80%) and set 3, game 8 (94%) in HOT20 and HOT30, respectively. Though not significant, both participants completed a higher percentage of the protocol in the HOT30 trial ($t_{(1)} = -6.00$; $P = .105$; $g_{av} = 2.03$).

5.3.3 *Thermoregulatory Measures*

5.3.3.1 Rectal Temperature

As seen in Figure 5.1 below, the rise in rectal temperature during the TSTP was different across all conditions ($F_{(12, 96)} = 3.481$, $P = .03$, $\eta_p^2 = 0.303$). Throughout set 1, all conditions saw a similar increase in rectal temperature until the last measurement of the set, where HOT20 had then increased more than TEMP (38.24 ± 0.25˚C vs 37.99 ± 0.2˚C, $P = .017$, $g_{av} = 1.00$). From this stage, rectal temperatures in TEMP remained relatively stable until the end of the TSTP whilst those in HOT20 and HOT30 continued to rise ($P < .05$). It can also be seen in Figure 5.1 below that rectal temperatures rised faster and higher in HOT20 compare with HOT30 from the start of set 2 until game 7 in set 3 (*P < .05)*.

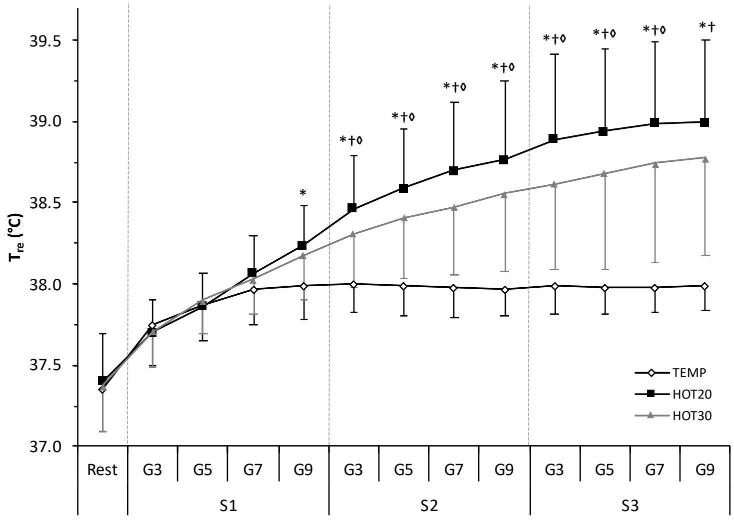

Figure 5.1: Rectal temperature during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 ($P < .05$). †Significant difference between TEMP and HOT30 ($P < .05$). ◊Significant difference between HOT20 and HOT30 ($P < .05$).

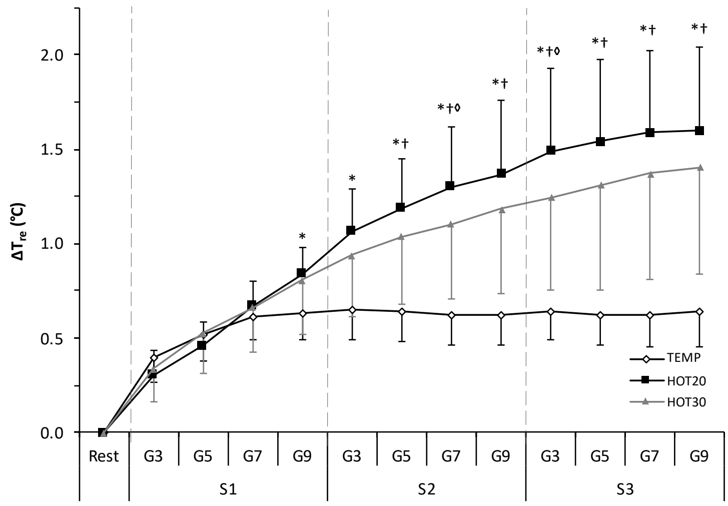

Figure 5.2: Change in rectal temperature during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 ($P < .05$). †Significant difference between TEMP and HOT30 ($P < .05$). ◊Significant difference between HOT20 and HOT30 ($P < .05$).

5.3.3.2 Mean Skin Temperature

Whilst there was no difference in resting values ($P > .05$), mean skin temperature was higher in both HOT20 and HOT30 compared with TEMP ($F_{(2, 16)} = 424.266$, $P < .001$, $\eta_p^2 = 0.981$). However, as can be seen in Figure 5.3 below, there was no interaction effect between conditions over time ($F_{(12, 96)} = 1.899$, $P = .163$, $\eta_p^2 = 0.192$).

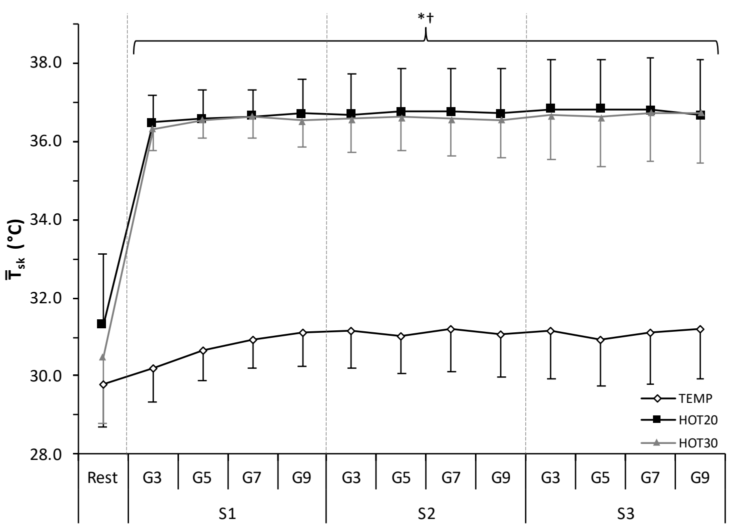

Figure 5.3: Skin temperature during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 ($P < .05$). †Significant difference between TEMP and HOT30 ($P < .05$).

5.3.3.3 Sweat Rate

Sweat rate had a main effect of trial ($F_{(2, 16)} = 75.640$; $P < .000$; $\eta_p^2 = 0.904$). Pairwise comparisons showed that the sweat rate in TEMP (0.582 ± 0.094 $L \cdot min^{-1}$) was lower than HOT20 (1.190 ± 0.181 $L \cdot min^{-1}$; $P < .001$; $g_{av} = 3.81$) and HOT30 (0.950 ± 0.198 $L \cdot min^{-1}$; $P = .001$; $d = 2.37$). Sweat rate was also higher in HOT20 than HOT30 ($P = .002$; $g_{av} = 1.15$).

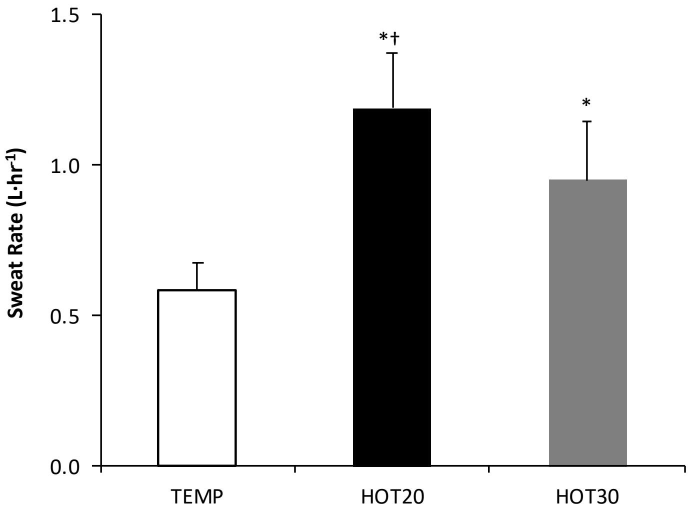

Figure 5.4: Sweat rate of the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference from TEMP ($P < .05$). †Significant difference HOT30 ($P < .05$).

5.3.4 *Physiological Measures*

5.3.4.1 Heart Rate

A condition x set x game interaction effect was observed through statistical analysis on heart rate ($F_{(12, 96)} = 1.966$, $P = .036$, $\eta_p^2 = 0.197$). Throughout the whole of the TSTP both HOT20 and HOT30 elicited a higher HR than TEMP ($P > .05$). HOT20 was also observed to be higher than HOT30 at the end of set 2 game 7 (164 ± 22 vs 157 ± 21; $P = .01$; $g_{av} = 0.29$), set 3 game 7 (166 ± 20 vs 159 ± 22; $P = .012$; $g_{av} = 0.30$) and set 3 game 9 (166 ± 20 vs 157 ± 21; $P = .012$; $g_{av} = 0.40$).

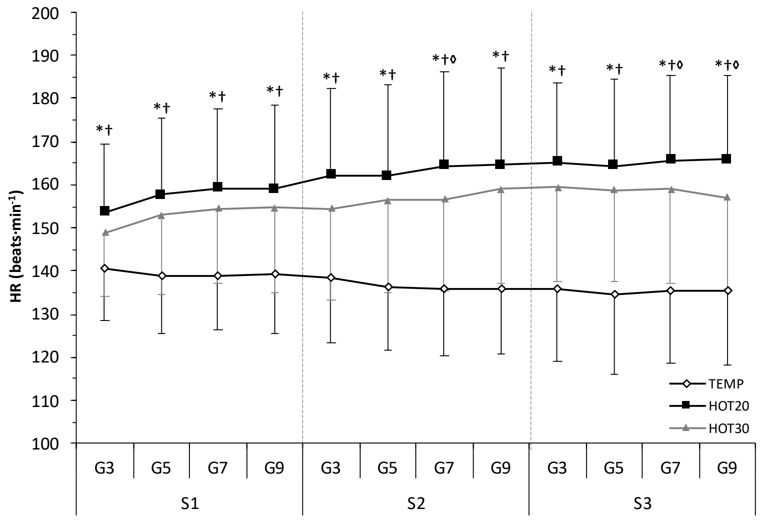

Figure 5.5: End of game heart rate during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 (P < .05). †Significant difference between TEMP and HOT30 (P < .05). ◊Significant difference between HOT20 and HOT30 (P < .05).

5.3.4.2 Mean Heart Rate

A 3-way interaction effect was not evident for mean HR ($F_{(12, 96)} = 2.491$, $P = .137$, $\eta_p^2 = 0.237$), though a condition x set interaction effect was significant ($F_{(4, 32)} = 19.963$, $P < .001$, $\eta_p^2 = 0.714$). As seen in Figure 5.6 below, mean HR was higher in HOT20 and HOT30 than TEMP (P < .05) throughout the TSTP. During set 3, HOT20 also elicited a higher mean HR than HOT30 (155 ± 23 vs 148 ± 24; $P = .035$; $g_{av} = 0.27$).

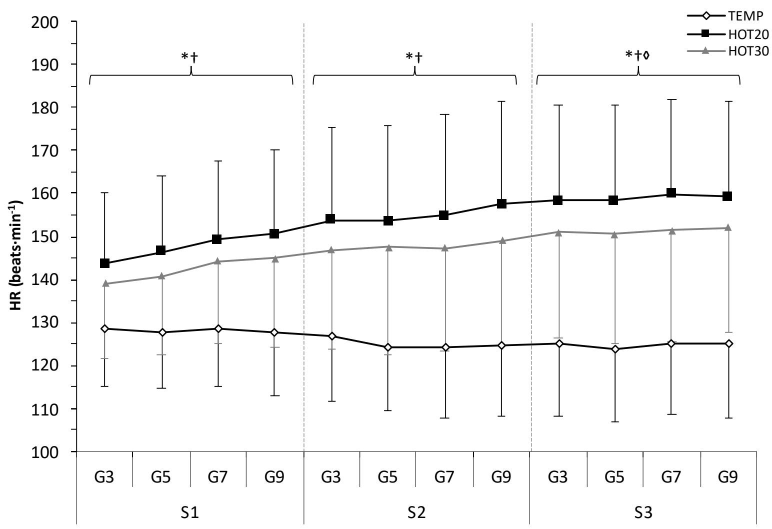

Figure 5.6: Mean heart rate during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 (P < .05). †Significant difference

between TEMP and HOT30 ($P < .05$). ◊Significant difference between HOT20 and HOT30 ($P < .05$).

5.3.4.3 Oxygen Uptake

Oxygen uptake showed a significant time x condition interaction effect ($F_{(4,24)} = 2.87$, $P = .045$, $\eta_p^2 = 0.323$). Pairwise comparisons revealed $\dot{V}O_2$ was significantly higher in the HOT20 trial (S1: 25.98 ± 3.03 $ml \cdot kg^{-1} \cdot min^{-1}$; S2: 26.88 ± 3.17 $ml \cdot kg^{-1} \cdot min^{-1}$; S3: 26.23 ± 2.72 $ml \cdot kg^{-1} \cdot min^{-1}$) compared with the TEMP (S1: 24.08 ± 2.42 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .014$; $g_{av} = 0.62$; S2: 24.18 ± 2.47 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .028$; $g_{av} = 0.86$; S3: 24.13 ± 2.78 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .012$; $g_{av} = 0.69$) and HOT30 trials (S1: 22.38 ± 2.29 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .006$; $g_{av} = 1.21$; S2: 22.24 ± 2.66 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .003$; $g_{av} = 1.44$; S3: 20.73 ± 2.07 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .002$; $g_{av} = 2.06$) during all 3 sets. $\dot{V}O_2$ was not significantly different between HOT30 and TEMP during set 1 (22.38 ± 2.29 vs 24.08 ± 2.42 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .197$; $g_{av} = 0.65$), however, it was significantly lower in HOT30 than TEMP in set 2 (22.24 ± 2.66 vs 24.18 ± 2.47 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .04$; $g_{av} = 1.44$) and set 3 (20.73 ± 2.07 vs 24.13 ± 2.78 $ml \cdot kg^{-1} \cdot min^{-1}$; $P = .12$; $g_{av} = 1.26$).

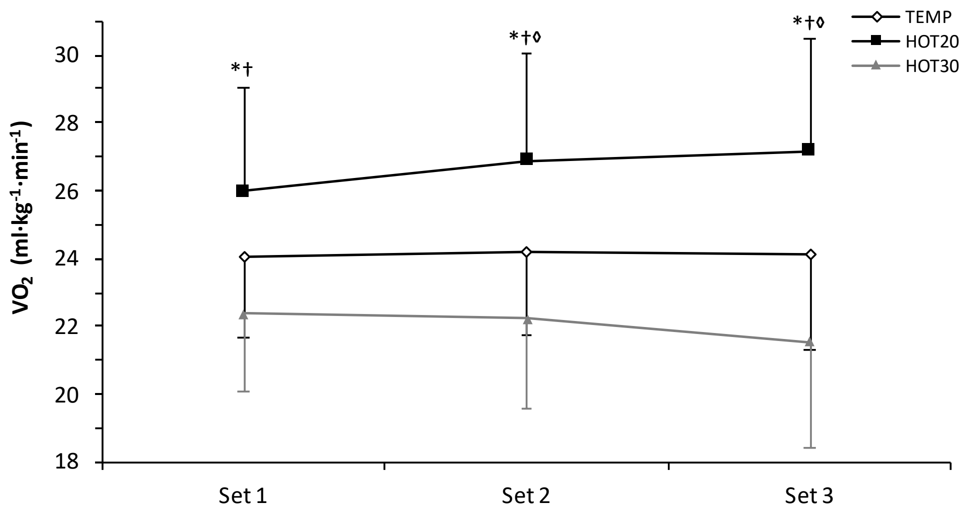

Figure 5.7: Oxygen uptake during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 ($P < .05$). †Significant difference between TEMP and HOT30 ($P < .05$). ◊Significant difference between HOT20 and HOT30 ($P < .05$).

5.3.4.4 Blood Lactate

Blood lactate concentration showed no main effect for time ($F_{(3,21)} = 3.50$, $P = .094$, $\eta_p^2 = 0.333$), condition ($F_{(2,14)} = 3.31$, $P = .067$, $\eta_p^2 = 0.321$) nor a significant time x condition interaction effect ($F_{(6,42)} = 0.79$, $P = .582$, $\eta_p^2 = 0.102$).

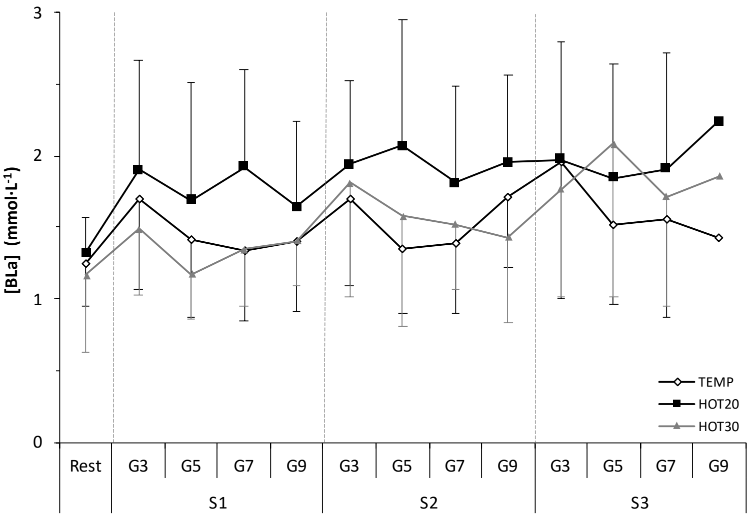

Figure 5.8: Blood lactate concentration during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD.

5.3.5 *Perceptual Measures*

5.3.5.1 Rating of Perceived Exertion

A significant condition x set interaction effect was observed for RPE ($F_{(4, 32)} = 7.751$, $P < .001$, $\eta_p^2 = 0.492$), whilst a 3 way interaction effect was not ($F_{(12, 96)} = 1.301$, $P = .231$, $\eta_p^2 = 0.14$). RPE was higher in HOT20 than TEMP in set 1 (12.3 ± 2.2 vs 9.9 ± 1.4; $P = 0.38$; $g_{av} = 1.18$), set 2 (14.3 ± 2.7 vs 11.1 ± 1.3; $P = 0.006$; $g_{av} = 1.36$), and set 3 (15.6 ± 3.2 vs 11.4 ± 1.6; $P = 0.002$; $g_{av} = 1.50$). HOT30 was also higher than TEMP during set 3 (15.3 ± 4.2 vs 11.4 ± 1.6; $P = 0.2$; $g_{av} = 1.11$).

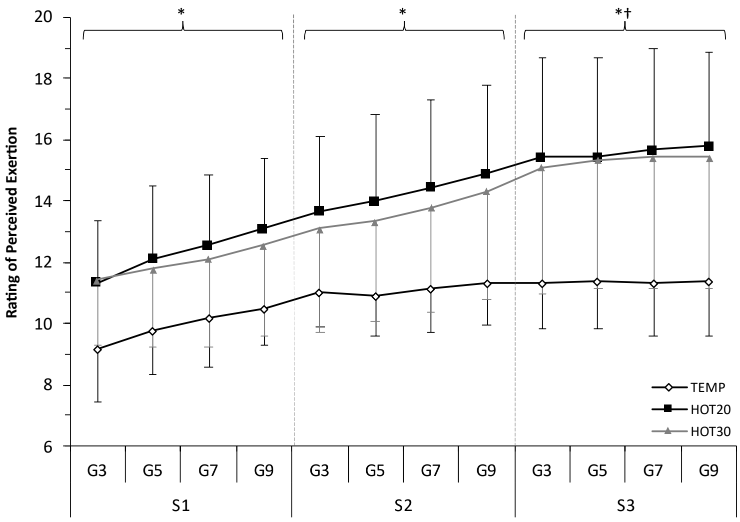

Figure 5.9: Rating of perceived exertion during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9),

mean ± SD. *Significant difference between TEMP and HOT20 (P < .05). †Significant difference between TEMP and HOT30 (P < .05).

5.3.5.2 Thermal Sensation

A significant 2-way (condition x set) effect ($F_{(4, 32)} = 3.489$, $P = .018$, $\eta_p^2 = 0.304$), but not a 3-way (condition x set x game) effect ($F_{(12, 96)} = 1.046$, $P = .414$, $\eta_p^2 = 0.116$) was apparent for TS. As seen in Figure 5.10 below TS was greater in HOT20 and HOT30 compared with TEMP in all 3 sets (P < .05) whilst no difference was observed between the hot conditions (P > .05).

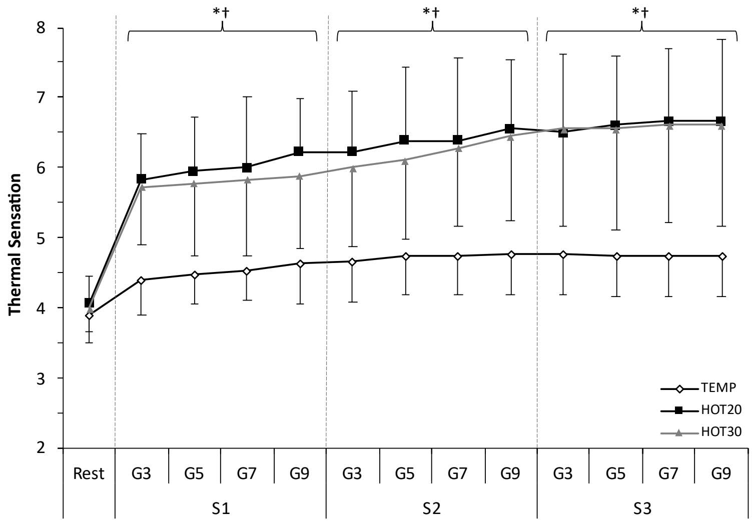

Figure 5.10: Thermal sensation during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 (P < .05). †Significant difference between TEMP and HOT30 (P < .05).

5.3.5.3 Thermal Comfort

Thermal comfort can be seen in Figure 5.11 below. Whilst a main effect was apparent ($\chi^2_{(35)} = 208.574$; $P < .001$), pairwise comparisons revealed no differences between conditions at any of the time points throughout the TSTP (P > .05).

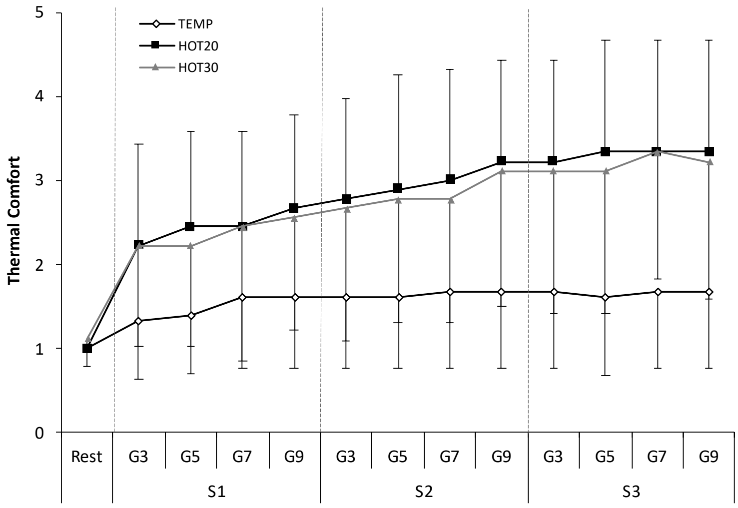

Figure 5.11: Thermal comfort during the TSTP in temperate (TEMP), hot with 20 s between-point rest (HOT20) and hot with 30 s between point rest (HOT30) conditions (n = 9), mean ± SD. *Significant difference between TEMP and HOT20 ($P < .05$). †Significant difference between TEMP and HOT30 ($P < .05$).

5.4 Discussion

The aim of this study was to assess the physiological and perceptual responses to increasing between-point rest length, in comparison to a temperate environment, during simulated tennis match play in hot humid conditions. The rise in T_{re} was attenuated in HOT30 compared to HOT20 from the start of the second set ($P < 0.05$) and heart rate was lower in HOT30 than HOT20 in the third set ($P < 0.05$). The hot conditions elicited increased thermal, cardiovascular, and perceptual strain compared to a temperate environment ($P < 0.05$).

Peak rectal temperature was lower in the trial with increased between-point rest by 0.22 ˚C in set 2 and 0.23 ˚C in set 3. This finding is a similar magnitude to the reduction of 0.25 ± 0.20 ˚C in core temperature following the 10-min extended break between sets 2 and 3 in female tennis players during match play (Tippet et al., 2011), and the reduction of 0.21 ˚C in core temperature following an extended half-time break in a simulated football protocol (Chalmers et al., 2019). This reduction is due to the longer rest decreasing the exercise-to-rest ratio allowing increased heat dissipation for the participants between-points. Heat production is dependent on the intensity of exercise; therefore, a fixed intensity protocol ensures the metabolic heat production is matched between trials and any change in core temperature demonstrates changes in the ability to dissipate heat. Whilst rectal temperature is decreased by 0.22 and 0.23˚ C in sets 2 and 3, respectively, skin temperature was not different between hot trials ($P > 0.05$). This is due to skin temperature being heavily influenced by the surrounding environment (Flouris & Schlader, 2015). A decreased sweat rate was observed in HOT30 compared with HOT20; participants had similar absolute sweat losses in both trials, however, the longer duration of protocol resulted in a reduced relative sweat rate.

Heart rate was higher during the hot conditions than the temperate condition. The elevated thermal strain will lead to an increased skin blood flow for heat dissipation, which leads to reductions in stroke volume and mean arterial pressure. Heart rate is then elevated to maintain cardiac output. Heart rate is lower by ~5 beats·min^{-1} in HOT30 than HOT20 in the second half of the protocol (see Figure 5.5 and Figure 5.6) which is similar to the magnitude of change observed following a reduction in core temperature similar to that in the present study (0.21 vs 0.23 ˚C). The reduced heart rate may evidence reduced thermal strain through enhanced heat dissipation via evaporative mechanisms. However, as skin temperature is the same in both hot trials it would suggest this is not the case and the reduced heart rate is more likely due to the longer rest length allowing increased recovery. A similar result was observed during a simulated football match where a decreased HR was apparent when an extended half time break was implemented (Chalmers et al., 2019).

Thermal perception influences playing style, decision making and length taken between points (Hornery, Farrow, Mujika, Young, et al., 2007; Morante & Brotherhood, 2008b). Mean RPE ranged from around 9-11 (very light to fairly light) in TEMP and 11-15 (fairly light to hard) in HOT20 and HOT30 (Figure 5.9). Perceived exertion was higher during HOT20 than TEMP for the duration of the TSTP, whilst HOT30 was only higher than TEMP in set 3; no difference was observed between hot conditions. The perceived exertion of 10 in set 3 was lower than 11-13 observed in tennis match play in temperate conditions, though results were comparable in hot conditions with an RPE of 15 in the TSTP being similar to 14-17 in match play (Périard, Racinais, et al., 2014b). The investigation by Périard, Racinais, et al., (2014b) was outdoors and therefore the players would also have been exposed to radiant heat which would increase skin temperature compared to the laboratory (Levels et al., 2014). Prior to the increase in core temperature, skin temperature influences thermal sensation which is thought to determine RPE (Flouris & Schlader, 2015); it is possible that a higher skin temperature would explain any difference early in the match and during temperate conditions. However, once core temperature rises, cardiovascular strain is likely the primary influence of RPE (Flouris &

Schlader, 2015), with skin temperature also a contributing factor (Tatterson et al., 2000). Heart rate and skin temperature data are comparable between the present study and Périard, Racinais, et al., (2014b) which might explain the similar RPE. It might also be due to comparing on-court match play which is unpredictable to a fixed intensity treadmill protocol. The other perceptual variables (TS & TC) were not different between hot conditions which is to be expected as these are influenced by skin temperature (Flouris & Schlader, 2015), which did not differ between hot conditions. Whilst the TS was higher in HOT20 and HOT30 compared with TEMP, there was no difference between temperate and hot conditions in TC. This is likely due to the variability in responses from participants, which can be seen in the error bars in Figure 5.11. Though, it can be seen in the same graph that TC was trending higher in the hot conditions.

Core temperature, skin temperature, cardiovascular strain, perceived exertion and thermal perception all contribute towards behavioural thermoregulation (Flouris & Schlader, 2015). Increasing between-point rest length attenuates the rise in T_{re} by 0.23 ˚C and heart rate by around 5 beats·min^{-1}. This might ameliorate behavioural reductions in intensity during tennis match play as perceived exertion is trending lower with the longer rest period, suggesting a reduction in cardiovascular strain (Flouris & Schlader, 2015). There might also be benefits for enhanced decision making and therefore their ability to build points effectively rather than attempting to end the point quickly (Morante & Brotherhood, 2008b). Skin wettedness would also increase players' thermal perception, especially in humid conditions with limited airflow (Fukazawa & Havenith, 2009), which should be considered in future studies.

Conclusion

Increasing between-point rest length from 20 to 30 s attenuates the rise in core temperature from set 2 onwards and lowers heart rate in the final set. These physiological changes might decrease cardiovascular strain, which has implications for reducing the prevalence and severity of heat illness. Other acute interventions such as cooling require specialist equipment and might not be plausible on the non-show courts at larger venues, for tournaments with smaller budgets, or lower levels of competition, including grassroots. However, longer between-point rest offers a very simple solution that might increase player safety and enhance performance in hot humid conditions.

6 Assessing Cooling Strategies During Tennis-Specific Treadmill Exercise in Hot and Humid Conditions

6.1 Introduction

Tennis tournaments are often held in hot conditions. Some of the biggest events on the calendar occur in particularly severe conditions with reported peak environmental conditions of 36 ˚C 50% relative humidity (RH) observed at the US Open, and 45 ˚C 10% RH at the Australian Open; two of the four Grand Slam tournaments. Core temperatures in such conditions have been reported to exceed 39.1 ˚C (Hornery, Farrow, Mujika, Young, et al., 2007; Périard, Racinais, et al., 2014b; Tippet et al., 2011).

At the Australian Open, male, and female players called for cooling devices, such as ice towels, more regularly in conditions >28 ˚C WBGT compared to environmental conditions <28 ˚C WBGT. More in-match and post-match heat stress calls, and heat stress retirements occurred in conditions >30.1 ˚C WBGT for males and females than in temperatures of 30.0 ˚C WBGT and below. Additionally, an increase in WBGT influenced match characteristics with male players hitting more aces and approaching the net less (Smith, Reid, Kovalchik, Woods, et al., 2018), while female players approached the net less, hit fewer winners and more double faults (Smith, Reid, Kovalchik, Wood, et al., 2018).

It is expected that a similar pattern would be apparent at other tournaments such as the US Open, where in 2014, large numbers of heat related retirements were seen in the aforementioned hot temperatures (Schranner et al., 2017). Additionally, the introduction of a shot clock, which times the between-point rest, prevents players from resting for a longer duration as has previously been demonstrated (Périard, Racinais, et al., 2014b); it also removes the umpires ability to be lenient. Therefore, the cooling devices that are being called upon by tennis players might be key to reducing heat incidences and performance decrements.

The ice towel strategy has efficacy in both hot humid conditions and hot dry conditions along with the newly suggested strategy of using a damp sponge to wet the skin and the use of a fan (FAN_{wet}) (Lynch et al., 2018; Schranner et al., 2017). Both interventions lead to reductions in rectal temperature (T_{re}), heart rate (HR) and thermal sensation (TS) compared against cold-water (10˚C) as their control condition. The ice towels are the currently advised strategy for tennis players (Lynch et al., 2018); a combination of an ice towel around the neck and cold damp towels on the head and the thighs. A potential downfall of the ice towel method is that conductive external cooling has previously been suggested to decrease muscle temperature (Siegel & Laursen, 2012), possibly leading to a reduction in peak power output (Gray et al., 2006) affecting the velocity of shots or players' ability to get to balls.

Naito et al. (2017) proposed that ice slurry may be a suitable alternative during hot humid conditions due to sweat having a lower evaporative potential. Ice slurry decreased the rise in rectal temperature and forehead skin temperature, HR and total sweat volume versus the cold-water trial (4 ˚C). Participants also felt more comfortable throughout the treadmill simulation when drinking the slurry, though they did not feel cooler or as though they were exerting less effort.

All three of these studies compared the cooling interventions to a cold-water trial. Whilst consuming cold-water is common practice for tennis players on court, it might be that cold-water elicits a cooling effect itself and the effect of these additional cooling measures has been underrepresented.

With ice towels and ice slurry both reducing the rise in core temperature by around 0.5 ˚C throughout a simulated protocol, they both show efficacy for cooling and increasing player safety, likely reducing incidence of heat illness. The elements of behavioural thermoregulation in tennis match play, including longer between-point rest (Périard, Racinais, et al., 2014b) and changes in tactics (Hornery, Farrow, Mujika, Young, et al., 2007; Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018), demonstrate the importance of heat perception alongside core and skin temperatures. The ice towel lowered the thermal sensation of participants, and along with the ice slurry reduced core temperature. Though these two interventions target different mechanisms to reduce core temperature: the towels through conduction at the skin and the slurry through internal heat transfer. With this idea of the two mechanisms, it might be that using both interventions simultaneously might lead to further attenuation of core temperature, whilst also combining the reductions in thermal sensation and perceived exertion from the ice towel, and thermal comfort from the ice slurry.

The aim of this study was to compare three cooling strategies (ice towel, ice slurry, and combined) on the physiological and perceptual responses during simulated tennis match play in hot humid conditions comparing against cold-water and a warm-water control. It was hypothesised that compared to the control and the cold-water, the ice slurry and ice towel conditions would attenuate physiological and perceptual strain. An additional cooling effect was hypothesised for the ice towel and slurry attenuating physiological and perceptual strain in comparison to the control and cold-water.

6.2 Methods

6.2.1 *Participants*

Nine male tennis players volunteered for this study (mean ± standard deviation [SD] age 26 ± 5 years, height 1.80 ± 0.45 m, body mass 77.71 ± 6.87 kg, percentage body fat (PBF) 15.6 ± 6.5 %, body surface area (BSA) 1.6 ± 0.8 m^2, gas exchange threshold (GET) 13.1 ± 2.1 $km \cdot hr^{-1}$ and maximal aerobic capacity ($\dot{V}O_{2max}$) 52 ± 6 $ml \cdot kg^{-1} \cdot min^{-1}$). Participants were moderately trained ($\dot{V}O_{2max}$ > 45 $ml \cdot kg^{-1} \cdot min^{-1}$), trained at least twice per week, played tennis competitively (in local, university or college leagues), non-smokers, free from any known cardiorespiratory disorders and had not been exposed to hot conditions for 6 weeks prior to testing. All experimental procedures were approved by the institution's ethics committee and conducted in accordance with the guidelines of the Declaration of Helsinki (World Medical Association, 2013).

6.2.2 *Experimental design*

After undertaking a preliminary testing and familiarisation session, participants returned to the lab to complete the TSTP (see section 3.11) five times in hot, humid conditions (36.3 ± 0.7 ˚C, 51.3 ± 1.5%, 30.8 ± 0.4 ˚C WBGT). Four with cooling interventions: cold-water (CW); ice slurry (SLU); ice towel (TWL); and ice towel and ice slurry (TWL+SLU). The final condition was a warm-water control (CTL). Experimental trials were completed in a randomised order and separated by at least 48 h to avoid any heat adaptation.

6.2.3 *Preliminary testing & familiarisation*

On arrival to the laboratory, participants were given a copy of the participant information. The pre-test medical questionnaire and consent forms were completed, once the participant was satisfied that they completely understood the testing requirements.

Height, body mass, fat percentage were recorded, as seen in section 3.4, prior to a ramped exercise test which was analysed for $\dot{V}O_{2max}$ and GET, detailed in section 3.5.

Each participant then ran the first set of the TSTP in the heat (~36 ˚C, 50% rh), to ensure they were accustomed to the intermittent nature of the protocol, acceleration speeds and hot, humid conditions. All participants were also familiarised with the perceptual measures of RPE (Borg, 1982), TS (Toner et al., 1986) and TC (Dobnikar et al., 2009).

6.2.4 *Environmental conditions*

The five interventions were conducted in similar temperatures, as seen in Table 6.1 below.

Table 6.1: The environmental conditions in each intervention

	CTL	CW	SLU	TWL	TWL+SLU
T_a (˚C)	36.4 ± 0.3	36.5 ± 0.1	36.2 ± 0.4	36.5 ± 0.2	36.2 ± 0.6
R.H. (%)	51.4 ± 0.9	51.2 ± 0.7	51.5 ± 0.9	50.8 ± 0.8	51.3 ± 1.0
WBGT (˚C)	30.8 ± 0.2	30.9 ± 0.1	30.6 ± 0.3	30.8 ± 0.2	30.8 ± 0.3

6.2.5 *Experimental procedures*

Experimental sessions were all completed in an environmental chamber (Watford Refrigeration & Air Conditioning Ltd., Hertfordshire, UK). Participants undertook sessions at the same time of day to account for circadian rhythmic changes and were asked to refrain from eating for 2 hours, undertaking strenuous activity for 48 hours, consuming alcohol for 24 hours and consuming caffeine for 12 hours, prior to testing. All participants were instructed to drink 500 ml of water a few hours prior to the trial to ensure arrival in a euhydrated state indicated by a urine osmolality > 700 $mOsm{\cdot}kg^{-1}$ (Sawka et al., 2007), measured on a Pocket Pal-Osmo (Advanced Instruments, Horsham, UK). If this threshold was not met, participants were given water before waiting 30 mins to reassess hydration status. Urine colour (U_{col}) was also assessed alongside osmolality (Armstrong, 2000).

Upon arrival at the laboratory, participants voided their bladder for the assessment of hydration status. Once euhydration was confirmed, a rectal probe (Eltek U-type VL-U-VL5-0, Eltek Ltd., Cambridge, UK) was self-inserted, 10 cm past the anal sphincter, to record rectal temperature (T_{re}), before nude body mass (NBM) and clothed body mass (CBM) (Adam GFK 150H, Adam Equipment Co. Ltd., Milton Keynes, UK) were recorded. Following hair removal, skin thermistors (iButton DS1922L, Measurement

Systems Ltd, Newbury, UK) were attached to the mid belly of the pectoralis major, triceps brachii, rectus femoris and gastrocnemius on the right side of the body using KT tape (KT Health, LLC, Utah, USA) and zinc oxide tape (Leukoplast, BSN medical GmbH, Hamburg, Germany); these logged every 5 s and were downloaded post-trial allowing the calculation of mean skin temperature ($\overline{T}_{sk}$). The rectal thermistor was recorded at a frequency of 5 s on a Squirrel 1000 data logger (Grant Instruments, Cambridge, UK) and downloaded post-trial. A HR belt was fitted (Polar H10, Polar Electro, Finland); and linked to a recording watch with a frequency of 5 s (Polar RS400, Polar Electro, Finland). Finally, a resting [BLa] was collected through fingertip capillary blood sampling and analysed (Biosen C-Line, EKF Diagnostics, Cardiff, UK). Once the participant had been prepared, resting physiological and perceptual measures were noted at room temperature, prior to entering the environmental chamber.

The experimental protocol consisted of a ten-minute seated acclimatisation period, a 5-minute warm up at a speed equivalent to 80% of the GET, and completion of the TSTP.

Environmental conditions were monitored on entry to the chamber, prior to the TSTP and at the end of each of the 3 sets, using a Kestrel 5400 heat stress meter (Kestrel Meters, USA). Post-warm up, HR, T_{re}, $\overline{T}_{sk}$ and perceptual scales were noted. Heart rate, T_{re}, $\overline{T}_{sk}$ and perceptual variables (RPE, TS and TC) were recorded at the end of games 3, 5, 7 and 9. TS and TC were collected again at the end of the sit-down period. A fingertip capillary blood sample to assess [BLa] was collected during the “change of ends” sit down after game 5 and 9 in each set. After every odd game, participants consumed a drink (2 $g \cdot kg^{-1}$) of thermoneutral water in CTL (35.6 ± 0.7 ˚C) and TWL (34.8 ± 0.4 ˚C); cold-water in CW (10.7 ± 2.5 ˚C); or ice slurry in SLU and TWL+SLU (both -0.5 ˚C). Drinks were consumed whilst sitting down; apart from after game 1 in each set, where the participant remained on the treadmill. This replicated change of ends in a tennis match. "Time" was called with 30 s left of the rest period to allow the participants to get back on the treadmill ready for the start of the next game. If participants needed to urinate, they did so between sets in the environmental chamber, after data had been collected; volume of urine was then accounted for in the sweat rate (SR) calculation.

Following the completion of the TSTP, NBM and CBM were recorded again. Participant’s T_{re} was then lowered through cooling measures and participants monitored until they were within 0.5 °C of their resting value.

The trial was terminated if participant's T_{re} reached 39.7 °C or volitional exhaustion occurred (Willmott et al., 2015).

6.2.6 *Water and cooling strategies*

Participants consumed 2 $g \cdot kg^{-1}$ of body mass at each change of ends. This was decided following pilot testing that around 150 ml was drank ad libitum during each break during tennis match play in hot conditions (~30 ˚C). This was also on the limit of ice slurry that as able to be consumed within the break. This allowed the volume to be matched between all trials.

Control - 1.5 L bottles were filled with a mix of boiling and cold-water prior to being placed in the chamber throughout the protocol to maintain the temperature ~34 ˚C. The water was consumed after every odd game.

Cold-water - 1.5 L bottles were filled from a water cooler and kept in a cool box with ice packs to keep it chilled throughout the protocol. The water was consumed after every odd game.

Ice slurry – Ice slurries were made using a Nutribullet Pro 1200 (NutriBullet LLC, USA). A mixture of cold-water (2 parts), ice cubes (3 parts) and sugar free double strength lemon squash (1 part) (Tesco, UK), and salt (~1.08 g) were blended in batches of 4 portions. It was stored in a cool room outside the chamber and placed next to the participants chair prior to the break. The salt added was within the limits of the expected sodium losses per hour, as reported by Ranchordas et al., (2013). Due to the lack of sugar, to prevent a confounding factor, the salt was needed to attain the desired slurry consistency. The slurry was consumed after every odd game.

Ice towel – For each trial, one towel (70 x 140 cm 100% cotton) was soaked with cold-water and wrung out. It was then filled with 3 kg of ice (small cubes) and separated into 3 equal sections using shoelaces. This protocol was in accordance with (Schranner et al., 2017) who received personal communication from the WTA and ITF medical commission. The towel was kept in a sealed cool box whilst the participant was on the treadmill and was placed around the participant’s neck every time they sat down for a break (after games 3, 5, 7 and 9). Following pilot testing, it was decided that one towel was sufficient for the whole trial.

Ice towel and ice slurry – The ice towel and ice slurry were made and implemented as described in the individual descriptions.

6.2.7 *Data processing*

The data processing for skin temperature (Equation 3.2), sweat rate (Equation 3.3), and protocol completion (Equation 3.4) is detailed in chapter 3.

6.2.8 *Statistical analysis*

Data were assessed for normality as detailed in section 3.12.2.1. If data violated normality, a Wilcoxon signed rank test or a Friedman's two-way Analysis of Variance (ANOVA) by ranks assessed between-trial differences.

Where data were normally distributed, they were assessed using Mauchly's test for sphericity prior to parametric ANOVA; if this was violated ($P < .05$), the Greenhouse-Geisser correction was used.

Hydration status, NBM, resting T_{re}, SR and percentage protocol completion were analysed using a one-way repeated measures ANOVA with condition (5: CTL, CW, SLU, TWL, TWL+SLU) as the independent variable. Rectal temperature, skin temperature, heart rate and RPE were analysed using a three-way ANOVA with the independent variables of condition (5), set (3: set 1, set 2, set 3) and game (4: game 3, game 5, game 7, game 9). Thermal sensation and thermal comfort were also analysed using a three-way ANOVA but with condition (5), game (12) and break (2: pre, post) as the independent variables. Where main and/or interaction effects were evident, Bonferroni corrected pairwise comparisons were performed to identify where differences existed.

All data were analysed using a standard statistical package (SPSS 24.0) with statistical significance being accepted at the level of $P < 0.05$. Data were reported as the mean ± standard deviation (SD) of every measurement taken during the time frame referred to, for all participants *e.g.,* Set 1 would consist of a mean of all participants over 4 time points (post-games 3, 5, 7 and 9). All analyses were performed using SPSS 24.0 for Mac (IBM, USA).

6.3 Results

6.3.1 *Preliminary Measures*

There were no significant differences between conditions for pre-trial hydration status ($F_{(4,32)} = 0.830$, $P = .450$, $\eta_p^2 = 0.094$), pre-trial nude body mass ($F_{(4,32)} = 1.092$, $P = 0.377$, $\eta_p^2 = 0.120$) or resting T_{re} ($F_{(4,32)} = 1.009$, $P = 0.418$, $\eta_p^2 = 0.112$).

6.3.2 *Protocol Completion*

All participants completed the TSTP in CW, SLU and TWL+SLU. In CTL and TWL, one participant did not complete the TSTP, due to T_{re} reaching 39.7 °C. They were stopped at the end of set 2 in TWL (63% completed), and after game 3, set 3 in CTL (73% completed). There was no difference in protocol completion (n=9) between trials ($F_{(4, 32)} = 1.000$, $P = 0.347$, $\eta_p^2 = 0.111$).

6.3.3 *Thermoregulatory Measures*

6.3.3.1 Rectal Temperature

Resting T_{re} was similar ($P = 0.418$) between CTL (37.27 ± 0.24 ˚C), CW (37.18 ± 0.15 ˚C), SLU (37.16 ± 0.16 ˚C), TWL (37.22 ± 0.23 ˚C) and TWL+SLU (37.20 ± 0.14 ˚C). There was no interaction effect for condition, set and game ($F_{(24, 192)} = 1.122$, $P = 0.364$, $\eta_p^2 = 0.123$), so differences were observed using the interaction of condition and set ($F_{(8, 64)} = 3.968$, $P = 0.001$, $\eta_p^2 = 0.332$). Rectal temperatures increased at a similar rate ($P > 0.05$) during the first set of the TSTP in all conditions (see Figure 6.1 below). As the TSTP progressed through the second set, T_{re} during SLU was lower than CTL (38.26 ± 0.38˚C vs 38.56 ± 0.39˚C, $P = 0.041$, $g_{av} = -0.70$), and though not significant, a similar effect was seen in TWL+SLU (38.27 ± 0.29˚C vs 38.56 ± 0.39˚C, $P = 0.082$, $g_{av} = -0.76$). As seen in Figure 5.1, the effects of the cooling interventions were more apparent during set 3, with lower rectal temperatures in both SLU ($P = 0.009$, $g_{av} = -0.83$) and TWL+SLU ($P = 0.014$, $g_{av} = -1.07$) compared with CTL; TWL+SLU was also lower than CW during set 3 ($P = 0.034$, $g_{av} = -0.66$). There was also a small effect of CW ($g_{av} = -0.33$) and TWL ($g_{av} = -0.36$) on rectal temperature in set 3 compared with CTL.

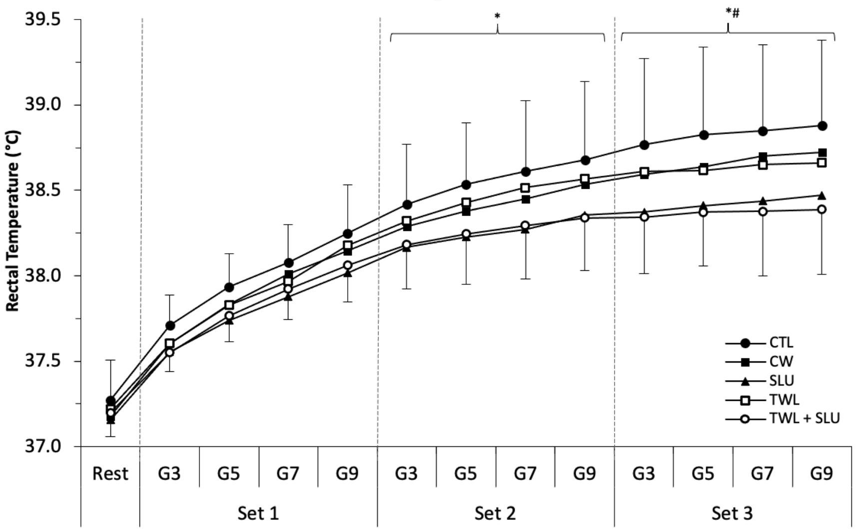

Figure 6.1: Rectal temperature during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD. * = SLU < CTL (P<0.05). # = TWL+SLU < CTL (P<0.05).

Table 6.2: Rate of rise in rectal temperature (˚C·min^{-1}) throughout the TSTP

	CTL	CW	SLU	TWL	TWL+SLU
Set 1	0.018 ± 0.007	0.018 ± 0.007	0.016 ± 0.007	0.019 ± 0.006	0.017 ± 0.006
Set 2	0.008 ± 0.005	0.008 ± 0.005	0.006 ± 0.006	0.008 ± 0.005	0.005 ± 0.004
Set 3	0.004 ± 0.004	0.004 ± 0.005	0.003 ± 0.003	0.002 ± 0.004	0.001 ± 0.004
TSTP	0.006 ± 0.002	0.006 ± 0.002	0.005 ± 0.002	0.006 ± 0.002	0.006 ± 0.002

6.3.3.2 Mean Skin Temperature

No interaction effect for condition, set and game was observed ($F_{(24, 192)}$ = 2.031, P = 0.095, η_p^2 = 0.202), but an interaction between condition and set was significant ($F_{(8, 64)}$ = 3.423, P = 0.024, η_p^2 = 0.300). Mean skin temperature remained relatively consistent throughout the TSTP in CTL, CW and SLU; while, as seen in Figure 6.2 below, TWL and particularly TWL+SLU decreased as the TSTP continued, after a slight initial increase. The cooling effect on mean skin temperature was most prominent in set 3 where the TWL+SLU intervention saw lower mean skin temperature in comparison to CW (35.13 ± 0.74 vs 36.13 ± 0.89 ˚C, P = 0.007, g_{av} = -1.10). There was also a trend towards $\overline{T}_{sk}$ being lower in TWL+SLU than CTL (P > 0.05; g_{av} = -0.82). Mean skin temperature decreased during set 3 in TWL and saw a small effect in comparison to CW (g_{av} = -0.42) and CTL (g_{av} = -0.22).

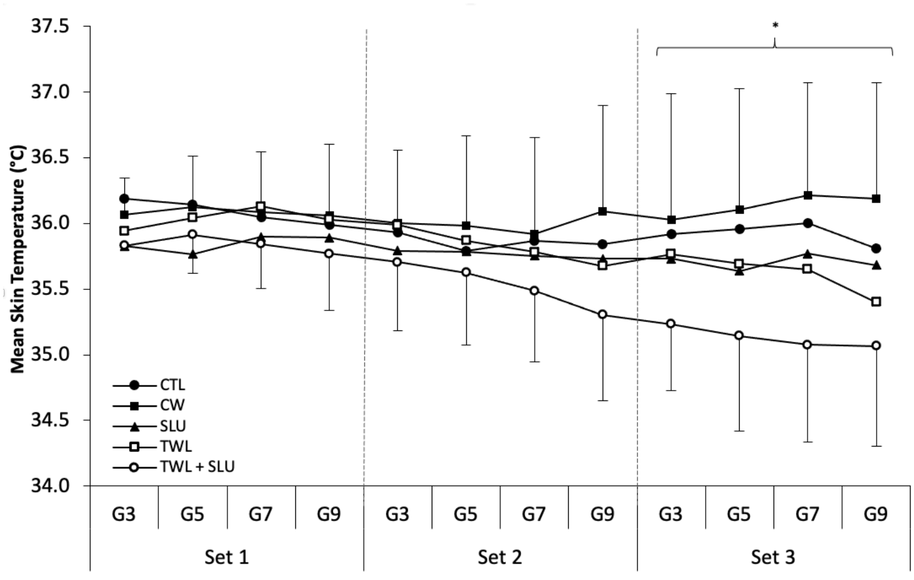

Figure 6.2: Mean skin temperature during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD. * = TWL+SLU < CW (P<.05).

6.3.3.3 *Sweat Rate*

There was a main effect of condition on sweat rate ($F_{(4, 32)} = 4.687$, $P = 0.034$, $\eta_p^2 = 0.369$) with the TWL+SLU condition eliciting a lower sweating rate than the CTL condition (0.946 ± 0.224 L·min^{-1} vs 1.214 ± 0.246 L·min^{-1}, $P = 0.017$, $g_{av} = -1.14$). As seen in Figure 6.3 below, there was a trend for CW ($g_{av} = -0.49$) and SLU ($g_{av} = -0.51$) to be lower than CTL, too. There was also a trend that the CW ($g_{av} = -0.63$), SLU ($g_{av} = -0.64$) and TWL+SLU ($g_{av} = -1.29$) conditions had reduced sweat rates in comparison to TWL.

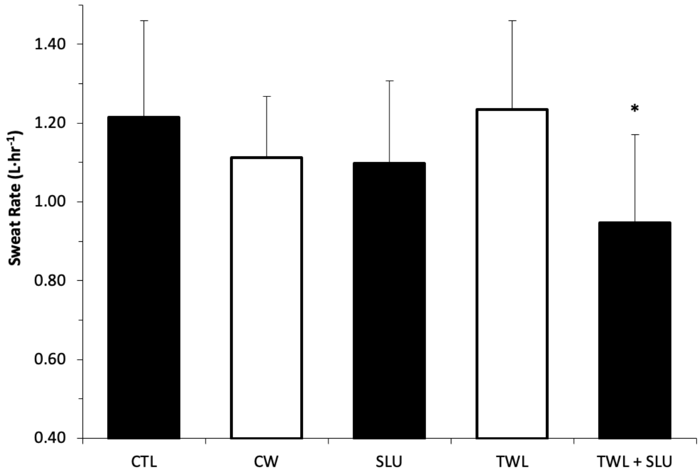

Figure 6.3: Sweat rate during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD. * = TWL+SLU < CTL (P<.05).

6.3.4 *Perceptual Measures*

6.3.4.1 *Thermal Sensation*

Thermal sensation (TS) demonstrated an interaction effect for condition and break ($F_{(4, 32)} = 5.059$, $P = 0.003$, $\eta_p^2 = 0.387$). Throughout the TSTP, there was a cooling effect of the break with TS decreasing as a result of the break in CW ($P = 0.019$, $g_{av} = -0.27$), SLU ($P = 0.003$, $g_{av} = -0.33$), TWL ($P < 0.001$, $g_{av} = -0.77$) and TWL+SLU ($P = 0.005$, $g_{av} = -0.55$), but this effect was not significant in CTL ($P = 0.101$, $g_{av} = -0.27$). This cooling effect was apparent as thermal sensation was lower post-break in SLU ($P = 0.043$, $g_{av} = -0.59$), TWL ($P = 0.014$, $g_{av} = -0.80$), and TWL+SLU ($P = 0.005$, $g_{av} = -0.99$) than CTL. Whereas pre-break, only TWL+SLU was lower than CTL ($P = 0.002$, $g_{av} = -0.80$). No differences were observed between CW and any other condition either pre- or post-break.

There was also a condition and game interaction effect ($F_{(44, 352)} = 2.44$, $P = 0.042$, $\eta_p^2 = 0.234$). TS over the course of the TSTP (Figure 6.7 below), remained relatively stable in the TWL+SLU condition whilst the other conditions saw increases of varying magnitudes throughout. From game 7 in the first set, TWL+SLU was lower at the break than CTL ($P < 0.05$); this continued until the end. There were a few points towards the end of the first set and start of the second set, as well as game 5 in the third set where TWL lead to lower TS scores ($P < 0.05$). The third set also saw some differences between CW and TWL+SLU ($P < 0.05$) and finished with a lower TS in SLU than CW ($P < 0.05$) for the last 2 breaks.

6.3.4.2 Thermal Comfort

Thermal comfort pre- and post-break throughout the TSTP can be seen in Figure 6.7 below. Whilst a main effect was apparent ($\chi^2_{(119)} = 461.267$; $P < .001$), pairwise comparisons revealed no differences between conditions at any of the time points throughout the TSTP ($P > .05$).

6.3.4.3 Rating of Perceived Exertion

RPE showed no interaction effect for either condition, set and game ($F_{(24, 192)} = 0.805$, $P = 0.562$, $\eta_p^2 = 0.091$) or condition and set ($F_{(8, 64)} = 1.972$, $P = 0.064$, $\eta_p^2 = 0.198$), and whilst there was a main effect of time ($F_{(2, 16)} = 15.017$, $P = 0.004$, $\eta_p^2 = 0.652$), there was no main effect of condition ($F_{(4, 32)} = 1.812$, $P = 0.211$, $\eta_p^2 = 0.185$). RPE increased throughout in all conditions whilst trending to be higher in CTL compared with TWL+SLU ($g_{av} = 0.54$) and in SLU ($g_{av} = 0.36$). There was also a small effect in CW ($g_{av} = 0.19$) and TWL ($g_{av} = 0.22$).

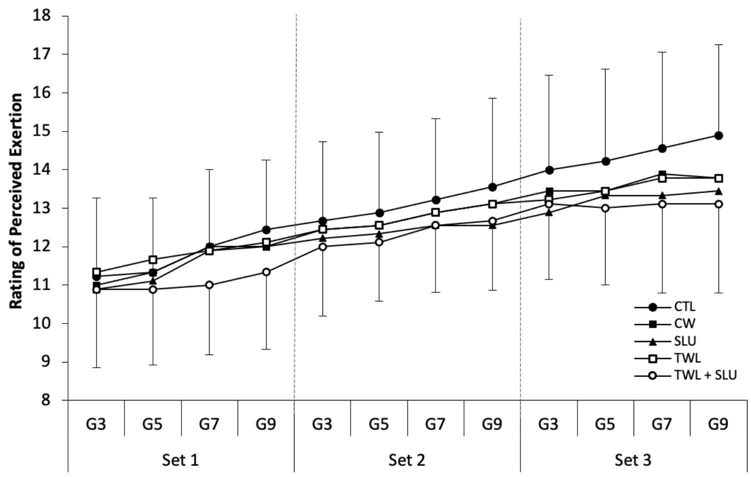

Figure 6.4: Rating of perceived exertion during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD.

6.3.5 *Physiological Measures*

6.3.5.1 Heart Rate

Heart rate showed no interaction effect for either condition, set and game ($F_{(24, 192)}$ = 0.706, P = 0.626, η_p^2 = 0.081) or condition and set ($F_{(8, 64)}$ = 1.382, P = 0.222, η_p^2 = 0.147), and whilst there was a main effect of time ($F_{(2, 16)}$ = 13.152, P = 0.04, η_p^2 = 0.622), there was no main effect of condition ($F_{(4, 32)}$ = 2.254, P = 0.085, η_p^2 = 0.22). Heart rate increased from the start in all conditions, though this was trending to be more of an increase in CTL compared with TWL+SLU (P = 0.116, g_{av} = 0.41) and a small effect in SLU (g_{av} = 0.24).

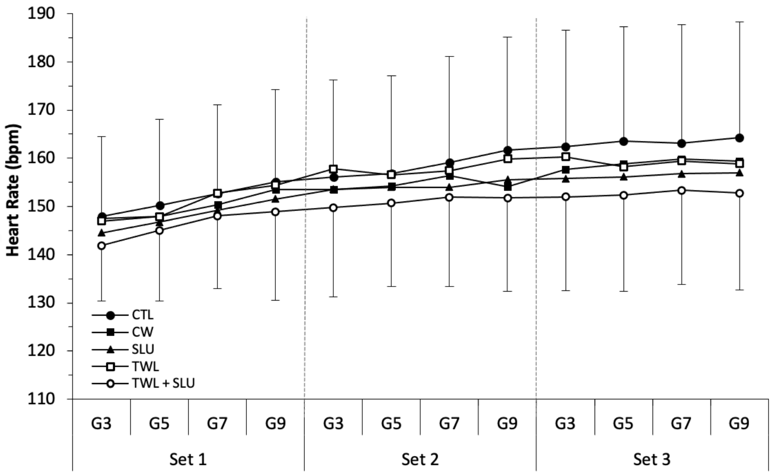

Figure 6.5: Heart rate during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD.

6.3.5.2 Blood Lactate

Blood lactate remained constant throughout the TSTP ($F_{(2, 16)}$ = 3.301, P = 0.063, η_p^2 = 0.292) and behaved no differently over time between conditions ($F_{(8, 64)}$ = 1.075, P = 0.381, η_p^2 = 0.118). However, there was a main effect of condition ($F_{(4, 32)}$ = 5.049, P = 0.003, η_p^2 = 0.387); TWL+SLU inducing lower BLa concentrations than CW (1.09 ± 0.22 vs 1.44 ± 0.34 mmol·L^{-1}, P = 0.002, g_{av} = -1.06) and a trend towards lower concentrations compared with CTL (1.09 ± 0.22 vs 1.46 ± 0.35 mmol·L^{-1}, P = 0.061, g_{av} = -1.10).

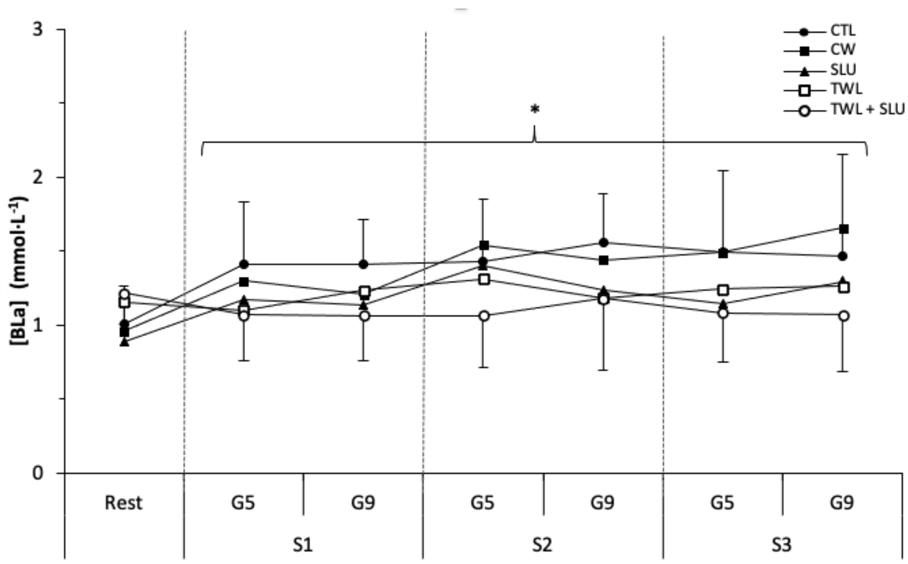

Figure 6.6: Blood lactate during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD. * = TWL+SLU < CW

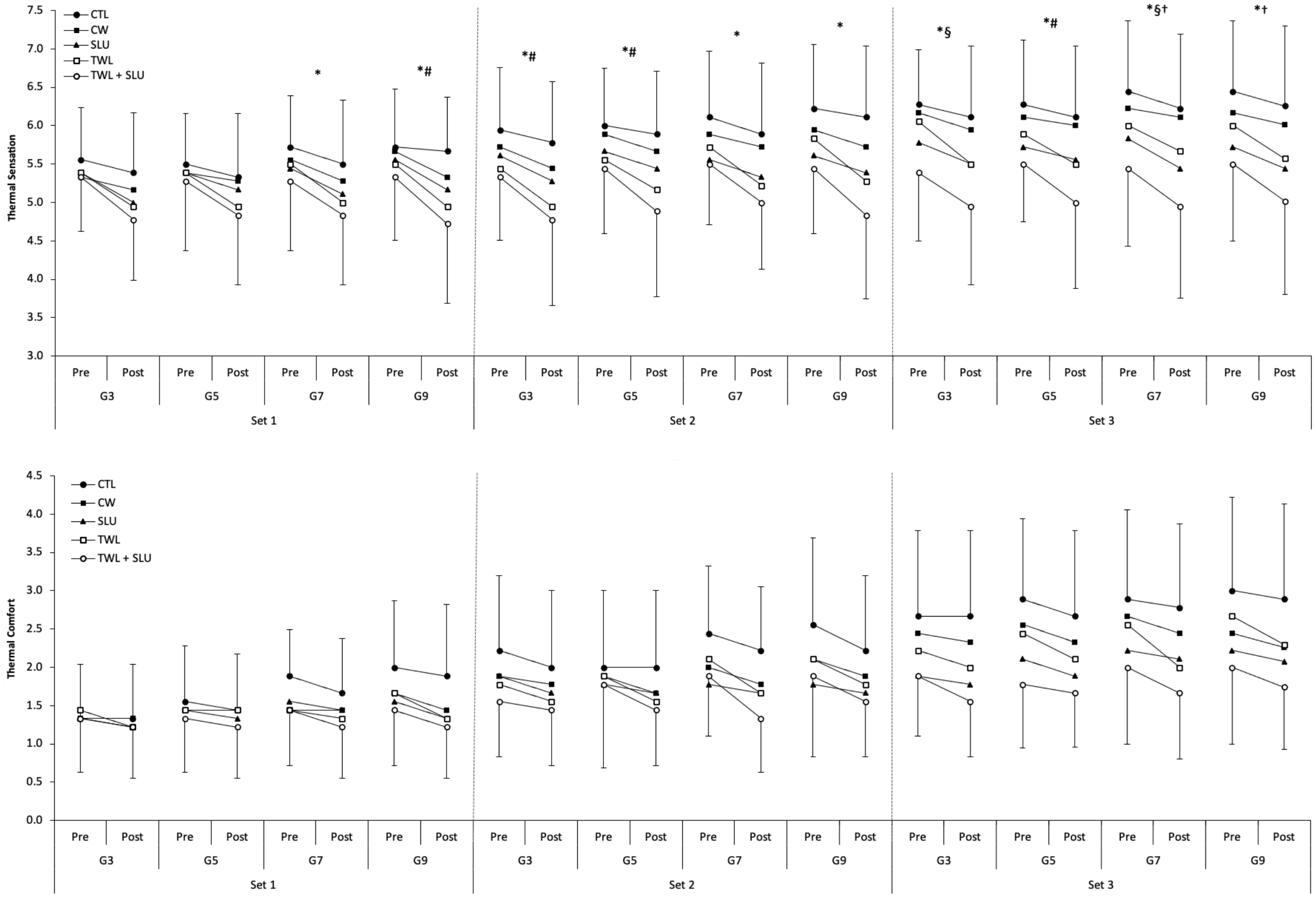

Figure 6.7: Thermal sensation and thermal comfort during the TSTP in CTL, CW, SLU, TWL and TWL+SLU trials (n=9), mean ± SD. * = TWL+SLU < CTL (*P*<.05). # = TWL < CTL (*P*<.05). § = TWL+SLU < CW (*P*<.05). † = SLURRY < CW (*P*<.05).

6.4 Discussion

The aim of this study was to compare three cooling strategies (ice towel, ice slurry, and combined) on the physiological and perceptual responses during simulated tennis match play in hot humid conditions comparing against cold-water and a warm-water control. It was hypothesised that compared to the control and the cold-water, the ice slurry and ice towel conditions would attenuate physiological and perceptual strain. An additional cooling effect was hypothesised for the ice towel and slurry attenuating physiological and perceptual strain in comparison to the control and cold-water. Compared to CTL, SLU and TWL+SLU trials saw a smaller rise in rectal temperature in the third set of the TSTP by ~0.4 and ~0.45 ˚C, respectively. Thermal sensation was lower from mid-way through set 1 throughout the TSTP in TWL+SLU than CTL. At varying points in the TSTP (see Figure 6.7 above), participants felt cooler in TWL than CTL, as well as cooler in SLU and TWL+SLU than CW. Sweat rate was reduced in the TWL+SLU trial compared with CTL. Internal cooling (SLU) and the combined cooling strategy (TWL+SLU) effectively reduced the rise in rectal temperature. All cooling methods (SLU, TWL and TWL+SLU) lowered thermal sensation throughout the duration of the TSTP at the end of the 'change of ends' break compared to CTL. TWL+SLU was also lower than CTL at the start of the 'change of ends' break.

Rectal temperature increase was slowed or attenuated compared to the control condition in the second set (SLU: ~0.3 ˚C) and the third set (SLU: ~0.4 ˚C and TWL+SLU: ~0.45 ˚C). A similar pattern was observed in a study comparing an ice slurry drink to a cold-water drink during a treadmill protocol representing match play tennis (Naito et al., 2018); the rise in core temperature was attenuated in the slurry trial by a similar margin from the mid-point of the protocol which lasted 82 minutes. However, no difference was observed between TWL and CTL in this study with a modest reduction of ~0.2 ˚C in SLU during the third set. Ice towels have previously reduced rectal temperature by ~0.5 ˚C during a simulated tennis match (Schranner et al., 2017). The studies that have been used for comparisons here did not use a warm-water control, rather a cold-water control: ~5˚C (Naito et al., 2018) and ~10 ˚C (Schranner et al., 2017) so a larger difference in rectal temperature rise would be expected in this study. The CW trial in this study did not demonstrate a significant difference in rectal temperature rise in comparison to any cooling strategy ($P > 0.05$). Rectal temperatures were similar between the TWL (38.63 ± 051) and CW (38.66 ± 0.44) conditions in set 3 of the TSTP ($g_{av} = 0.06$) with small and moderate effect sizes seen for SLU (38.42 ± 0.49; g_{av} = 0.47) and TWL+SLU (38.37 ± 0.35; g_{av} = 0.66) compared to CW in set 3. Therefore, this study did not see as large an attenuation of rectal temperature compared with the aforementioned studies.

There are some differences between the protocol in this study and the two comparative articles which might explain the smaller effect of cooling interventions in this study. The games (2 min 35 s vs 1 min 36 s) and the sets (29 min 27 s vs 18 min 48 s) were shorter, though, they did undertake 4 sets rather than 3, therefore the protocol was a similar total length (~92 min vs ~81 min). The implication of this is that participants had 19 sit-down breaks in these studies where cooling was administered. The impact on the comparison between this study varies between condition as, in the present study the participants remained on the treadmill and consumed a drink after the first game in each set, due to players not being allowed to sit down during matches in this change over. Therefore, this means that during the TWL trial participants only received 11 periods of cooling and in the SLU trial 14 periods of cooling; the TWL+SLU consisted of 14 ice slurries, 11 of which were combined with the ice towel. Not only did the TWL trial have fewer occurrences in this study compared to Schranner et al. (2017), participants did not have cold damp towels placed over the head and thighs, which would have increased the skin contact surface area with cool or cold materials, leading to an increased rate of conductive heat loss. It is possible that this increased surface area and frequency explains the cooling effect of ice towels compared to cold-water in that study not seen here. The cooling effect of the slurry in this study was around half of that seen previously (Naito et al., 2018). Whilst the previous study had 5 more breaks where ice slurry was consumed, a larger volume was consumed per change of ends in this study (2 g·kg^{-}1 vs 1.25 g·kg^{-1}); meaning more ice slurry was consumed in the present study in total (28 g·kg^{-1} vs 23.75 g·kg^{-1}). Ice slurry may be effective as consumption might reduce brain temperature due to the proximity to the mouth and oesophagus to the carotid arteries (Mariak et al., 1999), or due to thermal receptors in the tongue, stomach and small intestine (Siegel & Laursen, 2012). A lower beverage temperature is thought to increase the gastric emptying rate (Costill & Saltin, 1974), therefore the ice slurry remains in the stomach for less time. It is possible that less volume more frequently, is a better strategy to cool the blood or affect thermal receptor due to the having ice slurry in the gut more of the time. However, the volume and timing of slurry consumption will require further research. Games do not last the same amount of time in reality so considering the amount consumed over a time period of 30 minutes or an hour, or an average set might be more suitable for players to use in practice.

Skin temperature was relatively stable in CTL and CW, with a slight lowering towards the end of the TSTP in the SLU trial. Ice slurry was not expected to affect skin temperature and this matches what has been reported in previous studies (Naito et al., 2018). For the external cooling interventions, it was expected that the skin temperature would be lower throughout the TSTP based on similar research (Schranner et al., 2017). A more pronounced decrease was observed in TWL+SLU with significance from CW and trend from CTL. However, TWL only saw a moderate effect from CW and a small effect from CTL. It appears that the combined approach of ice towel and slurry simultaneously further reduces skin temperature. Though an effect was expected in TWL. A simple explanation for this might be the additional cold towels placed on the head and thighs which would have had a direct impact on the skin temperature measurement at the thigh and possibly the upper arm. Both of which go make up part of the weighted skin temperature equation. As skin temperature is assessed through a weighted mean, this measurement is dependent on the chosen sites. The neck would have been much cooler with the application of an ice towel (Sunderland et al., 2015) than the sites measured therefore, it is likely that the actual skin temperature was lower than reported here. The additional effect of the ice slurry reducing core temperature internally whilst the ice towel increased conductive heat loss at the skin lead to a lower rectal temperature in SLU and TWL+SLU compared with CTL ($P < 0.05$) in sets 2 and 3, and set 3, respectively. Whilst the rectal temperature seen in SLU did not lead to a decreased skin temperature, it might have contributed to the skin temperature remaining lower in TWL+SLU.

There was an increase in heart rate through the first 30 minutes of the TSTP, a common response to exercise, and more so when exercising in the heat due to the increased heat strain demanding an increase in skin blood flow and the heart rate being increased to maintain cardiac output. However, there was no change between conditions or a different response between conditions over time. A decrease in rectal or core temperature could decrease thermal strain enough that in a compensable environment at the same intensity of exercise, as the TSTP is, the heart rate might decrease as skin blood flow is not as high. The reduction of rectal temperature in SLU and TWL+SLU and the added decrease in skin temperature in TWL+SLU was still not enough for HR to decrease; suggesting that the heat loss mechanism of increase skin blood flow was unaffected. For most interventions, the skin temperatures remaining relatively stable throughout, so the body is still trying to dissipate heat through shunting blood to the skin. Though as seen in Figure 6.5 above, the HR in TWL+SLU appears to be lower than the other conditions, particularly CTL. Whilst there is no significance between these conditions, likely due to the relatively large standard deviation, there does seem to be a trend towards a decrease with the combined cooling approach.

Heart rate has previously been observed to be lower due to the use of both ice towel and ice slurry interventions during tennis-specific exercise on a treadmill. Ice towel decreased heart rate compared to a cold-water control by around 40 minutes into the protocol with around a 10 beats·min^{-1} reduction in the intervention trial (Schranner et al., 2017). Though, participants began to drop out of the trial after this time point and the data following this is uncertain. It is possible that individual heart rates were near max if participants were under a level of heat strain which caused them to be withdrawn due to rectal temperature or volitional exhaustion. A similar observation was made when ice slurry was compared to cold-water consumption with HR ~10 beats·min^{-1} lower after 40 minutes (139.4 ± 8.9 vs 150.9 ± 11.9 beats·min^{-1}), increasing to 19 beats·min^{-1} after 81 minutes (146 ± 8.2 vs 165 ± 10.6) (Naito et al., 2018). In this study, heart rates were no different between any condition ($P > 0.05$) in the second set, though HR was ~10 beats·min^{-1} lower in TWL+SLU compared to CTL after 60 min (152 ± 19 vs 162 ± 23 beats·min^{-1}; $g_{av} = -0.47$) and a small effect but, no different from CW (154 ± 23 beats·min^{-1}). Whilst there was no significant reduction in set 3 or at the end of the TSTP ($P > 0.05$), HR in TWL+SLU was ~ 10 beats·min^{-1} lower in both set 3 (153 ± 20 vs 163 ± 24 beats·min^{-1}; $g_{av} = -0.41$) and the final measurement of the TSTP (153 ± 20 vs 164 ± 24 beats·min^{-1}; $g_{av} = -0.45$) compared to CTL showing a small effect in both. No difference was seen between SLU, TWL and CW (157 ± 23; 158 ± 23; 159 ±24, respectively) in set 3 of the TSTP; this is probably to be expected at rectal temperature and skin temperature saw similar patterns in comparison to the previous data.

Blood lactate was lower in TWL+SLU (1.09 ± 0.32 mmol·L^{-1}) than CW (1.44 ± 0.34 mmol·L^{-1}). However, whilst this is a significant difference, the levels of lactate observed in all conditions in this study were slightly lower than the expected lactate of 2-4 mmol·L^{-1} previously observed in match play (Fernández-Fernández et al., 2007, 2008; Mendez-Villanueva et al., 2007). So, the impact of this within the TSTP is not impactful. However, it would be useful to assess this during on-court match play in hot conditions to assess if this might be a beneficial effect. Lactate has not been reported in similar research studies therefore, it must not be high enough to cause concern in these conditions or that treadmill protocols do not induce lactate production similar to on-court values. This might be due to the unidirectional nature of the treadmill and the lack of ball striking reducing the anaerobic component.

There was a consistent difference throughout the TSTP in thermal sensation (TS) between CTL and TWL+SLU. No other interventions saw a consistent difference from either CTL or CW ($P > 0.05$) all the way through though. However, as seen in Figure 6.7 above, over the course of the TSTP, TS spread as expected with CTL and CW increasing whilst SLU, TWL and TWL+SLU remained more constant. Previous data suggests that the use of an ice towel would lower TS compared to cold-water (Schranner et al., 2017), however, ice slurry did not impact on participants' TS (Naito et al., 2018). When the internal and external cooling interventions in this study were administered alone, a similar small effect was observed in comparison to CW (SLU: $g_{av} = -0.21$; TWL: $g_{av} = -0.26$) and a moderate effect versus CTL (SLU: $g_{av} = -0.42$; TWL: $g_{av} = -0.51$). However, combining the two (TWL+SLU) lead to a moderate effect versus CW ($g_{av} = -0.64$) and a large effect versus CTL ($g_{av} = -0.85$). This would suggest that the internal and external mechanisms of thermal reception can have a dose response leading to an additive effect when stimulated simultaneously.

All conditions apart from CTL saw a reduction in TS following the break ($P < 0.05$). Though, the data show that both CTL and CW reduced by a similar amount pre- to post-break (CTL pre: 6.0 ± 0.7; CTL post: 5.8 ± 0.8; CW pre: 5.8 ± 0.7; CW post: 5.6 ± 0.8). This is further supported due to all three cooling interventions (SLU, TWL and TWL+SLU) being lower than CTL post-break ($P < 0.05$) whereas CW was not different ($P > 0.05$).

The TWL and TWL+SLU saw a trend towards an increased reduction in TS following the break in comparison with SLU. This is possibly suggesting that the ice towel has a larger cooling sensation effect than the ice slurry. Though the combination of internal and external cooling (TWL+SLU) lead to lower values throughout the TSTP whilst also seeing a similar cooling effect over the break. Notably, the pre-break TS was lower in TWL+SLU than CTL ($P < 0.05$). This is similar to previous data using ice towels (Schranner et al., 2017) the cooling intervention lead to reduced TS throughout the protocol with an added cooling effect following the sit-down break. Naito et al. (2018)

used a 9-point thermal sensation scale rather than the 17-point scale used in this study so direct comparisons are difficult to make, though they did not see a significant difference between thermal sensation in the ice slurry trial and the cold-water trials. This might have been due to high standard deviations, possibly as a result of a scale with fewer points on or a large variation in perception amongst the participant group.

Thermal comfort during the TSTP behaved similarly to thermal sensation (see Figure 6.7 above). During the first half of the initial set, the thermal comfort was similar between conditions before CTL appearing to increase in comparison the other conditions. However, no differences were observed throughout the TSTP. Regardless of this, the cooling interventions saw some good effects compared to control with TWL (g_{av} = -0.50) and SLU (g_{av} = -0.67) showing medium effects and TWL+SLU (g_{av} = -0.80) a large effect compared to CTL for the whole TSTP. Seemingly this would agree with TC, though a slightly different scale was used, during a similar treadmill protocol in the same environmental conditions (Naito et al., 2018).

Perceived exertion (RPE) appeared to increase linearly (see Figure 6.4) as the TSTP ensued. This is a slower rise compared with Schranner et al. (2017), though as participants began to drop out for them due to overheating after set 2, this increased rectal temperature is likely the cause of this increase in RPE.

Coinciding with the rectal temperature, mean skin temperature and heart rate, the perceptual variables saw increases throughout the TSTP; in line with the previous research (Chalmers et al., 2019; Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017). Exactly where the point is during tennis matches that players would start to change their behaviour through shortening points or increasing rest lengths is not fully known, though these phenomena have been observed previously (Hornery, Farrow, Mujika, Young, et al., 2007; Morante & Brotherhood, 2008b; Périard, Racinais, et al., 2014b).

The cooling intervention of TWL+SLU was evidenced to curtail this rise in both physiological heat strain and the participants perception of the heat, possibly suggesting that this behavioural thermoregulation might not occur if this strategy was used in tennis match play. However, there is no ability to blind the participants to the cooling interventions such as those implemented in the present study. Therefore the participants' expectation that certain cooling techniques should have a beneficial effect cannot be discounted (Ross et al., 2013). Previously in a test to exhaustion perceptual results of RPE and TS were compared at the point of exhaustion in an attempt to rule out this effect;

however (Siegel et al., 2010), this approach is not possible in this study without a fixed physiological comparison. Some participants reported discomfort when consuming the ice slurry or having the ice towel around their neck; despite this, the physiological and perceptual variables show varying effect across cooling conditions compared to the control.

Ice slurry is thought to lead to enhanced performance through a number of thermoreceptors within the mouth, gut and small intestine relaying information to the brain, alongside lowering core temperature (Siegel & Laursen, 2012). If performance could be enhanced through your brain thinking you are cooler, this would likely show through a reduction in TS, too.

Reduced thermal and physiological strain should allow a higher intensity to be achieved during points or the subconscious thermoregulatory behaviours to be avoided. Though, the further implications of this on core temperature are not yet known during tennis match play. Diminishing these behavioural changes might lead to similar peak core temperatures without cooling, though arguably, if a player can perform at a higher intensity for longer before reaching this point that could give them an advantage over their opponent.

In agreement with the hypothesis, ice slurry attenuated physiological and perceptual strain compared to the control and cold-water. However, the ice towel strategy only attenuated thermal perception with no effect on physiological strain. The combined strategy demonstrated an additive effect attenuating physiological and perceptual strain to a greater extent than each strategy alone. Ice towel might only enhance performance whilst ice slurry and combined strategies might reduce the risk of heat illness and improve performance during simulated tennis match play in hot humid conditions

7 Heat Alleviation Strategies During Tennis Match Play in Hot Conditions: A Pilot Survey of Current Practice and Perceptions

7.1 Introduction

Heat alleviation strategies are becoming more prominent within tennis in recent years as tournaments experience increasing temperatures. Research into the prevalence of heat-related incidences suggests that as the conditions become hotter and/or more humid the number of incidences will increase in both men's and women's competition (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018). The WTA and ITF have heat policy rules in place for all tournaments which they govern (International Tennis Federation, 2021; Women's Tennis Association, 2021), however this is not the case for the ATP or the Grand Slam Board (Association of Tennis Professionals, 2021; Grand Slam Board, 2021). Individual Grand Slams implement their own heat policies with cooling devices and extended breaks are made available, and suspension of play at temperature thresholds. The Australian Open uses a heat policy which is similar to the WTA and ITF policies and has been working with researchers to ensure an evidence-based policy is in place. Temperatures consistently above 32 ˚C and peaks of 36 ˚C and 50% relative humidity meant court-side temperatures of 49 ˚C were seen at the US Open in 2018. This led to a heat policy being introduced where cooling fans were on all courts for the players to use at change of ends and an unprecedented rule allowing both males and females to be able to have an extended 10-minute break before the third (female) or fourth (male) set. Indeed, Novak Djokovic and Marton Fuscovics used the break to have an ice bath in the changing rooms. In addition to these policies, players often use heat alleviation strategies in hot conditions.

There is lots of research on heat alleviation strategies with methods including ice vests, ice slurry, menthol application, and cold-water immersion being investigated in a variety of sports (Chalmers, 2017). Chronic strategies, *e.g.* heat acclimation, are considered the gold standard when preparing for exercise in the heat (Gibson et al., 2019). However, acute strategies can alleviate heat strain and offer an additional benefit to chronic strategies (Gibson et al., 2019). Effective acute strategies achieve two key elements: a reduction in body temperature or enhancement of heat loss, and a reduction in thermal perception (Tyler, Sunderland, et al., 2015).

Implementing strategies during match play (mid-cooling, per-cooling or intermittent cooling) can be beneficial to performance (Ruddock et al., 2017), can be used alone or with additional effect from pre-cooling (Best et al., 2018). The important factors that affect a strategy's effectiveness are the temperature, the duration of use and the surface area coverage (Ruddock et al., 2017; Tyler, Sunderland, et al., 2015).

Some cooling strategies are not accessible for lower levels of sport, *e.g.,* ice towels and slurries, due to lack of facilities, therefore it is important to find methods that are both effective and accessible to be used across a range of sports (Chalmers, 2017). This could be achieved through a simple use of cold-water being poured, sprayed or drank (Morris & Jay, 2016), or cold towels placed on the skin. Local strategies of cooling such as the towels, lead to a greater reduction in thermal discomfort (Best et al., 2018; Bongers et al., 2015). Strategies previously shown to negate the physiological and/or perceptual effect of the heat (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017) and ensure the safety of the players during tennis match play reduced core temperature and physiological strain, as well as likely enhancing performance capabilities likely through the perceptual improvements. The current guidance for implementing acute heat alleviation strategies is that practitioners should have a "toolbox" of methods available in order to tailor to the individual needs (Gibson et al., 2019), this should also apply to tournaments and governing bodies.

The success of heat alleviation strategies is dependent upon the physiological and/or perceptual changes as a result of implementation (Tyler, Sunderland, et al., 2015). However, the application of strategies is dependent on the athletes' and coaches' perceptions of the effectiveness or practicalities of using these strategies. Recent evidence has suggested a number of strategies which might be beneficial to players on-court such as various cooling methods (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017), and taking advantage of the heat policies including the extended 10-minute break which can be implemented on- or off-court with additional heat alleviation strategies (Tippet et al., 2011).

Heat alleviation strategies are not used consistently in tennis, possibly due to little evidence for tennis-specific heat alleviation strategies which are effective during match play and inconsistent heat policies. Bridging the gap between science and application through understanding current practice is important as demonstrated by previous research (Halperin, 2018; Laursen, 2016; Reid & Schneiker, 2008; Shaw et al., 2016; Turner et al., 2018). However, the current practice of players and advice given to players by coaches and support staff is not yet known and no previous research has assessed their perceptions of heat alleviation strategies.

The primary aim of this study was to identify the heat alleviation practices used by tennis players during match play and the recommendations made by support staff. The secondary aim was to assess the perceptions of heat alleviation strategies and opinions on their effectiveness.

7.2 Methods

7.2.1 *Participants*

Eleven tennis players (current or retired) and six support staff (including coaches, medical staff, and sport scientists) completed the survey; a response rate of 24%. Inclusion criteria were tennis players and support staff who had played in or supported players in hot conditions. All participants provided informed consent following reading relevant information and having the opportunity to email the experimenter.

7.2.2 *Questionnaire and experimental design*

The study was a descriptive, single time-point cross-sectional survey design, using a questionnaire as the data collection tool. The questionnaire was developed with the support of three researchers within the research group. Experience in the team included tennis playing and coaching, tennis science support and experience supporting multiple athletic populations in the heat. The questionnaire was piloted with these researchers, then post-graduate researchers, and finally a tennis science practitioner with significant international experience provided feedback to help shape the content of the questions. The survey was updated multiple times throughout the design and piloting process to ensure it was easily understood, could gather accurate and useful information about heat alleviation strategies and perceptions of them. The final survey was formatted using Qualtrics (Qualtrics, London, England) and distributed through social media channels (Twitter, Instagram, Facebook, LinkedIn) and professional networks.

The study and questionnaire were approved by the institution's ethics committee and conducted in accordance with the guidelines of the Declaration of Helsinki (World Medical Association, 2013).

7.2.3 *Questionnaire structure*

All efforts were made to format the survey to be as quick as possible for participants to complete, whilst it was attempted to gather as much information as possible. The estimated survey completion time was 15-30 minutes depending on answers and subsequent follow-up questions. Around 90% of the questions were formatted as closed response options; closed-response such as Likert scale ratings, yes or no response, or a number of relevant options for them to choose. The remaining 10% were open-response where they were asked to clarify answers and provide extra details.

The final questionnaire had five sections: (a) participant characteristics; (b) heat alleviation strategies - value and knowledge gathering; (c) heat alleviation strategies – current practice; (d) heat alleviation strategies - perceptions; (e) perceived benefits and drawbacks (see appendix 10.5). Participants' roles were clarified and subsequently a response-dependent branching structure specific to either player or support staff was used to ensure they only had to answer relevant questions. During section (c) participants were asked follow-up questions only for the heat alleviation strategies they were currently using (within the last 2 years). In section (d), participants were asked a set of 32 questions if they were using at least one heat alleviation strategy, or 20 questions if they were not using any heat alleviation strategies. Within each of the sub-topics, a question was phrased in the opposite direction to decrease responder bias and ensure participants had to read and respond to each statement (Baumgartner & Steenkamp, 2001). All perception statements were presented in a randomised order for each participant.

7.2.4 *Data Processing and Analysis*

The player and support staff responses to the perceptual questions (forty-five statements) in section (d), for those who currently used (within the last 2 years) a heat alleviation strategy (user), were prospectively grouped into 16 sub-topics (2 statements in each) before these sub-topics were grouped into overarching themes of: performance (5 sub-topics), physiology (5 sub-topics), psychology (3 sub-topics) and understanding (3 sub-topics).

The non-user (those who had not used a heat alleviation strategy within the last 2 years) perception statement responses were grouped into 10 topics (2 statements in each) of: advice, understanding, time, equipment, ease of use, feeling hot, awareness of others use, opponent's perception, performance/physiology and influence of others. All statements for both users and non-users contained the same sentiment but were phrased so the focus was on the player for both populations.

Responses to all sections were grouped and differences between groups (players and support staff) were identified by the researcher. A content analysis (Hsieh & Shannon, 2005) was used to identify any themes within the open-ended questions in section (e).

7.3 Results

7.3.1 *Participants*

Eleven tennis players (7 male; 4 female) completed the survey, of which seven were British, two were Irish, one was Danish and one was dual nationality British and French. Most (n=9) were 18-24 years old, with the Irish players (n=2) being 45-54 years old. Fifty-five percent of the players currently reside and train in England, three in the USA and two in Ireland. The males had competed at a variety of levels including regional and county competition, national competitions, ITF junior events and the over 45 Potter Cup. Females had previously competed in regional and county competition, national competitions, ITF juniors, ITF 15s and NCAA division 1 college tennis.

Six support staff (3 science practitioners and 3 tennis coaches) completed the survey, of which 4 had previously competed as a player. Five worked with juniors and one with 18 to 24-year-olds, supporting both male and female players from Ireland (n=3), Italy (n=1), Malaysia (n=1) and Australia (n=1) and training bases in the same locations. The junior players being supported have competed over a range of standards including males: regional or county competition, ITF juniors, ITF 15s and Grand Slams; and females: regional and country competition, junior ITF, ITF 15s, ITF 25s+ and the Fed Cup. The senior male player(s) have competed in ITF 15s, ITF 25s, on the Challenger circuit and in ATP 250s. Junior rankings included 1, 3 and 10 nationally, and 1500 ITF for singles and 1 and 2, nationally for doubles. Senior ATP rankings included 850 for singles and 371 for doubles.

7.3.2 *Cooling – value and usages*

In response to the question "Cooling refers to any attempt to cool down whilst competing in hot conditions *e.g.,* cold drinks, ice towels, fans, shade. Do you think cooling is…?" with a 7-point scale ranging from extremely useless (1) to extremely useful (7), 5 players reported the belief that cooling was moderately useful and 6 players believed it to be extremely useful; the majority (83%) of support staff believed cooling was extremely useful (7) with one believing it was slightly useful (5).

All respondents were asked where they sought advice or might have received advice from with a summary of answers in Table 7.1 below.

Table 7.1: Where cooling advice was sought or received from.

	Player (n = 11)	Support Staff (n = 6)
Never had or sought any advice	4 (36%)	-
Read about it myself	6 (55%)	4 (67%)
Players	4 (36%)	2 (33%)
Coach(es)	4 (36%)	-
Another coach^	-	-
Team captain	2 (18%)	1 (17%)
NGB medical staff	1 (9%)	3 (50%)
Tour medical staff	1 (9%)	-
Tournament official	-	-
Tour supervisor	-	1 (17%)
Commercial supplier	-	-
Academic	2 (18%)	3 (50%)
Parents	1 (9%)	1 (17%)
Home nation institute practitioner	-	1 (17%)
Athletic trainer	1 (9%)	-
Own research*	-	3 (50%)

* Only support staff asked. ^ Only players asked

All respondents were asked at the start of each strategy about their previous and current use of that strategy, as seen in Table 7.2 below. Respondents who currently used (within the last 2 years) the strategies were then asked further questions about how they implemented these. Strategies including ice vests and ice slurry were the least used whereas it was more frequent for respondents to use the practical solutions such as cold drinks, seeking shade, pouring water and making specific clothing choices when playing in the heat.

Table 7.2: Player and support staff previous and current use of heat alleviation strategies.

Heat Alleviation Strategy	Never used and never will		Have not used, but would consider in the future		Have used previously but not anymore		Use currently (within the last 2 years)	
	Players (n = 11)	Support Staff (n = 6)	Players (n = 11)	Support Staff (n = 6)	Players (n = 11)	Support Staff (n = 6)	Players (n = 11)	Support Staff (n = 6)
Ice towels	-	-	6 (55%)	2 (33%)	2 (18%)	1 (17%)	3 (27%)	3 (50%)
Ice slurry	6 (55%)	-	5 (45%)	5 (83%)	-	-	-	1 (17%)
Ice vest	10 (91%)	1 (17%)	1 (9%)	5 (83%)	-	-	-	-
Fans	4 (36%)	-	4 (36%)	3 (50%)	-	1 (17%)	3 (27%)	2 (33%)
Water spray	2 (18%)	1 (17%)	5 (45%)	4 (67%)	3 (27%)	3 (50%)	1 (9%)	-
	Players (n = 10)	Support Staff (n = 6)	Players (n = 10)	Support Staff (n = 6)	Players (n = 10)	Support Staff (n = 6)	Players (n = 10)	Support Staff (n = 6)
Cold drinks	1 (10%)	-	1 (10%)	2 (33%)	-	-	9 (90%)	4 (67%)
Seeking shade	-	-	1 (10%)	-	-	1 (17%)	9 (90%)	5 (83%)
Cold water immersion / shower	4 (40%)	1 (17%)	4 (40%)	3 (50%)	-	1 (17%)	2 (20%)	1 (17%)
Water pouring	1 (10%)	-	1 (10%)	3 (50%)	-	2 (33%)	8 (80%)	1 (17%)
Clothing choices	-	-	1 (10%)	2 (33%)	-	1 (17%)	9 (90%)	3 (50%)
Increased between-point rest	1 (10%)	3 (50%)	2 (20%)	2 (33%)	-	1 (17%)	7 (70%)	-
10-min extended break	3 (30%)	-	5 (50%)	5 (83%)	-	-	2 (20%)	1 (17%)

7.3.3 *Cooling – Current Practice*

7.3.3.1 Ice Towels

Players responded using ice towels across a range of environmental conditions predominantly every change of ends during match play. This timing was also recommended by the support staff. Most respondents who use ice towels currently, only use an ice towel around the neck with one person using an ice towel around the neck and a cold wet towel on the head (see Table 7.3).

Table 7.3: Details of ice towels implementation.

	Player (n = 3)	Support Staff (n = 3)
In which conditions do you use this strategy?		
Hot & Dry	1 (33%)	1 (33%)
Hot & Humid	1 (33%)	-
Both	1 (33%)	2 (67%)
When do you use this strategy?		
Every change of ends	2 (67%)	3 (100%)
Every other change of ends	-	-
End of a set	-	-
During the extended break	1 (33%)	-
When feeling particularly hot	-	-
Whenever possible	-	1 (33%)
When do you begin using this strategy?		
Before the match	1 (33%)	-
At the start of the match	-	2 (67%)
In the middle of the match	2 (67%)	-
Towards the end of the match	-	1 (33%)
Do you start to use this strategy:		
Before you get hot (preventative)	3 (100%)	3 (100%)
When you are too hot (reactive)	-	-
How do you use this strategy?		
Ice towel around neck and cold wet towel on head and lap	-	-
Ice towel around neck and cold wet towel on head	1 (33%)	-
Ice towel around neck and cold wet towel on lap	-	-
Ice towel around neck	2 (67%)	3 (100%)

7.3.3.2 Ice Slurry

Only one member of support staff and no players reported currently using ice slurry as a heat alleviation strategy. The support staff respondent advised players to use ice slurry as a strategy in both hot dry and hot humid conditions, consuming at every change of ends from the start of the match. They advised consumption of 50-99 ml of ice slurry at each change of ends.

7.3.3.3 Fans

Most players and support staff reported using a fan in hot humid conditions with one player using in all hot conditions. The timing of the strategy varied between respondents with the majority using regularly or whenever possible with some using when feeling particularly hot or during the extended break. Support staff advised using a fan from the start of the match whereas players would begin using a fan from the middle or towards the end of a match. There was no consistency of fan placement.

Table 7.4: Details of the fans strategy.

	Players (n = 3)	Support Staff (n = 2)
In which conditions do you use this strategy?		
Hot & Dry	-	-
Hot & Humid	2 (67%)	2 (100%)
Both	1 (33%)	-
When do you use this strategy?		
Every change of ends	-	1 (50%)
Every other change of ends	1 (33%)	-
End of a set	-	-
During the extended break	2 (67%)	-
When feeling particularly hot	1 (33%)	-
Whenever possible	1 (33%)	1 (50%)
When do you begin using this strategy?		
Before the match	-	1 (50%)
At the start of the match	-	1 (50%)
In the middle of the match	2 (67%)	-
Towards the end of the match	1 (33%)	-
Where do you place the fan?		
In front of you	1 (33%)	-
To the side of you	1 (33%)	1 (50%)
Behind you	-	1 (50%)
No specific placement	1 (33%)	-

7.3.3.4 Water Spray

Only one respondent replied that they currently use water spray as a strategy. The player has used it in a hot dry condition, at every change of ends from the middle of the match onwards.

7.3.3.5 Cold Drinks

The majority of respondents reported that they use cold drinks as a heat alleviation strategy in all hot conditions. The general consensus was that they should be used as much as possible or at the least during every change of ends. Most responded that they should consume whatever they feel necessary at the time with two support staff suggesting it should be consumed based on volume: one suggested 50-99 ml and the other 200-249 ml.

Table 7.5: Details of the cold drinks strategy.

	Players (n = 8)	Support Staff (n = 4)
In which conditions do you use this strategy?		
Hot & Dry	-	-
Hot & Humid	-	-
Both	8 (100%)	4 (100%)
When do you use this strategy? (select all that apply)		
Every change of ends	7 (88%)	2 (50%)
Every other change of ends	-	-
End of a set	-	-
During the extended break	-	-
When feeling particularly hot	2 (25%)	-
Whenever possible	3 (38%)	2 (50%)
When do you begin using this strategy?		
Before the match	3 (38%)	3 (75%)
At the start of the match	4 (50%)	1 (25%)
In the middle of the match	1 (13%)	-
Towards the end of the match	-	-
How do you advise consumption?		
Volume	-	2 (50%)
Body mass	-	-
Sweat rate	-	-
Whatever is felt to be necessary	8 (100%)	2 (50%)
No advice given*	-	-

* Only support staff asked

7.3.3.6 Seeking Shade

Seeking shade was reported as a currently used as a strategy by nearly all the respondents to this survey. They felt it should be used whenever possible whether sitting down in the chair or not from before the match has started right through to the end of the match. The support staff would advise all the different ways to seek shade (as seen in Table 7.6), however, a lower percentage of players said they used them.

Table 7.6: Details of the seeking shade strategy.

	Players (n = 9)	Support Staff (n = 5)
In which conditions do you use this strategy?		
Hot & Dry	2 (22%)	-
Hot & Humid	-	-
Both	7 (78%)	5 (100%)
When do you use this strategy?		
Between points	2 (22%)	2 (40%)
Between games (not changing ends)	2 (22%)	1 (20%)
Every change of ends	5 (56%)	3 (60%)
Every other change of ends	-	-
End of a set	2 (22%)	-
During the extended break	1 (11%)	-
When feeling particularly hot	3 (33%)	-
Whenever possible	3 (33%)	2 (40%)
When do you begin using this strategy?		
Before the match	3 (33%)	4 (80%)
At the start of the match	-	1 (20%)
In the middle of the match	4 (44%)	-
Towards the end of the match	1 (11%)	-
Where or how do you seek shade?		
Under an umbrella or shelter (e.g. attached to a chair)	3 (33%)	5 (100%)
Wearing a cap or hat	6 (67%)	4 (80%)
Shade created by court permanent structures, stadium or stands	5 (56%)	5 (100%)

7.3.3.7 Cold Water Immersion / Showering

Cold water immersion during match play would be advised by one of the support staff respondents. They would suggest using it in any hot conditions, whenever possible towards the end of a match. It would be implemented in the changing or locker room and involve submersion for 6-10 minutes in cold-water, definitely containing ice.

7.3.3.8 Water Pouring

Pouring water on yourself was more popular with players than support staff. It was reported as a strategy which is implemented in all hot environments from the middle of the match onwards. The majority reported using this strategy when feeling particularly hot whilst one player would used it at every change of ends. All users would pour water over the head only.

Table 7.7: Details of the water pouring strategy.

	Players (n = 8)	Support Staff (n = 1)
In which conditions do you use this strategy?		
Hot & Dry	-	-
Hot & Humid	-	-
Both	8 (100%)	1 (100%)
When do you use this strategy?		
Every change of ends	1 (13%)	-
Every other change of ends	-	-
End of a set	1 (13%)	-
During the extended break	1 (13%)	-
When feeling particularly hot	6 (75%)	1 (100%)
Whenever possible	1 (13%)	1 (100%)
When do you begin using this strategy?		
Before the match	-	-
At the start of the match	-	-
In the middle of the match	7 (88%)	1 (100%)
Towards the end of the match	1 (13%)	-
How do you pour water over yourself?		
Over head	8 (100%)	1 (100%)
Upper body only	-	-
Lower body only	-	-
Whole body	-	-

7.3.3.9 Clothing Choices

Players and support staff reported that they were likely to make different clothing choices when competing in hot conditions. The most likely clothing changes were what is worn on the top half and to ensure that clothing is white in colour (see Table 7.8). Whilst players said they change into fresh clothes at various stages throughout a match, it is important that they change whenever needed to remain comfortable.

Table 7.8: Details of clothing choices.

	Players (n = 9)	Support Staff (n = 3)
In which conditions do you use this strategy?		
Hot & Dry	1 (11%)	-
Hot & Humid	1 (11%)	-
Both	7 (78%)	3 (100%)
What do you wear differently to usual when competing in hot conditions?		
Top half (T-shirt etc)	5 (56%)	3 (100%)
Bottom half (Shorts/trousers/leggings etc)	2 (22%)	2 (67%)
Accessories (sweat bands/caps etc)	4 (44%)	2 (67%)
Clothing material (cotton/polyester etc)	5 (56%)	2 (67%)
Ensure clothing is white in colour	6 (67%)	2 (67%)
Other	-	-
When do you change into fresh clothes during a match in hot conditions? (select all that apply)		
End of set 1	4 (44%)	-
End of set 2	4 (44%)	-
End of set 3	2 (22%)	-
End of set 4	1 (11%)	-
I do not change	1 (11%)	-
When needed to stay comfortable	4 (44%)	3 (100%)
Extended break	1 (11%)	-

7.3.3.10 Increased Between-Point Rest

Players responded that they implement an increase in between-point rest in hot dry and hot humid conditions either after a long rally or when feeling particularly hot. There was no consistency in responses as to when players might start wanting to take longer between-points, though the majority would start during the middle of the match. Four of the respondents who reported that they use this strategy did not have a shot clock at their competitions, however of the three players who did, two of them felt they are no longer able to use this strategy and one feels they can sometimes. All players felt that umpires were more lenient when penalising with time violations when in hot environmental conditions. No support staff responded they would advise this as a heat alleviation strategy.

Table 7.9: Details of increased between-point rest implementation.

	Players (n = 7)	Support Staff (n = zero)
In which conditions do you use this strategy?		
Hot & Dry	-	-
Hot & Humid	-	-
Both	7 (100%)	-
How often do you increase your between-point rest length? (select all that apply)		
Every point	-	-
After a long rally	5 (71%)	-
When feeling particularly hot	5 (71%)	-
Whenever possible	-	-
Tactically to slow down the opponent	2 (29%)	-
Other	1 (14%)	-
When do you begin using this strategy?		
At the start of the match	1 (14%)	-
In the middle of the match	4 (57%)	-
Towards the end of the match	2 (29%)	-
Are you still able to take longer between-point breaks since the intro. of the shot clock?		
Yes	-	-
No	2 (29%)	-
Sometimes	1 (14%)	-
There is no shot clock at my competitions	4 (57%)	-
Do you feel umpires are more lenient with time violations in hot conditions?		
Yes	7 (100%)	-
No	-	-

7.3.3.11 10-min Extended Break

Few respondents (n=2) were current users of the extended 10-min break. Though, both respondents said they would try to get away from the court to the changing room or closest convenient place and implement a variety of cooling strategies throughout (see Table 7.10).

Table 7.10: Details of 10-min extended break implementation.

	Players (n = 2)	Support Staff (n = 1)
In which conditions do you use this strategy?		
Hot & Dry	-	-
Hot & Humid	-	-
Both	2 (100%)	1 (100%)
Where do you go during the 10 minute extended break?		
Stay on court	-	-
The changing/locker room	1 (50%)	1 (100%)
The court building	-	-
The closest convenient place to cool down	1 (50%)	-
Other	-	-
Do you use any cooling methods during this period? (including air conditioning)		
Yes	2 (100%)	1 (100%)
No	-	-
How do you advise consumption?		
Ice towels	1 (50%)	1 (100%)
Ice slurry / slushy	-	1 (100%)
Fans	-	-
Water spray	-	-
Cold drinks	1 (50%)	-
Seeking shade	2 (100%)	1 (100%)
Cold water immersion / shower	-	-
Pouring water on yourself	1 (50%)	-
Air conditioning	1 (50%)	1 (100%)
Other: "Sit with ice"	1 (50%)	-

7.3.3.12 Combinations of Heat Alleviation Strategies

The combinations of heat alleviation strategies that would be implemented during tennis match play for players (Table 7.11) and support staff (Table 7.12) can be seen below. Further to the detail of the 10-minute extended break in section 7.3.3.11, players and support staff would find an air-conditioned environment, if possible, with players also opting to sit with ice on their laps.

7.3.4 *Perceptions of Cooling*

The player and support staff responses to a series of statements designed to determine the perception of heat alleviation strategies using a Likert scale response are in Figure 7.2 below and Figure 7.2 below.

Table 7.11: Combinations of heat alleviation strategies implemented by players.

	Heat Alleviation Strategy	*Yes/Users (%)*	Ice towels	Ice slurry	Ice vest	Fans	Water spray	Cold drinks	Seeking shade	Cold water immersion / shower	Water pouring	Clothing choices	Increased between-point rest	10-min extended break
Players	Ice towels	1/3 (33%)		-	-	-	-	-	-	-	1 (100%)	-	-	-
	Ice slurry	-	-		-	-	-	-	-	-	-	-	-	-
	Ice vest	-	-	-		-	-	-	-	-	-	-	-	-
	Fans	2/3 (67%)	-	-	-		-	2 (100%)	1 (50%)	-	2 (100%)	2 (100%)	-	-
	Water spray	1/1 (100%)	1 (100%)	-	-	-		-	-	-	-	-	-	-
	Cold drinks	4/8 (50%)	1 (25%)	-	-	1 (25%)	-		2 (50%)	-	4 (100%)	4 (100%)	1 (25%)	1 (25%)
	Seeking shade	5/9 (56%)	2 (40%)	-	-	1 (20%)	1 (20%)	2 (40%)		-	4 (80%)	3 (60%)	-	1 (20%)
	Cold water immersion / shower	2/2 (100%)	1 (50%)	-	-	-	1 (50%)	1 (50%)	1 (50%)		1 (50%)	1 (50%)	-	-
	Water pouring	5/8 (63%)	2 (40%)	-	-	1 (20%)	1 (20%)	3 (60%)	3 (60%)	1 (20%)		3 (60%)	-	1 (20%)
	Clothing choices	4/9 (44%)	2 (50%)	-	-	-	1 (25%)	2 (50%)	3 (75%)	1 (25%)	3 (75%)		-	1 (25%)
	Increased between-point rest	2/7 (29%)	2 (100%)	-	-	-	1 (50%)	1 (50%)	2 (100%)	-	2 (100%)	1 (50%)		1 (50%)
	10-min extended break	2/2 (100%)	1 (50%)	-	-	-	-	1 (50%)	2 (100%)	-	1 (50%)	-	-	A/C, Sit with ice

Yes/Users (%): The number of respondents who said they combined the strategy with other strategies as a percentage of total users

Table 7.12: Combinations of heat alleviation strategies advised by support staff.

	Heat Alleviation Strategy	*Yes/Users (%)*	Ice towels	Ice slurry	Ice vest	Fans	Water spray	Cold drinks	Seeking shade	Cold water immersion / shower	Water pouring	Clothing choices	Increased between-point rest	10-min extended break
Support Staff	Ice towels	1/3 (33%)		1 (100%)	-	-	-	1 (100%)	1 (100%)	-	-	-	-	-
	Ice slurry	1/1 (100%)	1 (100%)		-	-	-	1 (100%)	1 (100%)	-	-	-	-	-
	Ice vest	-	-	-		-	-	-	-	-	-	-	-	-
	Fans	1/2 (50%)	1 (100%)	-	-		-	-	-	-	-	-	-	-
	Water spray	-	-	-	-	-		-	-	-	-	-	-	-
	Cold drinks	3/4 (75%)	1 (33%)	1 (33%)	-	-	1 (33%)		2 (67%)	-	-	-	1 (33%)	-
	Seeking shade	4/5 (80%)	3 (75%)	-	-	2 (50%)	2 (50%)	3 (75%)		-	-	-	2 (50%)	-
	Cold water immersion / shower	0/1 (0%)	-	-	-	-	-	-	-		-	-	-	-
	Water pouring	0/1 (0%)	-	-	-	-	-	-	-	-		-	-	-
	Clothing choices	2/3 (67%)	1 (50%)	1 (50%)	-	-	1 (50%)	2 (100%)	1 (50%)	-	-		1 (50%)	-
	Increased between-point rest	-	-	-	-	-	-	-	-	-	-	-		-
	10-min extended break	1/1 (100%)	1 (100%)	1 (100%)	-	-	-	-	1 (100%)	-	-	-	-	A/C

Yes/Users (%): The number of respondents who said they combined the strategy with other strategies as a percentage of total users

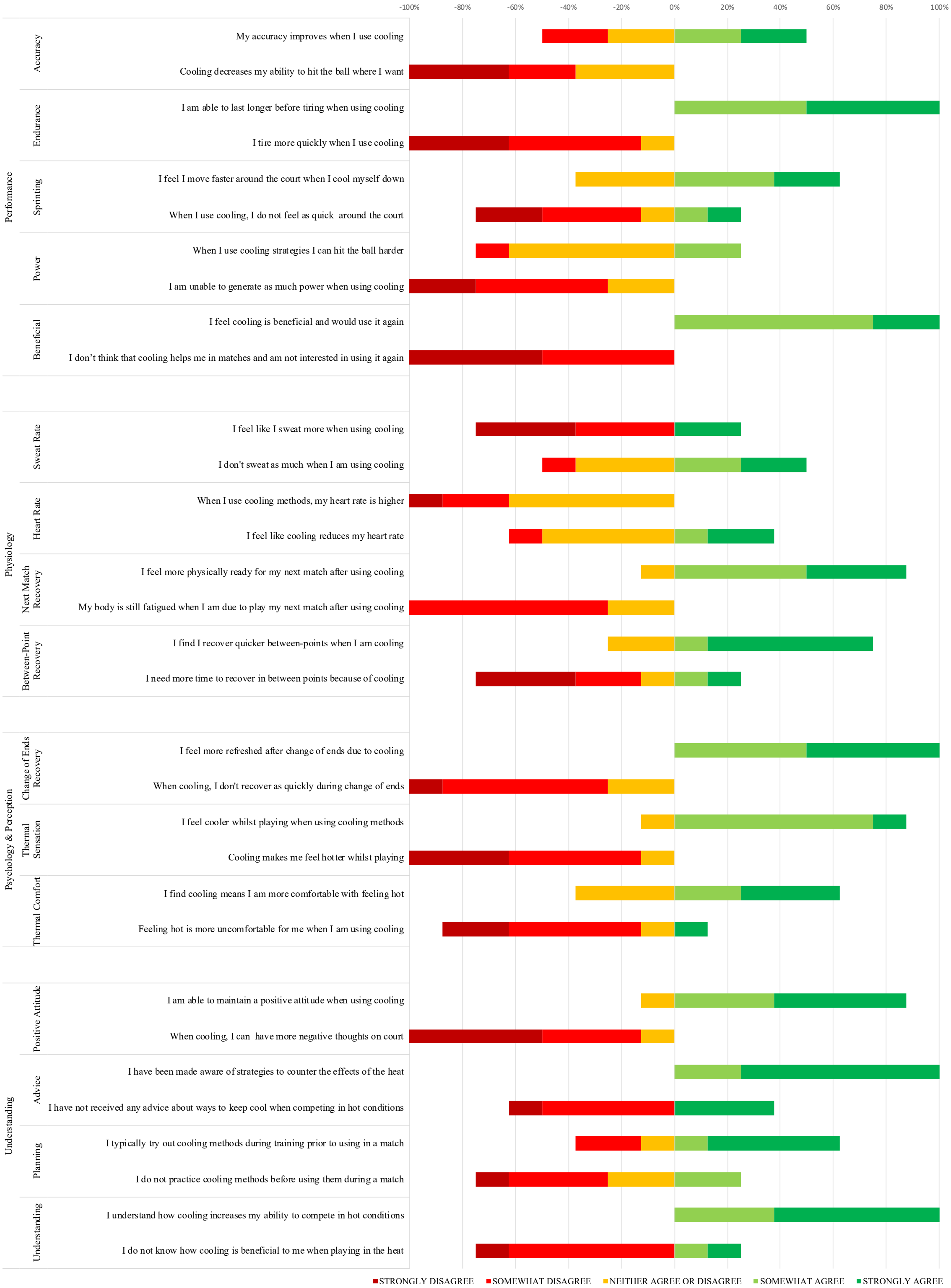

Figure 7.1: The perceptions of cooling and other acute heat alleviation strategies of players who currently use at least one strategy.

Figure 7.2: The perceptions of cooling and other acute heat alleviation strategies of support staff who currently use at least one strategy.

7.4 Discussion

7.4.1 *Key Findings*

The primary aim of this study was to identify the heat alleviation practices used by tennis players during match play and the recommendations made by support staff. The secondary aim was to assess the perceptions of heat alleviation strategies and opinions on their effectiveness. The primary finding was that both players and support staff believe that heat alleviation strategies are useful during tennis match play in hot conditions; though heat alleviation practices used were variable, with the strategies requiring no equipment being more widely used than those that required specific or more complicated equipment. The responses to the perceptual statements suggest that there are performance benefits from using heat alleviation strategies through both physiological and perceptual means; and that both players and support staff overall understand how heat alleviation strategies are beneficial.

7.4.2 *Beliefs and Advice*

Both players and support staff believe that heat alleviation strategies are beneficial when competing in hot conditions. All players were split across the top two levels of response (moderately and extremely useful), with most support staff also believing they are extremely useful and one believing they are slightly useful. The underpinning belief on heat alleviation strategies is an excellent base for implementing these strategies during competitions that have external rewards as it increases the likelihood for implementation.

Where advice is sought can assist in considering future educational plans. Four (36%) of the players responding to the survey said they had not received or sought any advice about cooling. This might be due to the levels of competition that they are playing at as some of these were players who were competing at lower levels including regional or county competitions. However, one of these players had competed in ITF junior events so you would expect that they likely had a larger support team or access to a range of support staff where they would be more likely to receive advice on keeping cool. The most frequent answer for players who had received some advice was for them to read about it themselves (55%); they were also likely to received advice from players and tennis coaches with 36% of respondents saying this was their source for each. Whilst players should take ownership of their performance, it is surprising that most players have either not had any advice or read about it themselves. Perhaps an element of the conditions in which these players are competing on a regular basis has an impact but, it would be a fair assumption that if the players are not used to the conditions that support staff would be more likely to advise them on strategies which would help alleviate the negative effects of the heat.

Support staff were most likely to read about it themselves with four respondents (67%) giving this answer. The other common answers were national governing body (NGB) medical staff, academics and through their own research; all with a 50% response rate. Another suggested they received advice from a home nation institute practitioner which is similar to the NGB reported above, therefore these people would be a good place to assess the advice that is being given and their understanding of heat alleviation strategies for tennis match play. Whilst it would be expected that science and medical practitioners make an effort to find out this information for themselves, it is apparent that coaches are also trying to increase their knowledge in this area.

Players need to be signposted to information sources which are accurate if they are going to look for themselves. It is also clear that their personal coaches and fellow players are a key source of information on heat alleviation, with medical staff also being consulted, therefore these are the parties that need to ensure adequate knowledge to educate the players. Resources and courses could reasonably be aimed at both players and support staff, with differentiation between populations as needed.

7.4.3 *Heat Alleviation Strategy Use*

The overarching trend for the data of the various heat alleviation strategies used is that the practical, low-cost options that require minimal equipment are the strategies that are most widely implemented. Nine out of ten players currently use (within the last 2 years) cold drinks, seeking shade and altering clothing choices when playing in hot conditions. Support staff also responded favourably to cold drinks and seeking shade with 67% and 83% of respondents, respectively; and a favourable (50%) response for clothing choices. Making heat alleviation strategies practical and accessible increases the possibility of implementation across a wider range of competition standards (Chalmers, 2017), this seems to highlight the fact that these are indeed the most widely used currently. Whether this is due to lack of knowledge of other available strategies or simply due to their accessibility is not known and awareness was not part of the questionnaire in this study. This might offer useful insight and should be considered for future research.

The way in which cold drinks are used to keep cool have some consistencies: being used in all hot conditions and whenever possible or every change of ends. However, there were some differing thoughts on when to begin using cold drinks in this way with players split between before the match and the start of the match; support staff advised before the match would be best. Whilst cold drinks are unlikely to cause a pre-cooling effect through decreasing core temperature, implementing practices before the match might have beneficial perceptual effects. The majority of responses regarding the volume to consume was 'whatever is felt to be necessary', which did not provide any quantification of what this might be. Two support staff advised consuming volumes of 50-99 ml and 200-249 ml. A difference of 100-150 ml at each change of ends over the course of an average match, as consumed during the TSTP in this thesis (see sections 4.2.5, 5.2.5 and 6.2.6), would be 1.4 – 2.1 L over the course of the match. It has been suggested that players in hot conditions consume 400 ml or more at each change of ends (Ranchordas et al., 2013), which is a similar difference again. One respondent's suggestion of 200-249 ml at each change of ends is probably sufficient to replace fluid to match sweat rates previously reported within tennis match play of 1-2.5 $L \cdot min^{-1}$ (Bergeron, 2003), though in extreme cases such as 3.5 $L \cdot min^{-1}$ (Ranchordas et al., 2013) higher volumes might need to be consumed and guidance should be provided on an individual basis. A rough guideline might be 300 to 400 ml every 15 mins of play as this is the most effective for replacing lost fluid and is around the gastric emptying rate of 1.2 $L \cdot hr^{-1}$ (A Review of Fluid and Hydration in Competitive Tennis, 2008) Therefore, 50-99 ml would replace about 30% of fluid lost (based on a sweat rate of 2 $L \cdot hr^{-1}$) which would lead to dehydration and increase heat illness risk. The guidance of 200-249 ml might be sufficient or nearly sufficient depending on the player.

The current practice for seeking shade seems to be common in tennis match play across both populations, though the only real trend in timing seems to be finding shade during the change of ends. Whilst the support staff would advise to use a selection of items, clothing or permanent structures (see Table 7.6), not all players use all these methods. This might be due to personal preference such as not wanting to wear a cap, or simply they have not considered them previously. Seeking respite from solar radiation, which might reduce radiative heat gain by as much as 100 W (Nielsen et al., 1988), may offer players an opportunity to dissipate heat at a more effective rate in comparison to heat gain and demonstrate the effectiveness of such a simple strategy.

Clothing choices can enhance a player's ability to dissipate heat and/or the effectiveness of cooling strategies. A popular strategy is to wear white clothing (see Table 7.8), which will curtail the absorption of heat from solar radiation, though might allow more radiation to penetrate the clothing (Gavin, 2003). Fewer respondents suggested they consider the clothing material. Colour and material of clothing affect heat balance: black clothing can enhance dry heat loss through an increased surface temperature; however, physiological strain has been reported to be significantly reduced whilst wearing white polyester compared to black cotton (Nielsen, 1990), though it has also been suggested that a cotton/wool blend is most effective at reducing core temperature in windy conditions (Kwon et al., 1998). It is likely that clothing material does not make a large difference to thermoregulation (Gavin, 2003) with little difference being observed between cotton and polyester (Gavin et al., 2001). Therefore, wearing white is the most beneficial and respondents do not need to consider material, as is current practice.

A large proportion of the player respondents (80%) currently use water pouring (see Table 7.2) to keep cool during match play, whilst only 17% of support staff currently recommend it. As seen in

Table 7.7 above there is good consistency of responses with water pouring implemented in all hot conditions, when feeling particularly hot in the middle of the match, by pouring cold-water over the head. Some research suggests that water dousing in a single dose might not be effective at reducing physiological markers such as core and skin temperature (W. M. Adams et al., 2016). However, other data presented at a conference, suggests that water dousing 4 times throughout a sport-specific intermittent treadmill protocol in 33 ˚C and 50% rh might delay the rise in rectal temperature, decrease heart rate and improve repeated sprint performance in comparison to no dousing whilst both euhydrated and dehydrated (Benjamin et al., 2020). Used for a longer duration, cold-water poured continuously, such as a shower or a hose for 60 minutes as a pre-cooling method reduced core temperature by 0.3 ˚C, though this increased to 0.6 ˚C after a further 15 minutes of rest prior to exercise commencement (Drust et al., 2000). However, it has the potential to enhance evaporative heat loss during hot, dry conditions, whilst during hot humid conditions it might offer short term comfort but lead to clothes becoming sodden (Morris & Jay, 2016). Dousing might have a significant physiological benefit (Benjamin et al., 2020) and it is likely to have a perceptual benefit (Morris & Jay, 2016).

The extending between-point strategy was fairly popular amongst players who were likely to implement the strategy either after a long rally or when feeling particularly hot. A small proportion (29%) responded that they would also use it tactically; possibly a reason why higher levels of competition have introduced a shot clock to prevent players taking too long between-points. Of the 3 respondents who use this strategy and have a shot clock, 2 do not find it possible to use this strategy and longer and one suggested it was possible sometimes. Though, all respondents believed umpires were more lenient with time violations (penalty for taking too long in breaks of play) when playing in hot conditions. As seen in chapter 0, increasing the between-point rest can significantly reduce the thermal physiological strain during tennis-specific exercise which aligns with current practice of players.

Ice towels, though only currently used by 27% of players, was currently advised by 50% of support staff suggesting moderate prevalence. Though, 55% of players and 33% of support staff said although they had not used this strategy previously, they would consider in the future. Ice towels necessitate particular facilities, such as an ice machine, to be utilised which might be why few respondents currently use it.

Of those who use the strategy, some use specifically for hot & dry, some for hot & humid and some in both conditions (Table 7.3 above). Those that do implement the strategy do so regularly at each change of ends though some begin implementation at the start and some in the middle of the match. Recent research has suggested that the ice towel method is an ice towel around the neck simultaneously with cold wet towels on the head and the lap (Lynch et al., 2018; Schranner et al., 2017). However, as seen in Table 7.3, 67% of player users and 100% of support staff users only implement an ice towel around the neck, with one player also using a cold wet towel on head. This towel-only strategy is likely to be less effective as using simultaneously with cold wet towels when comparing data in chapter 0 above with that of Schranner et al. (2017). Reasons as to why players only implement a towel-only strategy should be explored with possible areas of education for a combined towel approach as well as further research of both strategies.

Ice slurry received a split response for players with 55% opposed to using in the future and 45% open to trying the method; support staff were in favour of future use with one currently using the method. Ice slurry (1.25 $g \cdot kg^{-1}$ at each change of ends) during a tennis-specific treadmill protocol lowers rectal temperature, heart rate, forehead skin temperature and thermal sensation in the second half of the protocol compared with cold-water (Naito et al., 2018). Data from chapter 0 found a similar trend to this study when 2 $g \cdot kg^{-1}$ at each change of ends saw a reduction in rectal temperature during the second half of the TSTP and a lower thermal sensation at the end of the TSTP, both compared to a thermoneutral control. The support staff respondent who currently uses this strategy suggested that it was used every change of ends from the start of the match as seen above but in volumes of 50-99 ml. For an athlete weighing 70 kg, this would equate to 0.7-1.4 $g \cdot kg^{-1}$; therefore, depending on the mass of the athlete prescribing this volume might not have an impact on physiological or perceptual strain. It would be better to prescribe relative to body mass rather than an absolute volume. The strategy is suggested for use within team sports which have a similar intermittent nature (Taylor et al., 2020) during the Tokyo 2020 Olympics. Players might need education and opportunities to try this strategy to become more open to it.

CWI elicited a similar response with some not open to use it in the future, however some responded that they use it currently. However, the player respondents extra detail suggested that they were not using them during match play, rather, before or after so this information will not be discussed further. However, the support staff currently recommending its use suggested CWI whenever possible towards the end of a match, in the changing room or equivalent for 6-10 minutes with ice. Whilst this has been seen on the professional tour, it would only be during a 10-minute extended break that a player would be allowed to stay in the changing room long enough to implement this strategy. CWI is effective at reducing core temperature (Ross et al., 2013) which might be vital if players are close to thresholds of heat illness. However, CWI can decrease nerve conduction and muscle contraction velocities (Racinais & Oksa, 2010) which, from a playing perspective, might mean players see a drop off in performance until the muscles rewarm. CWI has not been researched in the context of the 10-minute extended break and is traditionally implemented for 30 minutes. Therefore, it is possible the reduced time cooling might see some reductions in heat strain whilst not impairing neuromuscular function.

Fans are currently used by around a quarter of respondents (see Table 7.2). Of those who use them, some use them during the extended break, and some use them throughout the match. The idea of using a fan is to increase the convective heat loss, through enhanced sweat evaporation, however, this is more likely to have a positive effect in a mildly humid environment rather than a dry environment where sweat is already evaporating readily; it might possibly lead to further heat gain in these situations. The use of a fan during a tennis-specific intermittent protocol in 45 ˚C 10% rh led to a similar rise in core temperature compared to a control condition (Lynch et al., 2018); more research is needed to identify the effectiveness of a fan in a more humid environment. The combination of a fan with a water spray is as effective as ice towels (ice towel around neck and cold damp towels on head and lap) at slowing the rise in core temperature and reducing thermal sensation during a tennis treadmill protocol in both hot dry and hot humid conditions (Lynch et al., 2018; Schranner et al., 2017). The water spray strategy is simple yet is only currently used by one of the respondents in this survey. Considering the key factors that determine the efficacy of a cooling strategy (Tyler, Sunderland, et al., 2015), as the skin surface area that has water sprayed on with a fan application increases so should the effectiveness of this technique.

The extended 10-min break is not used by many of the respondents. This might be due to the standard of player, though more respondents have competed or supported at a level which would implement this within the heat policy. Therefore, it might be that the respondents have not played in conditions or met the requirements within a match *i.e.,* reaching a deciding set under ITF jurisdiction. The remaining respondents will not have been offered this break officially due to not competing at a high enough level. Thirty percent of players expressed that they would never want to use this strategy, whereas the other 50% of players and all support staff (83%) who had not previously implemented this break were open to using it in the future. The break has previously reduced core temperatures by 0.25 ± 0.20 ˚C in a sanctioned WTA tournament (Tippet et al., 2011). This study combined both players who took the 10-minute extended break and those who were not offered this break but had a bathroom break. The behaviours in both situations were similar with a towel dry and a change of clothes. Whilst the extended break demonstrated a larger core temperature decrease (0.30 ± 0.14 ˚C vs 0.17 ± 0.27 ˚C), a bathroom break is an effective strategy that players can use should the conditions be hot but not high enough for this rule to be implemented.

Ice vests are not currently used by any of the respondents in this survey with 91% of players expressing they would not want to use it in the future but, support staff open to using it as a potential strategy. Ice vests were better than ice slushy for half time cooling during a team-sport simulated intermittent protocol (Brade et al., 2014). Ice vest use with cold towels on the head and lap, similar to the ice towel approach used by Schranner et al. (2017) and Lynch et al. (2018), implemented as pre-cooling before an on-court tennis conditioning session showed a moderate-large effect (*d* = 0.7-1.0; $P > 0.05$) on total an high intensity distance covered whilst significantly lowering thermal sensation (Duffield et al., 2011). In the study players were pre-cooled for 30 minutes, so though it might be a good technique covering a large surface area increasing conductive heat loss, the hassle of getting a vest on and off at each change of ends would likely make it impractical and might be the reason that players are opposed to using it.

Combining some or many of these strategies, for example an internal and external cooling method simultaneously enhances cooling capacity compared to individual use (Bongers et al., 2015). This combination, as seen in chapter 6, alongside other strategies such as seeking shade, increasing between-point rest is likely to have a large beneficial effect on physiological and perceptual heat strain as well as performance. It is also possible that when combining these strategies, they could each be used moderately, but because there are more avenues for heat exchange, the overall effect is as least, if not more, beneficial. The combinations currently implemented by players and support staff who responded to this survey are in Table 7.11 and Table 7.12. There are no patterns emerging regarding the combinations of techniques for players or support staff. This internal and external cooling combined approach was more effective than an ice vest or ice slushy alone, with the combined approach eliciting higher total mean power and work performed during an intermittent cycling protocol (Brade et al., 2014). The idea of using a variety of strategies and combining them aligns with the suggestion that practitioners should consider a 'toolbox' of strategies (Gibson et al., 2019).

7.4.4 *Perception of Heat Alleviation Strategies*

The perceptions for the respondents who had used at least one heat alleviation strategy featured in the survey can be seen in Figure 7.2 and Figure 7.2 above. Players often gave directional answers *i.e.,* agree, or disagree, whereas support staff to answer neither agree or disagree. The answer of neither agree or disagree has been presented as a negative within the figure, if there is no clear beneficial perception then it is less likely that strategies will be willingly used or suggested. Though, if a strategy does not interrupt a player's habits and standard behaviour during match play then adding a strategy is likely to be more favourable.

The group of performance statements were focussed around different physical elements important for match play (Kovacs, 2006) and the playing abilities on speed and accuracy of their shots. Players and support staff felt that cooling or heat alleviation strategies were beneficial for them during match play, particularly for the physical aspect of endurance. The support staff felt that this enabled players to move around the court more quickly, and players tended to agree. The response for tennis speed and accuracy suggested they felt these were not affected positively or negatively by heat alleviation strategies. These elements decrease as players become fatigued (Davey et al., 2002) and without applied research it is unclear whether cooling techniques or similar would attenuate this decline in skilled performance as a match continues. Physiological and perceptual strain is thought to be a key factor affecting accuracy and shot speed (Hornery, Farrow, Mujika, & Young, 2007) and if tactical play of attempting more winners and shortening points is a consequence of playing in the heat (Morante & Brotherhood, 2008b) then cooling potentially increases within-point as well as within-match endurance.

The physiological statements considered physiological markers of sweat rate and heart rate, and the ability to recover over different periods: between-point, change of ends, and for the next match. Players gave mixed responses about the effect of heat alleviation techniques on sweat rate whilst the support staff were confident it did not have a positive or negative effect. Whilst an increase in sweat rate is not anticpated, the sudomotor response will be suppressed regardless of core and skin temperatures, decreasing evaporative heat loss potential, when consuming cold drinks such as ice slurry (Burdon et al., 2013; Morris et al., 2016; Siegel et al., 2012). This effect can be seen in Figure 6.3 in chapter 0. Sweat rate is lower with strategies such as airflow (W. C. Adams et al., 1992) and the technique enhances sweat evaporation giving an overall benefit (Lynch et al., 2018).

Some respondents do not think heart rate is affected when using cooling strategies. Others across both populations think that heart rate would be reduced. This is in line with previous research where a rise in heart rate has been attenuated during tennis-specific treadmill exercise through intermittent cooling (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017), which might be a repeated reduction in heart rate as pre-cooling has been observed to decrease heart rate, but quickly recover to baseline levels (Ross et al., 2011). It would be expected that as thermal strain was decreased, heart rate might decrease due to less demand for increased skin blood flow.

Players and support staff think that recovery between points is quicker when using heat alleviation strategies. There is no evidence to suggest whether this is the case and would be dependent on the preceding point length, distance covered etc. Sixty percent of support staff did express that players would need longer for recovery between points; however, this might be due to thinking about implementing such strategies otherwise the results would be contradictory. Players and support staff agree that cooling strategies allow players to be more refreshed following a change of ends. Though, the present survey did not explore the reasons they believed this. Strategies including ice towels, spray and fan, and ice slurry have previously been suggested to decrease thermal sensation following a change of ends which would likely make players feel more refreshed (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017); data in Figure 6.6, chapter 0 also demonstrates this. The perception is that by the next match any fatigue is gone, and players are physically ready when they use heat alleviation strategies (see Figure 7.2 and Figure 7.2). Technical changes which might affect accuracy and shot speed due to fatigue are exacerbated in the heat though, the underpinning cause is not known. It is possibly due to peripheral fatigue, as demonstrated by a reduction in neuromuscular system integrity (Périard, Girard, et al., 2014), though if a match is at least 24 hours, any remaining fatigue might be due to perceptual rather than physiological reasons (Kraemer, Piorkowski, et al., 2000).

The perceived effects of cooling and other heat alleviation strategies on psychological and perceptual factors from the respondents are definitely positive. Thermal sensation, thermal comfort and the ability to maintain a positive attitude throughout a match are all believed to be improved by cooling. The improvement in thermal sensation following cooling is supported extensively in the literature (Lynch et al., 2018; S. A. Morrison et al., 2014; Naito et al., 2018; Otani et al., 2017; Schranner et al., 2017), and is supported in chapter 0 of this thesis. Thermal sensation is thought to be a key factor affecting effective playing time and a reduction *i.e.,* players feeling less hot, would likely lead to players requiring less time between points and able to implement their pre-planned tactics rather than needing to adjust due to the heat (Fernández-Fernández et al., 2006; Hornery, Farrow, Mujika, Young, et al., 2007; Morante & Brotherhood, 2008b; Périard, Racinais, et al., 2014b; Torres-Luque et al., 2011).

The final statements were around if advice had been received or given, the understanding of these strategies' effect on performance and whether they were tested during practice. The players' answers on receiving advice were unclear as all respondents said they have been made aware of potential heat alleviation strategies, but some also stated they had not been advised how to keep cool; this was similar for the support staff. This is a confusing result which would benefit from being followed up with interviews or similar in future studies. It does not appear to be common practice for cooling techniques to be tested prior to match play but most respondents would not use a method without trialling it prior a match. Using these methods during practice sessions or matches will help players become accustomed to what they perceive to be the better strategies for them in various conditions and should not rely on what is provided, if anything, by the tournament. Support staff believe they explain the physiological and perceptual benefits of heat alleviation strategies to their players and the players are confident they know how they are beneficial. Based on the large variety of practice within this study, this understanding may, in some cases, be questionable as optimal practices are not always being implemented.

One of the support staff who completed this survey, does not currently use any of the heat alleviation strategies covered in this study. Their perceptions of these strategies ability to aid tennis performance is very positive and they would be willing to suggest using and testing such methods to their players. However, the barrier appears to be accessibility of equipment and ease of use, highlighting the need for a 'toolbox' of strategies (Gibson et al., 2019) and for these to include practical and accessible techniques (Chalmers, 2017).

7.4.5 *Benefits and Drawbacks of Cooling During Match Play*

The overarching themes identified on the benefits of cooling or heat alleviation strategies were *"performance"*, *"physiological"*, *"perceptual"* and *"psychological"*. Players did not mention performance, whereas this came through from the support staff, including that cooling *"allows athletes to perform at their best"* and that it gives them the *"ability to maintain high level for longer"*. Neither group mentioned any key performance measures discussed previously including accuracy and shot power. Though not directly mentioning performance, players did express how heat alleviation strategies mean they *"feel less fatigued and tired during matches"* and that it *"keeps [them] from getting fatigued by the heat"*; one of the support staff stated they felt players had *"increased energy on court"*. Feeling or being less fatigued is likely to have an impact on the aforementioned performance measures as we know both accuracy and shot speed decline with increasing levels of fatigue (Davey et al., 2002; Hornery, Farrow, Mujika, &

Young, 2007), though any improvement on these measures as a result of cooling is yet to be documented during match play.

The players previously stated that they perceived to understand how cooling benefits them, however, only one respondent mentioned the physiological improvements, and this was not a confident answer: *"reduces overheating, reduces HR?"*. Instead, the players' answers really highlighted the perceptual benefits of cooling or how they feel differently when using these techniques. One theme within the answers was that these strategies can *"refresh you"* or are *"refreshing, particularly when playing in hot, arid conditions"*. This also relates back to the idea of feeling less fatigued. Another player alluded to the between-point recovery and said they *"feel like using cooling aids speed up [their] recovery between long points"*. This is a reference to a physiological benefit but even if that benefit is not meaningful, the perception that recovery is quicker might lead to a better performance from the player. The support staff appear to understand the physiological impact of cooling with answers such as *"limit or reduce the increases in core temperature"*, *"takes strain off the heart and body"* and *"reduced core temperature and HR"*. These answers demonstrate that they are aware of the physiological responses being targeted by heat alleviation strategies, though it is not clear whether these are being communicated well enough to the players. The perceptual improvements were picked up less by support staff with only one referring to a decrease in RPE.

Another key area highlighted across both populations was the effect of heat alleviation on cognitive function and mindset. A player said it allowed them to *"remain calm"* rather than becoming *"agitated and frustrated"* with a member of support staff agreeing with this by stating *"it keeps players calm, upbeat and positive to compete"*. An improvement in cognitive function might allow players to more easily stick to pre-planned tactics or be able to adjust these 'in the heat of battle'.

These responses confirm some of the key elements that heat alleviation strategies target, while also suggesting possible future directions with variables such as fatigue, cognitive function and mindset.

The comments on drawbacks of heat alleviation strategies were themed into *"equipment", "maintaining zone/rhythm"* and *"knowledge"*. The theme of equipment is the issue of accessibility and availability of strategies; similar to what has been discussed previously. One of the players said it is *"difficult to put into practice i.e., not everyone has an ice towel"* and one of the support staff making the point that *"cooling options* *depend on tournament/club facilities, infrastructure".* This highlights the importance to educate about the variety of strategies available so players and support staff feel they have options regardless of where they are competing; also highlighting again that simple solutions might be the best solutions.

The second theme of *"maintaining zone/rhythm"* is the idea that any heat alleviation strategies being implemented need to fit in with the player's process or routine on court and not prove a distraction. A player commented on factors such as cooling *"taking time out of their breaks during changeovers and between points"*, with support staff suggesting *"more complex [solutions] are difficult to maintain rhythms through and affect performance"*; it was also mentioned that the player must be comfortable with the strategy. One of the players suggested they did not feel comfortable taking extra time to implement these techniques, which might be due to the perceived judgement of opponents or the umpire. Another player made the point that *"they are 'in the zone' when they feel hot and adrenaline pumping… [cooling aids] can make them feel too relaxed and they make more cheap errors"*. These points all highlight the need for trialling heat alleviation techniques during practice to enable to the player to become accustomed and find a technique which works both physiologically and allowing the beneficial elements previously mentioned.

It is apparent that although both players and support staff believe they understand how cooling can increase the ability to compete in the heat, more education is needed. One of the players wrote, *"the body uses energy on adapting to the change in temperature, so you have to use cooling moderately"*, which clearly shows that they do not have a grasp on the underpinning physiology. A support staff raised the question of *"how much is required to maximise performance?"* and another commented on the need to *"keep the equipment free from moisture so players can still grip the racket"*. The question of dosage can be resolved through a mixture of education in the effectiveness of various methods and suggested doses/durations. The latter suggests there also might be some underlying scepticism surrounding heat alleviation. When competing in the heat a player is very likely to be sweating extensively, probably with sweaty hands already. Players often use a towel to wipe away sweat throughout matches and the same is possible following any cooling, should it mean their hands get moist or wet.

7.4.6 *Limitations*

Due to low number of responses this survey might not be a valid representation of tennis players or support staff. The low engagement and response rate may have been due to the lack of access to potential respondents. To increase the response rate, various tournaments were going to be attended to recruit participants, this was prevented because of the lockdowns associated with COVID-19. The length of the survey and that a specialist population was required to answer the survey might have also contributed to low engagement and response rate.

7.4.7 *Conclusion*

Players and support staff believe heat alleviation strategies to be useful during tennis match play in hot conditions, though heat alleviation practices for each method are largely inconsistent and the strategies requiring minimal equipment are more widely used than others. The perception is that heat alleviation strategies benefit performance, through physiological, perceptual, and psychological means which was supported by qualitative data. Several areas to be considered are accessibility, player rhythms, and that players and support staff require further education on implementation and physiology. Some differences identified between players and the support staff as to whether they would consider using various strategies and the ways some of the techniques are implemented. Simple solutions will provide easier access across all levels of competition though, if the facilities are available then effective strategies such as ice towels would be used.

8 General Discussion

8.1 Thesis Aims

The research presented in this thesis sought to assess the efficacy of acute heat alleviation strategies during simulated tennis match play in a hot humid environment and begin to gain an understanding of current implementation. Tennis in the heat is an area of research which has a relatively small body of knowledge, as is per-cooling in intermittent sports. At the start of this programme of research there was no published research considering heat alleviation strategies for tennis match play, but the rationale was increasingly evident, as seen in the introduction to this thesis. Given the reactive and unpredictable nature of tennis match play, these interventions needed to be initially investigated in a controlled environment; for this reason, the TSTP was designed to replicate the physiological demands of tennis match play. It was clear that a range of strategies should be considered as practicality would be an important part of end usage. Therefore, simple concepts such as increasing rest length were assessed alongside efficacious methods of internal and external cooling, the novelty being in a tennis specific situation and in similar peak environmental conditions to those seen at the US Open. Thermal physiological and perceptual variables were assessed throughout the TSTP to assess any influence of the strategies allowing implications on safety and performance to be discussed.

This thesis also investigated the current practice and perceptions of tennis players and support staff. At the start of the programme of research there was no knowledge of the practice on the various tennis tours. During this programme of research, the ice towel strategy has been identified as being advised to players through the author's personal communication with a WTA practitioner (Schranner et al., 2017). Research should not only be informed though previous literature but also through applied practice and the need or potential use of any intervention to be considered. It is important that the relationship between research and application involves two-way communication *i.e.* if an intervention is not perceived to be practical then it will not be used even if research has shown it to have a large effect. In addition, if there are practices that are being used within tennis currently then it is important to know what they are and how they are used as these could inform future research projects.

A protocol based on the physiological demands, match characteristics and time-motion of tennis match play was designed to assess physiological responses. Therefore, the initial investigation (chapter 4) assessed the tennis-specific tennis protocol designed as part of this thesis for reliability and validity. The following experiments then focussed on acute heat alleviation strategies based on the principles of the heat balance equation. The strategies were selected based on published evidence for influencing intermittent performance, those that are reportedly used currently at professional tennis tournaments and those that are practical for use during tennis match play. Chapter 5 assessed a practical intervention of increasing the between-point rest length by 10 seconds from 20 to 30 seconds. This study coincided with the rule change in 2019 at the Grand Slam tournaments which saw and increase of between-point rest length from 20 to 25 seconds. Chapter 6 then focussed on per-cooling strategies implemented during tennis match play in the heat to assess and compare an external cooling strategy currently implemented during match play, an internal cooling alternative, and a combined internal and external approach. This approach reflected the gap in the knowledge of the efficacy of various in-play cooling interventions during tennis match play in the heat. The final study, presented in chapter 7, bridges the gap between the research and applied environments through summarising some current practice and perceptions to heat alleviation of players and support staff.

This general discussion will initially summarise the findings of these experimental chapters within this thesis prior to discussing the efficacy of the various interventions for increasing safety of players and performance during tennis match play in hot humid conditions. Based on these conclusions and an assessment of the current heat policies practical recommendations for players, support staff and tournaments will be given. The limitations of this thesis and future directions within this area of research will also be considered.

8.2 Summary of Main Findings

Study 1 (chapter 4) investigated the validity and reliability of the tennis-specific treadmill protocol. The TSTP is a valid assessment of tennis match play based on similar $\dot{V}O_2$, heart rate and blood lactate values in comparison to those previously reported in tennis match play within the literature and represented match play work rates and activity profiles. The protocol demonstrated good test-retest reliability with the majority of variables being either reliable (ICC > 0.8; CV < 10%) or highly reliable (ICC > 0.9; CV < 5%) in accordance with defined criterion for reliability (Greg Atkinson & Nevill, 1998; Currell & Jeukendrup, 2008). The typical errors for all variables can be seen in chapter 4 and were similar in both temperate and hot, humid conditions. This random error combined with the smallest worthwhile change will enable the interpretation of effects in moderately trained tennis players. Consequently, the TSTP was validated for use in the assessment of interventions in subsequent studies.

Study 2 (chapter 5) assessed the effectiveness of increasing the between-point rest length of 20 seconds allowed in the Grand Slams (Grand Slam Board, 2017) to 30 seconds as a passive and practical solution. The study also assessed the physiological and perceptual responses to the protocol in temperate conditions, which enabled the effect of the hot, humid conditions to be observed. Hot humid conditions induce higher physiological and perceptual heat strain than a temperate environment. A 10 second increase in between-point rest length from 20 to 30 seconds attenuated the rise in physiological heat strain through a lower rise in T_{re} from the start of set 2 and consequently, a lower HR in set 3 ($P < 0.05$). The longer rest length also delayed the rise in RPE during the first 2 sets, though no effect on thermal sensation was observed. Considering the error free change, a 30 second between-point rest length attenuates the rise in physiological strain during the first set compared to a small effect seen in the 20 second trial. The longer rest period also attenuates the rise in rectal temperature throughout the TSTP, particularly during the second and third sets.

Study 3 (chapter6) investigated the effect of active cooling throughout the TSTP on thermal physiological and perceptual responses. Internal (ice slurry ingestion) was compared with external (ice towel around neck) and a combined approach (internal + external) against a thermoneutral control and cold-water. Internal cooling of ice slurry ingestion reduced rectal temperature during set 2 and 3 compared with the thermoneutral control and reduced thermal sensation towards the end of the protocol. The external cooling reduced the thermal sensation at a few points throughout the protocol but not consistently. An unexpected result was the effectiveness of the combined internal and external approach which reduced thermal sensation from the end of set 1 and attenuated the rise in rectal temperature in the final set. The combined strategy was more effective at alleviating physiological and perceptual heat strain than internal or external alone compared with both the thermoneutral control and cold-water with the biggest effects seen after 60 minutes.

Study 4 (chapter 7) provided insight into current practice and perceptions of heat alleviation strategies. Players and support staff consider heat alleviation strategies to be useful during tennis match play in hot conditions. Heat alleviation practices for each strategy are largely inconsistent with those strategies requiring minimal equipment being more widely used than others. The perception is that heat alleviation strategies benefit performance, through physiological, perceptual, and psychological means. Though, there is a need for education on heat management and alleviation strategies in the future.

Table 8.1: A summary of the error-free effect compared to trials with 20 s between-point rest consuming cold-water, the potential benefit on safety and performance, and the practicality of the heat alleviation strategies during simulated tennis match play in hot humid conditions

	T_{re}	T_{sk}	HR	RPE	TS	TC	Safety	Performance	Practicality
↑ BP Rest									
TSTP	↓*	↔	↔	↔	↔	↔			
S1	↔	↔	↔	↔	↔	↔	✓✓	✓	✓✓✓
S2	↓*	↔	↔	↔	↔	↔			
S3	↓*	↔	↔	↔	↔	↔			
Ice Slurry									
TSTP	↔	↔	↔	↔	↔	↔			
S1	↔	↔	↔	↔	↔	↔	✓✓	✓✓	✓
S2	↔	↓*	↔	↔	↔	↔			
S3	↓*	↓*	↔	↔	↓*	↔			
Ice Towel									
TSTP	↔	↔	↔	↔	↔	↔			
S1	↔	↔	↔	↔	↔	↔	✓✓	✓✓	✓✓
S2	↔	↔	↔	↔	↔	↔			
S3	↔	↓*	↔	↔	↔	↔			
Combined									
TSTP	↓*	↓*	↔	↔	↓*	↔			
S1	↔	↔	↔	↔	↓*	↔	✓✓✓	✓✓✓	✓
S2	↔	↓**	↔	↔	↓*	↔			
S3	↓*	↓***	↔	↔	↓**	↓*			

↑ BP Rest: Increased between-point rest (30 vs 20 s). Combined: Ice towel and ice slurry. TSTP: Mean of protocol; S1: Mean of set 1; S2: Mean of set 2; S3: Mean of set 3. Tre: Rectal temperature; Tsk: Skin temperature; HR: Heart rate; RPE: Perceived exertion; TS: Thermal sensation; TC: Thermal comfort. ↔ = no change; ↓* = small effect decrease; ↓** = medium effect decrease; ↓*** = large effect decrease. Safety and Performance: ✓ = possibly beneficial; ✓✓ = likely beneficial; ✓✓✓ = very likely beneficial. Practicality: ✓ = not very practical; ✓✓ = practical; ✓✓✓ = very practical

8.3 Comparison of Acute Heat Alleviation Strategy Effects

This thesis has assessed the efficacy of some acute heat alleviation strategies during simulated tennis match play in a hot humid environment and begun to gain an understanding of current practice. However, it is important to compare the various strategies to see whether one might be more beneficial than the others, and why. In the experimental chapters within this thesis, statistical hypothesis testing was implemented to assess the effect of the intervention on the key variables, along with Hedges' g_{av} to give an understanding of the size of the effect (detailed within sections 5.3 and 6.3). In this discussion the error free change will be considered based upon the typical error from the reliability testing in chapter 4 to be confident of real change and allow comparisons between the strategies. A summary can be seen in Table 8.1 above.

After accounting for the typical error, increasing the between-point rest length from 20 to 30 seconds has a small attenuating effect (0.24 ˚C) on the rise in T_{re} (HOT20: 1.58 ± 0.48 ˚C vs HOT30: 1.34 ± 0.59 ˚C) with small effects also observed in sets 2 and 3. Peak T_{re} was lower with 30 s rest (0.22 ˚C) during the second set and the mean T_{re} was 0.24 ˚C lower in the final set during the longer rest trial. A similar response was observed when consuming 2 $g \cdot kg^{-1}$ ice slurry at each break in play ('change of ends'). Mean T_{re} was 0.3 ˚C lower (CTL: 38.46 ± 0.35 ˚C vs SLU: 38.16 ± 0.35 ˚C) and peak T_{re} was 0.4 ˚C lower (CTL: 38.90 ± 0.50 ˚C vs SLU: 38.50 ± 0.51 ˚C) compared with the control condition of warm-water; confident of a small effect. A small effect was not apparent in the rise in core temperature until the final set (CTL: 1.54 ± 0.48 ˚C vs SLU: 1.30 ± 0.50 ˚C), and there was a medium effect of the ice slurry attenuating peak T_{re} in the second and third sets and mean T_{re} in the third set. No effect was observed on core temperature in the ice towel trial. Therefore, it might be expected that the combined strategy (ice slurry and ice towel) would see similar effects to the ice slurry trial, however, overall, they were slightly more pronounced. The small effect observed during set 1 in ice slurry was not evident in the combined trial but, a small effect was observed on attenuating rise in T_{re} during the TSTP (TWL+SLU: 1.26 ± 0.36 ˚C vs CTL: 1.54 ± 0.48 ˚C) and a moderate reduction in peak T_{re} (TWL+SLU: 38.47 ± 0.32 ˚C vs CTL: 38.90 ± 0.50 ˚C) was observed compared to the control. Based on these results, the combined strategy seems more effective than the ice slurry which in turn, seems more effective than increasing between-point rest. Although, participants consumed cold-water rather than warm-water during the HOT20 trial in chapter 5 and it is common practice for players to drink cold-water during competitions. So, whilst the ice slurry and combined strategies are efficacious in reducing core temperature compared to a control condition, the comparison versus the cold-water trial is important for a direct comparison to be made with the increased between-point rest. When considering the effect in comparison to a cold-water control, the ice slurry only has a small effect in the third set on mean T_{re} (0.24 ˚C lower) and peak T_{re} (0.25 ˚C lower). Similarly, the combined strategy does not attenuate the rise in T_{re} until the third set (0.25 ˚C lower), as well as mean T_{re} (0.29 ˚C lower) and peak T_{re} (0.30 ˚C lower). Therefore, when comparing the efficacy of all the strategies in this thesis at reducing core temperature during simulated tennis match play, the increased between-point rest length and the combined cooling strategies seem to be the most efficacious. A comparable study which investigated ice towels (ice towel around neck with cold camp towels on head and thighs) and spray and fan cooling strategies during simulated tennis match play in hot humid conditions observed a 0.40 and 0.44 ˚C reduction in the rise of T_{re} by the end of the protocol compared to the control condition (Schranner et al., 2017) and an equivalent reduction in the rise of core temperature (~0.4 ˚C) was seen in a similar study but investigating ice slurry consumption (Naito et al., 2018). These corroborate the results observed in this thesis.

Skin temperature is not affected by increasing the between-point rest. This is expected as the player is still in a hot environment which has been suggested to be a driver in skin blood flow as cardiac output was elevated by ~1 $L \cdot min^{-1}$ during exercise at the same $\dot{V}O_2$ and core temperatures with participants all in a euhydrated state; thought to be a result of a threefold increase in skin blood flow in 35 ˚C compared to 8 ˚C (González-Alonso, Mora-Rodríguez, et al., 2000). There is a possibility that the 8 ˚C condition caused peripheral vasoconstriction which exacerbated this effect, nevertheless, the heat stress appears to influence skin blood flow.

Internal, external, and combined per-cooling throughout simulated tennis match play reduce mean $\overline{T}_{sk}$ and peak $\overline{T}_{sk}$. The ice slurry (internal) and ice towel (external) reduced mean $\overline{T}_{sk}$ in the third set compared to the cold-water control by 0.43 ˚C and 0.50 ˚C, respectively. A similar small effect of the ice slurry and towel was observed on peak $\overline{T}_{sk}$ in set 3 with reductions of 0.45 ˚C and 0.46 ˚C, respectively. Ice slurry also reduced peak $\overline{T}_{sk}$ by 0.32 ˚C in set 2, showing ice slurry might induce this effect more quickly. Combined cooling saw a larger effect than each strategy alone: a medium effect in set 2 lowered mean $\overline{T}_{sk}$ by 0.46 ˚C and peak $\overline{T}_{sk}$ by 0.46 ˚C and a large effect in set 3 lowered mean $\overline{T}_{sk}$ by 1.00 ˚C and peak $\overline{T}_{sk}$ by 1.10 ˚C. These suggested a medium effect reduction of 0.57 ˚C across the TSTP in mean $\overline{T}_{sk}$ and a large effect reduction of 0.48 ˚C in peak $\overline{T}_{sk}$ in the whole TSTP. The additive effect of combining these two strategies likely means that ice slurry and ice towel reduce $\overline{T}_{sk}$ through different mechanisms. The ice slurry reduces core temperature and cools the central blood temperature leading to a lower temperature of the blood flow in the skin. It would also create a larger arterial-venous differentiation of temperature at the muscular level, likely increasing heat removal from the muscles (Crandall & González-Alonso, 2010). The ice towel likely lowers $\overline{T}_{sk}$ through the conductive release of heat from the skin that is in contact with towel. It is also possible that the towel came into direct contact with the chest sensor, however, the raw data suggests that the towel reduced skin temperature in both the upper body measurements (chest and tricep). Both chest and tricep sensors reducing in temperature probably means direct contact with the towel did not occur as the tricep would not have come into contact with the towel, therefore, the difference might be due to the blood in the surrounding areas being cooled due to the ice towel being positioned around the neck.

After accounting for error, there was little effect on heart rate by any of the heat alleviation strategies in this thesis. The only confident effect observed was during set 3 of the combined cooling trial where a reduction of 10 beats·min^{-1} in the pre-break HR occurred compared to the control. No effect on heart rate was observed through increasing between-point rest, ice slurry and towel versus control or any cooling strategy versus cold-water consumption. This result is representative of the literature that has researched the effect of cooling during exercise in compensable environments (Ansley et al., 2008; Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b), however, in an uncompensable environment heart rate has been observed to decrease with cooling (Kenny et al., 2011), thought to be due to the severity of the thermal strain (Tyler, Sunderland, et al., 2015). A main effect on heart rate was observed in trials implementing ice towels (around the neck and cold wet towels on the head and thighs) and spray and fan strategies during simulated tennis match play (Schranner et al., 2017). The reduction was shortly before participants ceased exercise which is likely to mean that their heart rates were near maximal. The heart rate was reduced by around 10 beats·min^{-1} which is a similar magnitude to that seen in the combined trial in this thesis, and the reduction during simulated tennis match play whilst using ice slurry ($P < 0.05$) (Naito et al., 2018).

The perceived exertion of the players during the TSTP was not affected by any of the heat alleviation strategies investigated in this thesis compared to the TSTP in hot humid conditions and a 20 s between-point rest length. However, compared with a temperate environment, the longer between-point rest does alleviate perceived exertion with only a medium effect with a 30 s rest in the heat rather than a large effect with a 20 s rest in the first 2 sets. As with the other variables, the effects are seen most in the final set when thermal strain is most severe. In the ice slurry and combined cooling trials, perceived exertion was lower by 1.1 and 1.3, respectively, compared to the control trial. Though there is not a confident effect of these strategies, the typical error is high due to high variation within the final set for the population in chapter 4. Therefore, it is likely that perceived exertion might be reduced with these cooling strategies, particularly if the protocol was to last longer. The observations that RPE was not affected are in line with previous studies involving cooling during endurance exercise (Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b). However, a reduction in RPE was observed in a trial with head cooling whilst cycling to exhaustion at 75% of $\dot{V}O_2max$. Though, the head cooling involved 3 fans (centre, 45˚ left and 45˚ right) placed 50 cm from the participant's face with a water spray (Ansley et al., 2008). This method of cooling would be extremely difficult to duplicate in a real-world situation and is quite an aggressive cooling strategy, possibly explaining the differing result. Though, spray and fan cooling intermittently during simulated tennis match play in hot and humid conditions led to a reduced RPE from the mid-way point and an ice towel condition reduced RPE throughout (Schranner et al., 2017). The perceived exertion in the control trial at the mid-way point was 16.6 ± 1.8, which is more than the 14.4 ± 2.4 observed in the final set of the control trial in chapter 6, though the control trial in chapter 5 elicited an RPE of 15.6 ± 3.2 in the final set. This might be due to a higher number of trials and the randomisation of trial order of completion in chapter 6, alternatively, it could be due to only a 5-game familiarisation in the heat, both of which could have meant participants were more aware of the sensation of completing the protocol in the heat.

Thermal perception was not affected by increasing the between-point rest, which was expected at there was no reduction in skin temperature and that is considered a key driver in perception of the heat (Flouris & Schlader, 2015). The cooling strategies led to a reduction in thermal sensation and comfort (see Table 8.1 above), though these reductions were more pronounced when comparing to a control than cold-water. On the comparison to control, it appears the ice towel makes participants feel cooler throughout the TSTP after the break, whereas the ice slurry affects thermal perception later, but the reduced thermal sensation and comfort lasts until the next break. The combined cooling strategy sees the additive combined effects of the two aforementioned individual strategies. The effects of the individual strategies are not as marked in comparison to the cold-water trial, although, the combined strategy does maintain the effect: thermal sensation reduced post-break throughout, and all thermal perception lowered throughout the final set. A similar post-break reduction was reported through a simulated match in hot humid conditions whilst using ice towels (Schranner et al., 2017), though ice slurry ingestion during the breaks in a simulated match did not have any effect of thermal sensation in similar environmental conditions (Naito et al., 2018). This might be due to a higher dosage (2 $g \cdot kg^{-1}$ vs 1.25 $g \cdot kg^{-1}$) of ice slurry consumed in chapter 6. The reduction of thermal sensation is corroborated in a study investigating the effect of continuous neck cooling on pre-loaded running time trial performance (Tyler et al., 2010).

Overall, the combined strategy attenuates the rise in core and mean skin temperature to the greatest extent, whilst also reducing post-break thermal sensation throughout and thermal sensation and comfort during the whole third set. Increasing between-point and ice slurry attenuated the rise in core temperature to a similar extent, however, ice slurry also lowered mean skin temperature in the second half of the TSTP and post-break thermal sensation in the third set. Ice towel induced the least change with only mean skin temperature effected in the last set. A summary of the error-free effects on key variables from each of the interventions in this thesis can be seen in Table 8.1 above.

8.4 Applied Use of Strategies

The physiological and perceptual effects of the heat alleviation strategies have been discussed in the section above, however, what is most important is whether these are meaningful effects, i.e., will they actually have an impact on heat illness prevalence (player safety) or match results (player performance). Unfortunately, there is not currently sufficient breadth or depth of published evidence to allow definitive conclusions about the magnitude of changes in physiological or perceptual responses required for meaningful effects on safety or performance in tennis in the heat, and therefore it cannot be conclusively stated whether the changes observed in this thesis are meaningful. Rather, the available literature base can be used to draw inferences about the potential effects of the interventions in this thesis on player safety and performance.

8.4.1 *Reducing incidence of heat illness*

When attempting to increase the safety of players on-court, the aim is to ensure that incidences of heat illness are minimised as much as is practically possible. Heat illness can be termed either as exertional heat stroke (EHS) or exertional heat exhaustion (EHE), both demonstrate signs or symptoms of organ system failure (likely through nervous system dysfunction) and the key difference for classification is rectal temperature with EHS classified with $T_{re} > 40$ ˚C and EHE with $T_{re} < 40$ ˚C (Armstrong et al., 2007). This classification of heat illness suggests that as core temperature rises players are at more risk of illness, therefore, preventing core temperature from going above 40 ˚C and if possible, 39 ˚C is likely to reduce the likelihood of heat illness.

The TSTP in control conditions elicited rectal temperatures of 39.01 ± 0.50 ˚C and 38.90 ± 0.50 ˚C in chapter 5 and chapter 6, respectively. These rectal temperatures are in agreement with those of 38.9 ˚C (Hornery, Farrow, Mujika, Young, et al., 2007) and 39.13 ˚C (Tippet et al., 2011) in comparable environmental conditions (~30 ˚C WBGT) and slightly lower than the peak of 39.4 ˚C observed in hotter conditions of 34 ˚C WBGT (Périard, Racinais, et al., 2014b). They are also similar to the control trial (~38.8 ˚C) in the same environmental conditions as this thesis during simulated match play (Naito et al., 2018), though they are lower than another study using simulated match play (Schranner et al., 2017) who reported high dropout rates and a peak rectal temperature of around 39.7 ˚C. This increased heat strain in this study might be due to the heat lamps used to replicate solar radiation which were not used in the Naito et al. (2018) study or this thesis. The aforementioned studies reporting on-court responses either reported behavioural thermoregulation through shortening of points (Hornery, Farrow, Mujika, Young, et al., 2007) or investigated the effect of an extended break between the second and third sets (Tippet et al., 2011). Therefore, rectal temperatures on-court are probably closer to those reported in Schranner et al. (2017). This highlights the need for the heat alleviation strategies in this thesis to lower peak rectal temperatures below 39-40 ˚C, as well as considerable attribution from exercise being reported when T_{re} is between 39 and 40 ˚C (Sawka et al., 1992).

Attenuation in the rise of T_{re} from increasing between-point rest length, ice slurry and combined strategies would likely ensure that T_{re} is reduced to be below 39 ˚C and definitely below 40 ˚C during the TSTP. However, due to individual differences, some players saw T_{re} increase to ~39.7 ˚C either during the TSTP (at which point exercise was ceased) or at the end of the protocol; those players who were unable to finish the TSTP would have seen T_{re} above 40 ˚C should they have continued. Due to ethical restrictions, it is beyond the scope in this thesis to assess how far these participants' rectal temperatures would have increased. The increased between point rest (n=2) and the ice towel (n=1) did not prevent the participants that overheated in the control trial from overheating with the heat alleviation strategy in place. One of the participants was at the lower range of aerobic capacity in the population but had a large BSA which should have allowed greater heat dissipation, another participant was trained (53 $ml \cdot kg^{-1} \cdot min^{-1}$) but was smaller in stature and therefore, had a reduced BSA. Some of these attributes might have contributed to less effective heat dissipation, however, the reason as to why these participants were not able to complete the protocol in unclear. It might have been due to the reasons suggested, or possible illness or medication (Keren et al., 1981; Roberts, 2006), though these should have been declared by the participants prior to exercise.

A couple of investigations into the effect of dehydration on the ability to dissipate heat from the working muscles suggested that dehydration impairs heat transfer from the working muscle (González-Alonso, Calbet, et al., 1999; González-Alonso, Quistorff, et al., 2000). However, another key result was that more than half of the metabolic heat liberated in the contracting muscles is dissipated directly into the surrounding tissue and environment surrounding the leg (the working muscle). Therefore, neck cooling through an ice towel may be more likely to attenuate core temperature increases during tennis as the upper body musculature is being used more than running which has traditionally been researched (Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b). If this effect exists, it is likely small, however, the TSTP would not elicit this response due to the lack of upper body movement.

Whilst only observed rarely (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018), players can collapse on court in hot environmental conditions and is a sign of possible EHS. A possible reason for collapse is cardiovascular insufficiency, which is caused by the simultaneous demand for blood flow at the working muscle and the periphery for heat dissipation. This can be further exacerbated in humid conditions as there is less evaporative heat loss which consequently causes an increase in skin blood flow to support non-evaporative radiation and convective heat loss (Armstrong et al., 2007). Combining whole-body intense exercise (such as tennis) and heat stress poses the greatest challenge to temperature regulation, mean arterial pressure, and oxygen delivery to the brain, heart and working muscles because the cardiovascular system is pushed to its limit sooner (González-Alonso, 2012; González-Alonso et al., 2008). However, athletes or trained individuals will have a higher cardiac output enabling them to meet this dual demand for longer during maximal exercise compared to untrained individuals (González-Alonso & Calbet, 2003). None of the strategies investigated within this thesis were effective in reducing heart rate apart from the combined strategy in set 3 compared with the control. This likely suggests that these strategies are not reducing the cardiovascular stress even though some are attenuating the rise in core temperature. Though as discussed previously, the observed responses were similar to other studies investigating cooling strategies in simulated tennis match play (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017) and the cardiovascular strain would still be expected to be high due to participants still being hyperthermic. The reduction in core and skin temperature may prevent the cardiovascular system reaching its regulatory capacity (González-Alonso, 2012), therefore increasing the ability to meet blood flow demand for working muscles and heat dissipation which would increase the safety of players.

Other studies which sought to understand the cause of collapse assessed the effect of hyperthermia on fatigue; observing that brain temperature is always higher than core temperature and heat removal from the brain is decreased compared to a control at the point of collapse (Nybo et al., 2002) and that as brain temperature increases from 37-40 ˚C whilst exercising, cerebral blood flow and maximal voluntary force production decreases simultaneously to changes in brain signalling and RPE (Nielsen & Nybo, 2003; Nybo & Secher, 2004). This is also supported by González-alonso et al., (2008) who reported that fatigue is not due to limited perfusion of muscle or falling blood pressure, but high brain temperature. Alongside this, it is known that athletes can experience prolonged hyperthermia without any signs or symptoms of related heat illness, though this is more likely in competition (Armstrong et al., 2007). Rectal temperatures of up to 41.9 ˚C have been reported in soccer, endurance running and cycling (Bangsbo, 1994; Cheuvront & Haymes, 2001; Costill et al., 1970; Maron et al., 1977; Racinais et al., 2019). In one of these studies, 34 of 40 cyclists competing at the UCI Road Cycling World Championships in 37 ± 3 ˚C 25 ± 16% RH recorded core intestinal temperatures of at least 39 ˚C; 10 of 40 exceeded 40 ˚C with the highest reported at 41.5 ˚C (Racinais et al., 2019). A similar observation in heat acclimatised male soldiers running a 21 km race in 27 ˚C 87% RH with 10 of 18 runners reaching core temperature exceeding 40 ˚C and 2 of these exceeding 41 ˚C (Byrne et al., 2006). Both studies were without incidence of heat illness. Brain temperature was not measured in these studies so the mechanism which allows these core temperatures to be reached without collapse, signs or symptoms of heat illness is unclear. Though, a relationship between attenuating the rise in brain temperature and delaying fatigue is likely with a combination of central and peripheral factors influencing fatigue (Ansley et al., 2008).

It is likely that brain temperatures are able to be regulated at a temperature lower than core temperature or they are just able to withstand a higher brain temperature. Other reasons might be these athletes' fitness levels increase the regulatory capacity of the cardiovascular system to the point they are able to meet demand for significantly longer or due to their acclimatisation status. This magnitude of thermal strain has rarely been observed due to ethical limitations and is only possible in competitive environments. It is possible that elite tennis players might reach similar core temperatures during tournaments in hot conditions, such as the Australian and US Opens. Regardless, if the brain temperature is the cause of collapse, then attenuating a rise will reduce the prevalence of heat illness. This could be achieved through heat alleviation strategies such as ice towel and ice slurry which cool the neck and throat area. This cooling effect could lower the temperature of the blood going to the brain increasing the arterio-venous differentiation which would enhance convective heat transfer (González-Alonso, 2012) and enable the maintenance of a lower brain temperature.

Based on the various situations and mechanisms discussed, it is likely that the strategies within this thesis would reduce heat illness incidence through attenuating the rise in core and possibly brain temperature, consequently decreasing the strain on the cardiovascular system. The combined internal (ice slurry) and external (ice towel) approach would be the most effective for reducing core and skin temperature, however, the possibility of using this alongside increased between-point rest would enhance the effectiveness of ensuring safety for players competing in the heat. This is further discussed in section 8.5.

8.4.2 *Enhancing performance*

There are many suggestions on what the key driver or drivers are that affect exercise performance in the heat. One suggestion is that a feedback-feedforward control mechanism prevented thermoregulatory catastrophe (Noakes et al., 2004), driven by the subconscious brain from the onset of exercise monitoring core and skin temperature

(Tucker et al., 2006). This is one of the suggestions of thermophysiological drivers alongside core temperature (Nielsen et al., 1993), skin temperature and cardiovascular strain (Périard et al., 2011), perceptual drivers of thermal sensation and thermal comfort (Flouris & Schlader, 2015) and perceived exertion (Tucker, 2009). It is likely that a complex interaction between all of these elements actually drives performance, possibly also including brain temperature (Nybo et al., 2002) as that appears to play a large part in the ability to remain in a state of prolonged hyperthermia (>40 ˚C) (Racinais et al., 2019).

Cardiovascular strain during exercise in the heat has been suggested to heavily influence perceived exertion and consequently, performance (Tatterson et al., 2000). The suggested mechanism is that as skin blood flow increases for heat dissipation, the heart rate increases to counter the drop in stroke volume and mean arterial pressure and maintain cardiac output (Ekelund, 1967; Rowell, 1974). However, prolonged exercise in the heat leads to too high of a demand to maintain cardiac output which decreases and oxygen delivery is then potentially limited through the arterio-venous differential widening (Rowell, 1974). These changes are thought to decrease the absolute $\dot{V}O_2max$ which therefore increases the percent of $\dot{V}O_2max$ at the same exercise intensity (Wingo et al., 2005). A reduction in $\dot{V}O_2max$ of 16% at a core temperature of around 39 ˚C (Nybo et al., 2001) and a reduction of 23% when core temperature is 39.8 ± 0.3 ˚C (Périard et al., 2011) have been observed. The participants in the latter study were well-trained ($\dot{V}O_2max$: 5.0 ± 0.4 $L·min^{-1}$), so whilst they were characterised as unacclimatised, their high fitness level would have meant their cardiovascular function was less effected by the heat due to the continuum of heat acclimation state (Crandall & González-Alonso, 2010). The core temperatures elicited in the control trials in this thesis have been in a similar range to those presented in these two studies and the players who participated in this thesis were not as highly trained, therefore, it would be reasonable to suggest that the $\dot{V}O_2max$ of the players might be reduced by around 20%. If this cardiovascular strain can be alleviated, an increase in $\dot{V}O_2max$ is likely to occur and consequently make the exercise relatively easier.

An elevated skin temperature is thought to impair prolonged submaximal exercise performance as it accompanies an increase in skin blood flow leading to increased cardiovascular strain: decreased stroke volume, mean arterial pressure and cardiac output (Ely et al., 2009, 2010; Kenefick et al., 2010). If skin temperature could be reduced it might allow a decrease in the demand for skin blood flow and alleviate some of the cardiovascular strain. Increasing between-point rest did not have any effect on skin temperature so is unlikely to affect performance in this way. However, all three cooling strategies in chapter 6 saw at least a small reduction in skin temperature with the combined approach seeing a large decrease in the final set of simulated match play which could mean it is reasonable to presume an impact on performance. However, core and skin temperature were still elevated by around 1 and 4 ˚C, respectively above resting values, which is still associated with significant reduction in $\dot{V}O_2max$ (Craig & Cummings, 1966; Nybo et al., 2001; Pirnay et al., 1970). Also, the skin blood flow increase is much smaller during exercise than during passive heat stress (Johnson, 1992; Kenney & Johnson, 1992), therefore, these cooling strategies might not reduce skin temperature enough to improve performance in this way.

The relationship between brain temperature, peripheral temperature and fatigue is likely to influence players' ability to perform. As mentioned previously, core temperatures ⩾41 ˚C were able to be maintained by athletes in both running (Byrne et al., 2006) and cycling (Racinais et al., 2019) race situations for prolonged periods without incidence of heat illness or related symptoms. Whereas previously there was considered to be a limiting core temperature of ~40 ˚C (González-Alonso, Teller, et al., 1999), this is clearly not now the limiting factor. Instead, it is thought that a combination of the brain temperature and peripheral thermoreceptors are key in limiting exercise performance in the heat (Ansley et al., 2008; Nybo et al., 2002) as well as cardiovascular strain (Périard et al., 2011). This theory might be the mechanism underpinning an improvement in performance observed in a number of time trial (faster completion or further distance covered) and test to exhaustion (longer duration of exercise) in the heat without concurrent thermophysiological alleviation (Tyler, Sunderland, et al., 2015).

Multiple studies have observed the performance benefit of neck cooling without affecting physiological parameters (Ansley et al., 2008; Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b). One of these investigated the effect of head cooling via 3 fans placed in front of participants' faces (centre, 45˚ left and 45˚ right) with a fine water mist sprayed every 30 s during a cycling test to exhaustion in 27-29 ˚C 40-60% RH (Ansley et al., 2008). The head cooling improved time to exhaustion by 51% (median: 45 vs 24 min) whilst no differences were observed in fractional oxygen uptake or heart rate. The investigators observed a tendency for T_{re} to be lower throughout the head cooling trial, but this was not significant. Skin temperature, tympanic temperature, prolactin and perceived exertion were lower throughout the trial ($P < 0.05$). At the point of fatigue tympanic temperature was still lower than the control, however, prolactin and perceived exertion were similar between trials. The authors suggested that the reduced tympanic temperature is a valid estimation of brain temperature, however, there are questions surrounding the validation of this method (Simon, 2007) and potential contamination from surrounding skin tissue. Nevertheless, these results suggest an increase in time to exhaustion due to lowered temperature in the head area, lowered skin temperature and a delay in the rise of perceived exertion. A temperature measurement in the head area was not measured in this thesis therefore, it is difficult to suggest whether any of the strategies affected brain temperature. Though, ice towel and ice slurry decreased skin temperature and thermal perception in the latter stages suggesting players might have increased time to fatigue.

A thermal threshold might exist that needs to be met prior to neck cooling having a beneficial effect (Tyler et al., 2010). The study investigated the effect of neck cooling on a 15-min treadmill time trial with and without a preceding 75-min submaximal (~60% $\dot{V}O_2max$) preloading phase in ~30 ˚C 50% RH. Following pre-loading, neck cooling increased the distance covered in 15-min (3030 ± 485 m vs 2741 ± 537 m), however, no effect of neck cooling was observed without the pre-loading phase. The improvements were evident with no differences between heart rate and rectal temperature between conditions, though perceptual responses were lowered following the pre-loading with neck cooling. The implication of this study is that performance can be enhanced without affecting core temperature or heart rate. Therefore, the intermittent neck cooling in this chapter 6 might lead to potential performance improvements. Although, the ice towel did not improve the thermal perception of players in chapter 6; if this is limiting factor then improvements may not be apparent with the ice towel strategy.

It is possible that enabling players to compete at higher intensities through strategies such as the ice towel or similar neck cooling (Tyler et al., 2010; Tyler & Sunderland, 2011a, 2011b) might increase core temperatures above the threshold for EHS (40˚C) . Though, if the rise in brain temperature can be attenuated through the same strategy then this might prevent fatigue and symptoms of EHS from emerging (Nybo et al., 2002). It is possible that brain temperature could elevate to dangerous levels post-match when core temperature is still elevated and the cooling strategy is no longer used, however the cessation of exercise and removal from the environment to a cool changing room would allow increased heat dissipation which would likely prevent any post-match illness. Cold-water immersion or similar could be utilised to ensure hyperthermia is not prolonged any longer than necessary.

Tennis performance is not only physical; there are also large elements of decision making, tactical play and reaction times affecting match outcome (Kovacs, 2007). Alertness, contentment and calmness might have an impact on players' ability to think clearly during matches and an increase in core temperature has been attributed to a decline in cognitive performance (Simmons et al., 2008). Cognitive performance was decreased in the trial where participants had high core and skin temperatures but, were not changed when only skin temperature was elevated. Head and neck cooling through a water perfused balaclava (~ 8 ˚C) did not attenuate the decline in cognitive performance. This would suggest that strategies such as the ice towel might enable improved performance physically but have no effect cognitively. The study by Simmons et al., (2008) did not have a trial where core temperature was elevated but skin temperature remained low which would have reinforced this suggestion. The core temperature was also only elevated by 1.1-1.2 ˚C which is not as large an increase as would be seen during tennis match play; possibly meaning greater reductions in cognitive performance would be seen with greater increases in T_{re}. However, there is also a possibility that the drop in cognitive performance was due to fatigue in the elevated core and skin temperature condition as the tests had already been completed twice within the session. If a reduction in cognitive performance exists because of increased core temperature it is unlikely that the strategies investigated within this thesis would alleviate that decline.

Cooling during on-court tennis match play has been evidenced to increase moderate to high intensity activity ($\geqslant$10 km·hr^{-1}) in the third set in comparison to a control condition with no cooling (Naito et al., 2021). The study assessed the use of an ice vest alone and combined with two frequencies of ice slurry ingestion (BINE: every break and L-BINE: end of set only). They also implemented the cooling strategies during a 30-min tennis-specific warm up and consequent 20-min rest prior to match play in 33.6 ± 1.7 ˚C 49 ± 7% RH. The intestinal temperature was reduced to the greatest extent in the BINE condition with lower T_{gi} throughout following the warm-up; the L-BINE strategy evidenced an effect on T_{gi} but, only from the start of the second set; and the ice vest did not affect T_{gi}. No differences were observed in peak, nadir or mean HR throughout the trials and the distance covered was not different either. However, moderate to high intensity activity (⩾10 km·hr^{-1}) in the third set was higher in the ice vest and the L-BINE trials than the control and BINE trials (P < 0.05). All players reported gastrointestinal distress in the BINE trial, thought to be caused by the fibre in the ice slurry being in excess of a standard Japanese diet (Naito et al., 2021). If fibre was not an affecting factor, it would be expected that BINE would also increase the moderate to high intensity activity in the third set whilst also lowering core temperature and thermal sensation compared with the other cooling strategies. No match characteristics were observed in this study, so the performance is only assessed on the intensity of the movement. The BINE strategy of ice vest and ice slurry is similar to the combined ice towel and ice slurry strategy in chapter 6. Therefore, it could be inferred that as T_{re} and thermal sensation were reduced when using the combined strategy that moderate to high intensity activity would also be improved on-court in the third set of a 2 to 3-hour match.

Based on the theory that a combination of the brain temperature and peripheral thermoreceptors (Ansley et al., 2008; Nybo et al., 2002), as well as cardiovascular strain (Périard et al., 2011) are key in limiting exercise performance in the heat it is likely that the cooling strategies in chapter 6 will all improve physical performance during tennis match play in the heat. The combined cooling approach will likely have the largest effect due to alleviating physiological and perceptual strain simultaneously to neck cooling. Increasing between-point rest is less likely to due to only affecting core temperature and not skin temperature, heart rate or thermal perception.

8.4.3 *Feasibility of the strategies and overall evaluation*

Chapter 7 sought to gain an understanding of current practice and perceptions of heat alleviation strategies. Table 7.2 demonstrates that most players use the more practical means of heat alleviation such as consuming cold drinks, seeking shade and pouring water on their heads. Increased between-point rest was said to be currently used by 70% of the players, however, 50% of the support staff said they had never suggested it and never would. This might be due to the support staff working with players at a higher level where the shot clock would prevent taking extra time. Increasing between-point rest is a very practical heat alleviation with no equipment required meaning it could be implemented across all tournaments and standards. Tournament referees might not want to implement this strategy due to time pressures on the schedule of play. If other heat alleviation strategies are possible then this is not essential but the question of "*does the increased demand on court time outweigh the benefits on player safety?*" be considered. Table 8.1

demonstrates that taking longer between points allows an attenuation in the rise of core temperature which might improve the safety element for the players, though if this strategy might increase performance or not is not yet known. Due to the practicality of this option, it should be recommended for all the lower levels of competition where facilities are not available for some of the more effective strategies.

Ice towels are the suggested cooling strategy during tennis and anecdotally is commonly seen during tennis matches in the heat. This is reflected in that most players and support staff either currently use ice towels or have previously used them. Those that have not used them are likely to be playing at a lower standard or in tournaments without access to ice machines. Importantly, 100% of respondents are open to using ice towels which would make this an obvious choice to promote. The drawback for this strategy is that not all places have ice machines and are capable of outputting ice to the extent for however many players are at a tournament. Though if ice can be accessed, wrapping it in a towel with a piece of tape or shoelace is quick and easy for players. The ice towel strategy is also likely to improve performance and possibly reduced risk of heat illness through a reduction in brain temperature.

Ice slurry attenuates the rise in both core and skin temperature towards the end of a simulated match and reduces thermal sensation compared to cold-water. These effects and the potential impact on brain temperature mean this strategy is likely to be beneficial for both improving safety and performance of players. However, it does require specialist equipment which might be difficult to attain. Not that it would not be possible to buy a cheap blender and have a coach (or another member of support staff or family member) make it for the player during a match. From Table 7.2 the support staff are open to the idea of internal cooling, but currently, 55% of the players would not be willing to try the strategy; further research would be required to understand the reasons for this. In isolation it is unlikely to be more beneficial than ice towels which are currently common practice on the tour and is a more complicated process to prepare.

The combined strategy is very likely to be beneficial for safety and performance (see Table 8.1). The feasibility of this strategy and openness of players and support staff can be inferred from the responses reported in Table 7.2 and as discussed earlier in this section. The combined strategy would require twice as much ice as either ice towel or slurry alone, however, due to the potential large benefit of implementing, if the facilities are available this is recommended to use.

Cooling measures are not always possible, even at grand slam events, for example, when competing on outside courts. The same would be apparent at events under all of tennis competition governing bodies (ITF, ATP, WTA); more so at lower tiered events where both tournament budget for running the costs are significantly lower, players' resources are fewer; with less prize money and fewer points on offer.

Increased between-point rest and ice towel are more feasible than ice slurry and the combined strategy based on the practicality of the method and the response from players and support staff in chapter 7. The responses to the questionnaire make it apparent that education is needed to ensure players and support staff are aware of how to reduce the risk of heat illness and enhance performance through using heat alleviation strategies. The choice of strategy should depend on the type of heat, *i.e.,* hot dry or hot humid, and will be heavily influenced by the facilities available at each tournament; this might mean different strategies are implemented each tournament.

8.5 Heat Policies in Tennis

The thresholds for modification and suspension of play in the current extreme heat policies (as detailed in section 2.3.5) are based on guidance in the ACSM position stand (Armstrong et al., 2007) which are suggested for acclimatised, fit, low-risk individuals wearing *"shorts, T-shirt, socks and sneakers"*. Acclimatised is defined in the paper as having trained in the heat for at least 3 weeks. There are many other factors that can predispose the players to or increase the susceptibility of a player to heat illness in lower temperatures than those in the guidelines (Keren et al., 1981; Roberts, 2006). It has also been suggested that heat illness occurs more often in humid environments (Armstrong et al., 2007). In addition, the heat policies are not consistent across all categories; the ATP do not have a heat policy (Association of Tennis Professionals, 2021), whilst the WTA has had a heat policy (in various forms) since 1992 (Women's Tennis Association, 2021). Similarly, the Grand Slam events implement their own heat policies whilst not publishing them clearly. If each policy accounts for the slight differences in environmental conditions, this is encouraged, however, the policies should all be transparent so others can be improved.

The best solution would be for the leading bodies (ATP, WTA, ITF and Grand Slam Board) to all adopt a global policy which would then cover all tournaments. The policy should include strategies which can be employed by tournament organisers to alleviate heat strain in players, some examples of which are in this thesis. It should also include considerations for players who might be fit, but not acclimatised; examples might include players arriving from different tournaments, returning from injury, or arriving from a location with a temperate environment. Additionally, independently of acclimatisation or fitness, exercise has been suggested to be modified to have longer breaks (Armstrong et al., 2007); demonstrated in this thesis to have a likely benefit on player safety and should be included in the policy. Even with the introduction of the shot clock, it is possible for umpires to show leniency with between-point rest due a button press initiating the countdown. This should be pressed as soon as the point ends, however, a small delay could assist struggling players, which anecdotally occurs in the heat. This behaviour should be consistent for all players so it would likely be easier to suggest an increase in the between-point rest length for everyone above a certain environmental threshold.

The body of tennis-specific on-court data during match play in the heat in all populations is lacking, the governing bodies should actively enable research to be able to enhance the safety and performance capabilities of the players. Armstrong et al. (2007) suggested that all athletes should be monitored for signs and symptoms of heat strain, early recognition is key to reducing the severity of heat illness and lasting effects. It is important to realise that players are unlikely to withdraw voluntarily when competing for ranking points and prize money. Monitoring core temperature through telemetry pills when conditions reach a certain threshold would increase the knowledge base and ensure player safety. Telemetry pills are much more affordable and would enable lots of data to be collected without causing the players any distraction; this data could be analysed alongside hawk-eye data to provide multiple insights.

8.6 Limitations

- The TSTP was designed on a range of data covering many aspects of match play, however, tennis has likely evolved since around 2006. Anecdotally, the courts are becoming slower and the points and matches longer. Particularly at Grand Slam events where males play best-of-five set matches. The TSTP was only three sets in length, and a further 2 sets would have seen greater thermal strain and likely a greater benefit of the heat alleviation strategies investigated. If the point duration and intensity of play is currently greater than previously reported then thermal strain for players is a more pressing issue than represented in the literature. However, until the data is available this is the basis on which the protocol must be designed.

- The TSTP entails unidirectional whole-body exercise (running), however, tennis movement is multidirectional, with change of direction and explosive full body action with an external weight (racquet) when playing shots. Therefore, the TSTP lacks external validity (Williams et al., 2010). However, the benefit of a laboratory-based protocol is that it allows the controlled assessment of parameters that would otherwise be highly variable in a competition setting enabling the interpretation of change due to an intervention.
- The between-point rest length of the TSTP was designed in accordance with the 2016 and 2017 rulebooks which stipulated 20 s between-point rest at the Grand Slams (Grand Slam Board, 2016, 2017). The rest length was increased to 25 s from the 2018 season to align with the other governing bodies (ATP, WTA and ITF). This could mean that the control condition in each of the experimental chapters within this thesis overestimated the level of heat strain, though the observed heat strain was in line with previously reported values. It also made chapter 5 more difficult to interpret as the magnitude of change of an increase in rest from 20 to 30 s might be different to an increase from 25 to 35 s or a smaller increase in rest from 25 to 30 s making recommendations for heat policy changes more difficult. However, it is possible that the results of this vindicate the decision to align the between-point rest length with the other governing bodies, whether that was the reason or not.
- The heat stress in the environmental chamber did not include an element of solar radiation and is therefore not entirely representative of the conditions that players are exposed to during on-court match play. This would reduce the level of thermal strain in the players and reduce the perceived benefit of the heat alleviation strategies. It also might negate some of the benefit of increasing between-point rest if the solar radiation is high and the player remained exposed throughout the rest period. The equipment was not available to use for this project but would be suggested to be included in future laboratory-based research where possible.
- The familiarisation (5 games in temperate conditions) of the participants was inadequate in chapter 4 which led to some variation between trials, particularly in the perceptual values. Participants not having experienced a high level of thermal strain prior to the first trial led to higher perceptions of thermal discomfort compared to the second trial where the thermal strain had been experienced. Unfortunately, this

mistake was not realised until the data collection had finished otherwise a third trial would have been added to the data for assessing reliability. It is likely that some of the effects of the strategies in this thesis are not identified due to the variability in chapter 4. After chapter 4, the familiarisation was adjusted to be a full set (~ 30 min) in similar conditions to the experimental trials (36 ˚C 50% RH). This was possibly still not enough for participants to fully appreciate a high level of heat strain but with multiple trials it is important to find a balance between error and participant retention.

- The sample throughout this thesis is not representative of the population that the findings are being targeted. Whilst a strength of the thesis was that tennis players were recruited for all experimental studies rather than only being recreationally active, the standards of the players recruited were mostly competing in regional and national tournaments, rather than elite players competing internationally. There were individual differences within the samples such as stature, body mass, percentage body fat and aerobic fitness; minimum or maximum thresholds were set depending on the variable might explain some of the variation in responses. Though, there are also large individual differences in the elite game and therefore, this is possibly representative of the population. The difficulty is making generalised recommendations that cover these differences.
- The sample in all laboratory-based studies in this thesis were male. Females are likely to respond differently to heat strain and heat alleviation strategies due to physiological differences (Elliott-Sale et al., 2021), therefore, the conclusions of experimental chapters 4 to 6 should be applied to the women's game with caution.
- The experimental setting was controlled to ensure any effects could be attributed to the strategies being investigated. However, the TSTP does not include any tennis-specific movement including the upper body and multi-directional patterns, no cognitive element which might impact significantly on perceptual values. The on-court game is a complex interaction of physiological and psychological demands which each individual respond to differently. It might be argued that this setting is too far from the 'real-world', but it is important to assess the potential benefits of the strategies prior to interfering with elite players routines which might impact on ranking and prize money. The results in this thesis should be interpreted to be applied

to the on-court match play, however with the caution that it is a different environment and that players could require or prefer different strategies or dosages.

- It was not possible to blind participants to the interventions in chapters 5 and 6 of this thesis. Therefore the participants' expectation that certain cooling techniques should have a beneficial effect cannot be discounted (Ross et al., 2013). Previously, perceptual results of RPE and TS were compared at the point of exhaustion in an attempt to rule out this effect; however (Siegel et al., 2010), this approach cannot be used in this thesis as a fixed physiological comparison is not apparent. Increasing between-point rest did not influence perceptual measures in the heat. In the cooling study, some participants reported discomfort when consuming the ice slurry or having the ice towel around their neck; despite this, the physiological and perceptual variables show varying effect across cooling conditions compared to the control.

8.7 Future Directions

Future directions from this thesis are extensive due to the formative stages of research into heat alleviation in tennis and the need for increased knowledge on the demands of playing tennis in the heat.

- *Profile on-court tennis match play in varying environmental conditions.* The physiological responses and related match characteristics during match play need to be known to assess what meaningful changes in various physiological parameters are for performance. It is likely that some players can withstand prolonged period of extreme hyperthermia (>40 ˚C) (Byrne et al., 2006; Racinais et al., 2019) and this data would add to the evidence for use of particular heat alleviation strategies in different conditions and allow an understanding of individual characteristics that might make players more susceptible to heat illness during tennis match play in the heat. Technology has developed and applied data should now be easier to collect and less intrusive for the players (Buller et al., 2019; Mendes Jr. et al., 2016; Sawka & Friedl, 2018). Players could wear wearable sensors and consume telemetry pills to gain data alongside hawk-eye.

- *Establish the threshold for cooling and magnitude or dosage required to benefit performance.* The effectiveness of heat alleviation strategies and particularly cooling is dependent on the surface area coverage, the temperature of the device used and the duration of use (Ruddock et al., 2017; Tyler, Sunderland, et al., 2015). The results of this thesis suggest that the strategies are not effective until the latter stages of the match. At what point in the match do the strategies need to be initiated or is it dependent on physiological or perceptual factors, and whether different dosages or magnitudes see similar effects such as the work by Naito et al. (2021) would be useful to know to inform heat policies or guidance for players and support staff.

- *Establish the extent of heat acclimatisation in tennis players.* The current heat policies use thresholds for modification and cancellation of play based on those suggested in the ACSM position stand (Armstrong et al., 2007). The thresholds presume that all players are acclimatised to the heat which might not be the case if players are not coming from hot climates or from a period of injury etc. Assessing the acclimatisation state in would allow these thresholds to be challenged and provide an idea of acclimatisation state of future study samples. It would also be interesting to investigate the effect of acclimatisation status on match characteristics and physiological and perceptual responses during tennis match play in the heat.
- *Examine the additive effects of heat alleviation strategies in acclimatised players.* The literature available on heat alleviation during simulated match play have used samples that are unacclimatised to the heat (Lynch et al., 2018; Naito et al., 2018; Schranner et al., 2017) and it is not clear whether the sample were acclimatised or not in a study which assessed on-court tennis match play (Naito et al., 2021). However, an additive effect of cooling on acclimation has been demonstrated previously within running time-trials (James et al., 2018) which might transfer to the tennis court. This relationship could be investigated using simulated match play.
- *Current practice and perceptions of heat alleviation strategies.* Whilst chapter 7 gather some data on the practice and perceptions of heat alleviations strategies in players and support staff, a much bigger sample is needed with respondents across all standards of the game to understand what the current situation is. This would help to assess the potential uptake of efficacious strategies which are put forward and gain an understanding of the education that needs to be provided for players and support staff on competing in the heat and how thermal strain can be alleviated and performance maximised.
- *Prevalence of heat illness incidence in ranging environmental conditions.* Some research has begun to understand this area summarising heat illness prevalence and

observing relationships with match characteristics using hawk-eye data at the Australian Open in men and women (Smith, Reid, Kovalchik, Wood, et al., 2018; Smith, Reid, Kovalchik, Woods, et al., 2018), however much more is needed to understand the issue. If heat illness risk could be quantified through identifying those most at risk and the major factors that are associated using individual characteristics such as aerobic fitness, morphology, acclimation status etc. (Keren et al., 1981; Roberts, 2006) in the context of tennis. This information could enable enhanced guidelines for return to play following heat illness or injury to reduce risk of heat illness.

- *Sex differences should be considered in all the above.* The body of knowledge is considerably bias towards men and there are numerous reasons as to why the female response is investigated and compared to the male response. Many investigations have not recruited women into their sample due to the need to adapt protocols or incorporate female-specific considerations (including this thesis) (Elliott-Sale et al., 2021). Female participation in elite sport is nearly equal to male participation with a 48.8% proportion of competitors expected to be female at the Tokyo 2021 Olympics (Elliott-Sale et al., 2021). Therefore, is important that we understand how both sexes respond to these environments and the effectiveness of heat alleviation strategies and adjust guidelines, advice, and policies accordingly.

8.8 Conclusions

The observed effects in this thesis on thermal physiology and perception from increasing between-point rest, ice slurry, ice towel, and combined ice slurry and towel suggest that they would all be effective at increasing both player safety and performance in tennis match play. A higher level of safety would be enabled through an attenuation in the rise of core body temperature, and potentially attenuating the rise in brain temperature which appears to be associated with symptoms of exertional heat stroke. In addition, it is unlikely that increasing between-point rest alone will enhance performance as there is no effect on skin temperature and thermal perception which may regulate behaviour. However, all three cooling strategies are likely to enhance performance. Ice slurry may enhance performance through a combination of an attenuated rise in core temperature along with reductions in skin temperature and thermal perception allowing a higher intensity to be self-selected. Ice towels only reduce skin temperature, though it is expected that this strategy will increase performance through the masking of the afferent signal to the brain relaying the body's level of thermal strain and again allowing a higher intensity to be self-selected. The combined strategy appears to have a significant additive effect initiating a lowering in skin temperature and thermal sensation at an earlier stage in simulated match play. Heat alleviation strategies are perceived to be useful by players and support staff during tennis match play in the heat, though, simple solutions are the most likely to be used, possibly as they are accessible to all levels of tennis, not just elite tournaments with special facilities.

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10 Appendices

10.1 Publications from this Programme of Research

Debney, Matthew J., Tiller, Nicholas B., O'Hagan, Ciara J., and Purvis, Alison, J. (2018) *Reliability of a tennis-specific treadmill protocol performed in temperate and hot conditions*. BASES Conference, Harrogate Conference Centre, Harrogate, November 2018

Debney, Matthew J., O'Hagan, Ciara J., Ruddock, Alan D., and Purvis, Alison, J. (2019) *3 Minute Thesis: Reducing Heat Strain in Tennis*. Creating Knowledge Conference, Sheffield Hallam University, Sheffield, June 2019

10.2 TSTP Treadmill Control Programme

Treadmill programme for 20 s between-point rest.

Time (mm:ss)	***Speed***	***Elevation***	***Acceleration***	***Total time (hh:mm:ss)***	***Total Distance***
00:15	13	0	7	00:00:15	51
00:14	0	0	7	00:00:29	54
00:13	15	0	7	00:00:42	104
00:14	0	0	7	00:00:56	108
00:12	10	0	7	00:01:08	140
00:14	0	0	7	00:01:22	142
00:19	13	0	7	00:01:41	207
00:14	0	0	7	00:01:55	210
00:12	20	0	7	00:02:07	269
00:14	0	0	7	00:02:21	277
00:14	10	0	7	00:02:35	314
00:24	0	0	7	00:02:59	316
00:15	13	0	7	00:03:14	367
00:14	0	0	7	00:03:28	370
00:13	15	0	7	00:03:41	420
00:14	0	0	7	00:03:55	424
00:12	10	0	7	00:04:07	456
00:14	0	0	7	00:04:21	457
00:19	13	0	7	00:04:40	523
00:14	0	0	7	00:04:54	526
00:12	20	0	7	00:05:06	585
00:14	0	0	7	00:05:20	593
00:14	10	0	7	00:05:34	630
00:24	0	0	7	00:05:58	632
00:15	13	0	7	00:06:13	683
00:14	0	0	7	00:06:27	686
00:13	15	0	7	00:06:40	736
00:14	0	0	7	00:06:54	740
00:12	10	0	7	00:07:06	771
00:14	0	0	7	00:07:20	773
00:19	13	0	7	00:07:39	839
00:14	0	0	7	00:07:53	842
00:12	20	0	7	00:08:05	901
00:14	0	0	7	00:08:19	909
00:14	10	0	7	00:08:33	946
00:24	0	0	7	00:08:57	947
00:15	13	0	7	00:09:12	998
00:14	0	0	7	00:09:26	1002
00:13	15	0	7	00:09:39	1052
00:14	0	0	7	00:09:53	1056
00:12	10	0	7	00:10:05	1087

00:14	0	0	7	00:10:19	1089
00:19	13	0	7	00:10:38	1155
00:14	0	0	7	00:10:52	1158
00:12	20	0	7	00:11:04	1217
00:14	0	0	7	00:11:18	1224
00:14	10	0	7	00:11:32	1261
00:24	0	0	7	00:11:56	1263
00:15	13	0	7	00:12:11	1314
00:14	0	0	7	00:12:25	1317
00:13	15	0	7	00:12:38	1367
00:14	0	0	7	00:12:52	1372
00:12	10	0	7	00:13:04	1403
00:14	0	0	7	00:13:18	1405
00:19	13	0	7	00:13:37	1470
00:14	0	0	7	00:13:51	1474
00:12	20	0	7	00:14:03	1533
00:14	0	0	7	00:14:17	1540
00:14	10	0	7	00:14:31	1577
00:24	0	0	7	00:14:55	1579
00:15	13	0	7	00:15:10	1630
00:14	0	0	7	00:15:24	1633
00:13	15	0	7	00:15:37	1683
00:14	0	0	7	00:15:51	1687
00:12	10	0	7	00:16:03	1719
00:14	0	0	7	00:16:17	1721
00:19	13	0	7	00:16:36	1786
00:14	0	0	7	00:16:50	1789
00:12	20	0	7	00:17:02	1849
00:14	0	0	7	00:17:16	1856
00:14	10	0	7	00:17:30	1893
00:24	0	0	7	00:17:54	1895
00:15	13	0	7	00:18:09	1946
00:14	0	0	7	00:18:23	1949
00:13	15	0	7	00:18:36	1999
00:14	0	0	7	00:18:50	2003
00:12	10	0	7	00:19:02	2035
00:14	0	0	7	00:19:16	2037
00:19	13	0	7	00:19:35	2102
00:14	0	0	7	00:19:49	2105
00:12	20	0	7	00:20:01	2164
00:14	0	0	7	00:20:15	2172
00:14	10	0	7	00:20:29	2209
00:24	0	0	7	00:20:53	2211
00:15	13	0	7	00:21:08	2262
00:14	0	0	7	00:21:22	2265
00:13	15	0	7	00:21:35	2315

00:14	0	0	7	00:21:49	2319
00:12	10	0	7	00:22:01	2351
00:14	0	0	7	00:22:15	2352
00:19	13	0	7	00:22:34	2418
00:14	0	0	7	00:22:48	2421
00:12	20	0	7	00:23:00	2480
00:14	0	0	7	00:23:14	2488
00:14	10	0	7	00:23:28	2525
00:24	0	0	7	00:23:52	2527
00:15	13	0	7	00:24:07	2578
00:14	0	0	7	00:24:21	2581
00:13	15	0	7	00:24:34	2631
00:14	0	0	7	00:24:48	2635
00:12	10	0	7	00:25:00	2666
00:14	0	0	7	00:25:14	2668
00:19	13	0	7	00:25:33	2734
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00:12	20	0	7	00:25:59	2796
00:14	0	0	7	00:26:13	2804
00:14	10	0	7	00:26:27	2841
00:24	0	0	7	00:26:51	2842
00:15	13	0	7	00:27:06	2893
00:14	0	0	7	00:27:20	2897
00:13	15	0	7	00:27:33	2947
00:14	0	0	7	00:27:47	2951
00:12	10	0	7	00:27:59	2982
00:14	0	0	7	00:28:13	2984
00:19	13	0	7	00:28:32	3050
00:14	0	0	7	00:28:46	3053
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00:14	10	0	7	00:29:26	3156
00:54	0	0	7	00:30:20	3158
00:15	13	0	7	00:30:35	3209
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00:14	0	0	7	00:31:16	3267
00:12	10	0	7	00:31:28	3298
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00:14	0	0	7	00:32:15	3369
00:12	20	0	7	00:32:27	3428
00:14	0	0	7	00:32:41	3435
00:14	10	0	7	00:32:55	3472
00:24	0	0	7	00:33:19	3474
00:15	13	0	7	00:33:34	3525

00:14	0	0	7	00:33:48	3528
00:13	15	0	7	00:34:01	3578
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00:14	10	0	7	00:35:54	3788
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00:15	13	0	7	00:36:33	3841
00:14	0	0	7	00:36:47	3844
00:13	15	0	7	00:37:00	3894
00:14	0	0	7	00:37:14	3898
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00:14	0	0	7	01:19:03	8266
00:13	15	0	7	01:19:16	8316
00:14	0	0	7	01:19:30	8320
00:12	10	0	7	01:19:42	8351

00:14	0	0	7	01:19:56	8353
00:19	13	0	7	01:20:15	8419
00:14	0	0	7	01:20:29	8422
00:12	20	0	7	01:20:41	8481
00:14	0	0	7	01:20:55	8489
00:14	10	0	7	01:21:09	8526
00:24	0	0	7	01:21:33	8527
00:15	13	0	7	01:21:48	8578
00:14	0	0	7	01:22:02	8582
00:13	15	0	7	01:22:15	8632
00:14	0	0	7	01:22:29	8636
00:12	10	0	7	01:22:41	8667
00:14	0	0	7	01:22:55	8669
00:19	13	0	7	01:23:14	8735
00:14	0	0	7	01:23:28	8738
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00:14	0	0	7	01:23:54	8804
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00:14	0	0	7	01:26:27	9054
00:12	20	0	7	01:26:39	9113
00:14	0	0	7	01:26:53	9120
00:14	10	0	7	01:27:07	9157
00:24	0	0	7	01:27:31	9159
00:15	13	0	7	01:27:46	9210
00:14	0	0	7	01:28:00	9213
00:13	15	0	7	01:28:13	9263
00:14	0	0	7	01:28:27	9267
00:12	10	0	7	01:28:39	9299
00:14	0	0	7	01:28:53	9301
00:19	13	0	7	01:29:12	9366
00:14	0	0	7	01:29:26	9369
00:12	20	0	7	01:29:38	9429
00:14	0	0	7	01:29:52	9436
00:14	10	0	7	01:30:06	9473

10.3 Ethics Applications

10.3.1 *Study 1 and 2*

Ref No: HWB-2016-17-S&E-07

Faculty of Health and Wellbeing Research Ethics Committee
Sport and Exercise Research Ethics Review Group
Report Form

Principal Investigator: Matthew Debney

Title: The effect of longer rest periods on physiological responses during a tennis-specific treadmill protocol in hot conditions.

Recommendation:

Approved	
Approved with attention to the items listed	x
Referred back to the applicant for a full resubmission to address all the conditions listed	
Not Approved for the reasons listed	

Comments:

Please see the attached SHUREC3 forms.

Reviewers: Mayur Ranchordas & Alan Ruddock

[redacted]
Signature : .... Date: 07.11.16
Donna Woodhouse
Chair, Sport and Exercise Research Ethics Review Group

Note: *Approval applies until the anticipated date of completion unless there are changes to the procedures, in which case another application should be made.*

Comments from the Reviewers have been addressed
(Supervisor should check that the comments have been addressed and sign below)

Signature of Supervisor
[redacted]... Date: ..[redacted].
Name of Supervisor : Alison Purvis

10.3.2 *Study 3*

Intermittent cooling during a tennis-specific treadmill protocol in hot, humid conditions

Ethics Review ID: ER9107366
Workflow Status: Application Approved
Type of Ethics Review Template: All other research with human participants

Primary Researcher / Principal Investigator

Matthew Debney
(Health and Wellbeing)

Converis Project Application::
Q1. Is this project: ii) Doctoral research

Director of Studies

Alison Purvis
(Health and Wellbeing)

Supervisory Team

Ciara O'Hagan

Alan Ruddock
(Centre for Sport and Exercise Science), (Centre for Sport and Exercise Science)

Q4. Proposed Start Date of Data Collection: 01/10/2018
Q5. Proposed End Date of Data Collection : 01/10/2019

10.3.3 *Study 4*

Current practice and perceptions of cooling during tennis matchplay in hot conditions

Ethics Review ID: ER15495719
Workflow Status: Application Approved
Type of Ethics Review Template: Very low risk human participants studies

Primary Researcher / Principal Investigator

Matthew Debney
(Health and Wellbeing)

Converis Project Application::
Q1. Is this project: ii) Doctoral research

Director of Studies

Alison Purvis
(Health and Wellbeing)

Supervisory Team

Ciara O'Hagan

Alan Ruddock
(Centre for Sport and Exercise Science), (Centre for Sport and Exercise Science)

Q4. Proposed Start Date of Data Collection: 26/08/2019
Q5. Proposed End Date of Data Collection : 01/01/2020

10.4 Participant Information

10.4.1 *Study 1*

<u>The repeatability of a tennis-specific treadmill protocol in hot conditions</u>

Note: This participant information sheet is a guide to the study, informing you, as a potential participant, of the study's aims, the methods used, as well as the potential risks, discomforts and possible participant exclusions. This will help you make an informed decision as to whether you wish to be a participant for this study.

What is it all about?

Tennis is a complex, reactive sport with many different factors able to influence the outcome of a match. It is often competed in extreme environmental conditions, which, increases the risk of heat related illnesses such as heat exhaustion and heat stroke. Examples include play being halted at the 2014 Australian Open with temperatures in excess of 40°C and a record high 10 players retiring in the first round of the 2015 US Open due to heat related issues whilst playing in conditions of 32°C and 60% relative humidity; even Wimbledon 2015 saw highs of 34°C. The impact of hot conditions on tennis-specific performance is not fully understood but does have negative effects on other sports.

There is not yet an established lab based protocol for tennis so it is the aim of this study to establish the validity and reproducibility of the Tennis-Specific Treadmill Protocol (TSTP), complying with previously reported average point length (Kovacs 2006), average running speed (Reid et al. 2016) and the official timings enforced by the International Tennis Federation (ITF). This can be undertaken in an environmental chamber where the conditions can be more accurately controlled; allowing a more extensive physiological profile to be recorded and possible interventions to be assessed in the future.

What impact will the research have?

This research hopes to establish a laboratory based exercise test that replicates the physiology and time-motion of tennis in hot conditions. This may then be used in the future to investigate interventions, such as cooling strategies, which, may be beneficial to both players' health and performance.

Who may participate?

Male tennis players aged between 18 and 40 years, regularly training (at least once per week) and competing (at least once per month) to a minimum of a good club standard (Local Division 2 and above or BUCS). They will also have to undertake a health check through the SHU medical screening questionnaire prior to being allowed to partake in the study.

Participants must be non-smokers. You must not have any known: cardio, respiratory, haematological or renal disorders; blood carried infections (Hepatitis, HIV); anal haemorrhoids, fissures or bleeding.

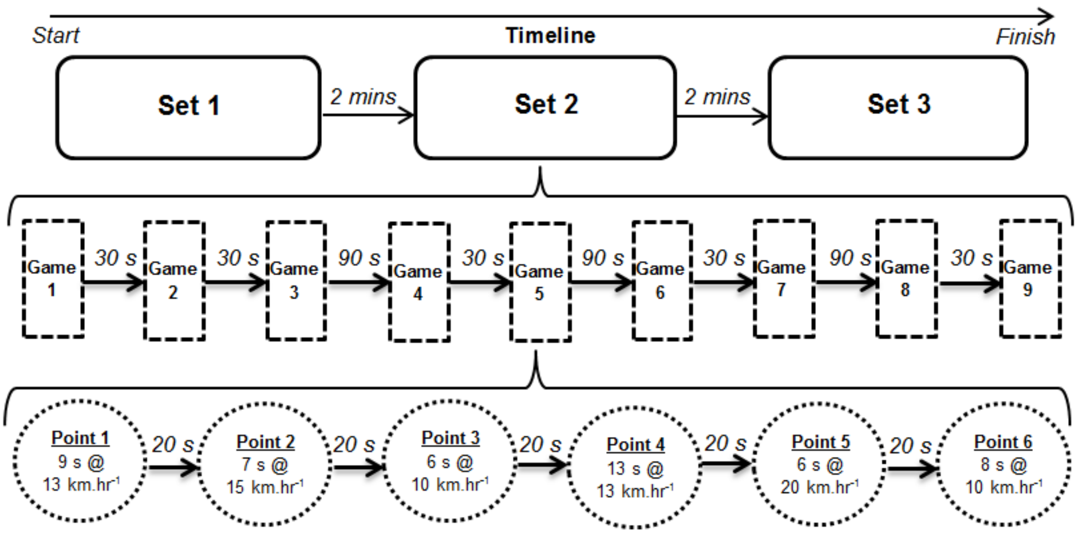
Where is it?

Environmental Chamber (A105), Sheffield Hallam Sport Science Laboratories, Collegiate Hall, Collegiate Crescent, Sheffield, S10 2BP

What do I have to do?

You will need to come to the labs 3 times. The first visit will be around an hour during which some familiarisation of the protocol will occur and a maximal aerobic capacity test (on a treadmill) along with some basic measures such as height, weight and body fat percentage.

The remaining 2 sessions will involve a full run-through of the tennis-specific treadmill protocol in the environmental chamber at 36°C and 50% Relative Humidity, similar to conditions at the US and Australian Opens. A visual representation of the protocol can be seen below.



What measures will be taken during the trials?

- **Body fat %:** This will be estimated using bioelectrical impedance on the In-Body machine.
- **Hydration status:** A urine sample will be required at the start of each testing visit to monitor hydration levels; however, this will be carried out in privacy.
- **Capillary blood sampling:** Fingertip blood samples (~100 μL) will be taken at rest and certain periods throughout the testing for the measurement of blood lactate.
- **Perception of effort, thermal sensation and thermal comfort scales:** All of these will be determined before and during the testing sessions using numerical scales.
- **Core temperature:** University ethics require all participants entering the heat chamber to have their core temperature monitored for your own safety. The most common method for this is through a rectal thermistor, these are pain-free and pose no health risk, though may cause slight discomfort.

- **Skin temperature:** Measured through 4 small thermocouples on the skin at the chest, tricep, thigh and calf.
- **Expired air:** An online system connected to a mouthpiece or mask. This will be worn continuously during the maximal aerobic test but, intermittently throughout the tennis-specific treadmill test.
- **Sweat rate:** This will be calculated using clothed body mass and nude body mass pre and post-protocol to assess sweat loss and sweat absorbed in clothes. This also informs us how much you need to rehydrate after the trial.
- **Heart rate:** A heart rate strap will be worn around the chest and paired with a watch, allowing monitoring throughout the protocol.

What is expected of me?

- ❖ Attend Sheffield Hallam's laboratories for 3 sessions with at least 48 hours between each session.
- ❖ Refrain from consuming alcohol in **24 hours** prior and no caffeine for **12 hours** prior to each session.
- ❖ Prepare for each session as though a competitive match e.g. easy training in the **48 hours** prior to testing.
- ❖ Please be aware of eating habits in the 24 hours before the initial session and attempt to replicate a similar diet for each subsequent session.
- ❖ Please arrive for your testing session **well hydrated** as dehydrated participants will not be allowed in the chamber, leading to delays. Hydration is achieved through regular drinking but, please ensure 500 ml of water is consumed 1-1.5 hours before attending or, the night before if testing is early the next morning).
- ❖ Maintain **normal** diet and activity/training patterns throughout the study.
- ❖ Following each session, you should **rehydrate** by drinking little and often throughout the day, following your trial.
- ❖ If you are ill or encounter a situation where you cannot attend a session, simply phone the lead investigator. For extended illness, you may withdraw as a participant or postpone testing until fully recovered.

What are the benefits of participating?

It is intended for the study to be published in a scientific journal and you are entitled to a copy of the final manuscript, upon request, as well as having the opportunity to gain first-hand experience of scientific research, and to learn how you cope when exercising in hot conditions. You will also be enabling us to establish a protocol which is intended to be used for further research, identifying methods of countering ill effects of the heat, helping to inform tennis governing bodies for recommendations.

Are there any risks?

There is a very minor risk of infection due to the blood taking procedures, however, this risk will be minimised by using sterilised equipment at all times. As with all exercise there is a small risk of musculo-skeletal injury which will be minimised through the use of a standardised warm up. Heat exposure may lead to heat illness such as heat exhaustion; however, participants will be monitored at all times and removed from the chamber if a health risk is posed. Participants are free to withdraw at any point throughout each session if they so wish. Due to the risks associated, exclusion criteria are in place (see who may participate) and a brief medical questionnaire will be used to assess suitability to participate in the research. The lead investigator is first aid trained and the laboratories are equipped with first aid kits.

Will my information remain confidential?

Your responses and measures will be confidential. No individuals will be identifiable from any collated data or any written report of the research whether published or not. All data will be kept on a password secure computer or in a locked office on the University premises where by only the experimenter or supervisors can access.

This study relies on volunteers like yourselves and you are reminded that you are free to withdraw from the study at any time, without justification and with no subsequent prejudice.

Please feel free to ask any questions you may have and ensure you fully understand what is required of you as a participant.

10.4.2 *Study 2*

<u>The effect of longer rest periods on physiological responses during a tennis-specific treadmill protocol in hot conditions</u>

Note: This participant information sheet is a guide to the study, informing you, as a potential participant, of the study's aims, the methods used, as well as the potential risks, discomforts and possible participant exclusions. This will help you make an informed decision as to whether you wish to be a participant for this study.

What is it all about?

Tennis is a complex, reactive sport with many different factors able to influence the outcome of a match. It is often competed in extreme environmental conditions, which, increases the risk of heat related illnesses such as heat exhaustion and heat stroke. Examples include play being halted at the 2014 Australian Open with temperatures in excess of 40°C and a record high 10 players retiring in the first round of the 2015 US Open due to heat related issues whilst playing in conditions of 32°C and 60% relative humidity; even Wimbledon 2015 saw highs of 34°C. The impact of hot conditions on tennis-specific performance is not fully understood but does have negative effects on other sports.

When playing tennis in hot conditions it has previously been evidenced that when given the option, people will adjust how they behave in an attempt to stop core body temperature increasing. This may be through changing tactics *i.e.* shortening points (Morante & Brotherhood 2008) or through choosing to take a longer rest in between points (Periard *et al.* 2014); a phenomenon is known as behavioural thermoregulation. The self-selected rest when playing in the heat was longer than the ITF ruling of 20 seconds, therefore would like lead to time violations during grand slam matches. It is not yet known what the impact of a longer between-point rest compared with the ITFs 20s standard is on the physiological responses. Therefore this study aims to identify and quantify any benefits of allowing a longer rest between points using the previously validated tennis-specific treadmill protocol.

What impact will the research have?

Through identifying any benefits of a longer between-point rest period and the impact this may have on reducing incidences of heat illness and even have an impact on on-court performance too. It is hoped any findings may help tennis governing bodies to implement changes to recommendations or rules or encourage further research into this sensitive area.

Who may participate?

Male tennis players aged between 18 and 40 years, regularly training (at least once per week) and competing (at least once per month) to a minimum of a good club standard (Local Division 2 and above or BUCS). They will also have to undertake a health check through the SHU medical screening questionnaire prior to being allowed to partake in the study.

Participants must be non-smokers. You must not have any known: cardio, respiratory, haematological or renal disorders; blood carried infections (Hepatitis, HIV); anal haemorrhoids, fissures or bleeding.

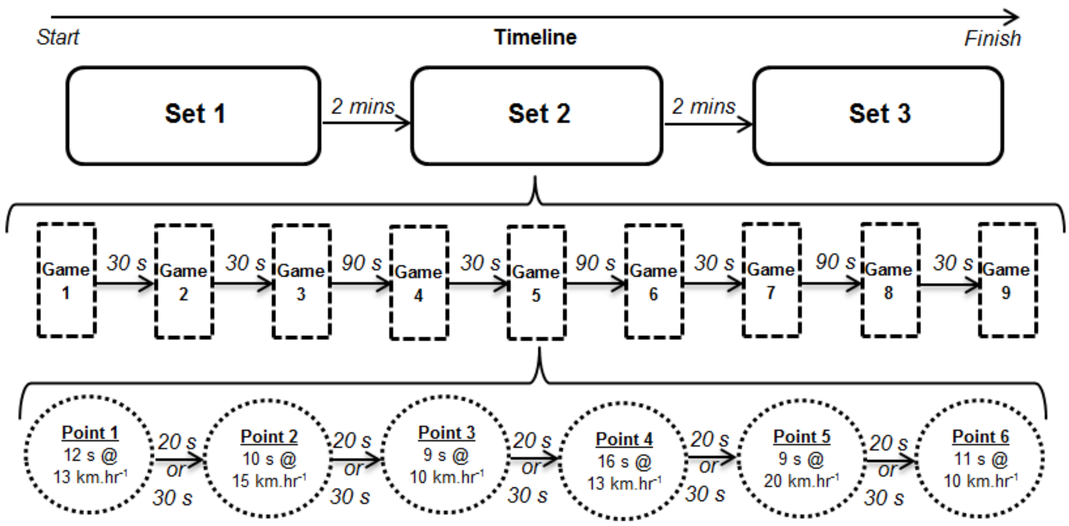
Where is it?

Environmental Chamber (A105), Sheffield Hallam Sport Science Laboratories, Collegiate Hall, Collegiate Crescent, Sheffield, S10 2BP

What do I have to do?

You will need to come to the labs 5 times. The first visit will be around an hour during which some familiarisation of the protocol will occur and a maximal aerobic capacity test (running on a treadmill) along with some basic measures such as height and weight.

The remaining 4 sessions will involve a full run-through of the tennis-specific treadmill protocol (see visual representation below) in the environmental chamber. Two of these will be at 36°C and 50% Relative Humidity, similar to conditions at the US and Australian Opens. One will have a between-point rest period of 20 seconds and the other will have a between-point rest period of 30 seconds. The remaining two will be in 20°C 50% Humidity, with 20 seconds between-point rest.



What measures will be taken during the trials?

- **Body fat %:** The InBody machine will determine this measure during the familiarisation trial.
- **Hydration status:** A urine sample will be required at the start of each experimental trial to ensure adequate hydration; this will be carried out in privacy.
- **Capillary blood sampling:** Fingertip blood samples (~100 µL) will be taken at rest and certain periods throughout the testing for the measurement of blood lactate.

- **Perception of effort, thermal sensation and thermal comfort scales:** All of these will be determined before and during the testing sessions using numerical scales.
- **Core temperature:** University ethics require all participants entering the heat chamber to have their core temperature monitored for your own safety. The most common method for this is through a rectal thermistor, these are pain-free and pose no health risk, though may cause slight initial discomfort.
- **Skin temperature:** Measured through 4 small metal thermistors on the skin at the chest, tricep, thigh and calf.
- **Expired air:** An online system connected to a mouthpiece or mask. This will be worn continuously during the maximal aerobic test but, intermittently throughout the tennis-specific treadmill test.
- **Sweat rate:** This will be calculated using clothed body mass and nude body mass pre and post the protocol to assess sweat lost and sweat absorbed in clothes. This also informs us how much you need to rehydrate after the trial.
- **Heart rate:** A heart rate strap will be worn around the chest and paired with a watch, allowing monitoring throughout the protocol.

What is expected of me?

❖ Attend Sheffield Hallam's laboratories for 5 sessions with at least 48 hours between each session.
❖ Refrain from consuming alcohol in **24 hours** prior and no caffeine for **12 hours** prior to each session.
❖ Prepare for each session as though a competitive match e.g. easy training in the **48 hours** prior to testing.
❖ Please be aware of eating habits in the 24 hours before the initial session and attempt to replicate a similar diet for each subsequent session.
❖ Please arrive for your testing session **well hydrated** as dehydrated participants will not be allowed in the chamber, leading to delays. Hydration is achieved through regular drinking but, please ensure 500 ml of water is consumed 1-1.5 hours before attending or the night before if testing is early the next morning).
❖ Maintain **normal** diet and activity/training patterns throughout the study.
❖ Following each session, you should **rehydrate** by drinking 1.5 times the amount of sweat lost during the trial. This will be explained to you at the end of each session.
❖ If you are ill or encounter a situation where you cannot attend a session, simply phone the lead investigator. For extended illness, you may withdraw as a participant or postpone testing until fully recovered.

What are the benefits of participating?

You will be entitled to a copy of your data, upon request, as well as having the opportunity to learn how you cope when exercising in hot conditions. It is also an opportunity to gain first-hand experience of scientific research. You will also be enabling us to record data which might have an impact on the future recommendations or ruling of tennis governing bodies such as the International Tennis Federation.

Are there any risks?

There is a very minor risk of infection due to the blood taking procedures, however, this risk will be minimised by using sterilised equipment at all times. As with all exercise there is a small risk of musculo-skeletal injury which will be minimised through the use of a standardised warm up. Heat exposure may lead to heat illness such as heat exhaustion; however, participants will be monitored at all times and removed from the chamber if a health risk is posed. Participants are free to withdraw at any point throughout each session if they so wish. Due to the risks associated, exclusion criteria are in place (see who may participate) and a brief medical questionnaire will be used to assess suitability to participate in the research. The lead investigator is first aid trained and the laboratories are equipped with first aid kits.

Will my information remain confidential?

Your responses and measures will be confidential. No individuals will be identifiable from any collated data or any written report of the research whether published or not. All data will be kept on a password secure computer or in a locked office on the University premises where by only the experimenter or supervisors can access.

This study relies on volunteers like yourselves and you are reminded that you are free to withdraw from the study at any time, without justification and with no subsequent prejudice.

Please feel free to ask any questions you may have and ensure you fully understand what is required of you as a participant.

10.4.3 *Study 3*

Intermittent cooling during a tennis-specific treadmill protocol in hot, humid conditions

Note: This participant information sheet is a guide to the study, informing you, as a potential participant, of the study's aims, the methods used, as well as the potential risks, discomforts and possible participant exclusions. This will help you make an informed decision as to whether you wish to be a participant for this study.

What is it all about?

Tennis is a complex, reactive sport with many different factors able to influence the outcome of a match. It is often competed in extreme environmental conditions, which, increases the risk of heat related illnesses such as heat exhaustion and heat stroke. Examples include play being halted at the 2014 Australian Open with temperatures in excess of 40°C and a record high 10 players retiring in the first round of the 2015 US Open due to heat related issues whilst playing in conditions of 32°C and 60% relative humidity; even Wimbledon 2015 saw highs of 34°C.

One method of reducing heat stress for players is cooling. There are a number of ways to cool e.g. cold shower, ice towels, spray and fan, ice slushy. The challenge is to find something that is practical and beneficial during a tennis match where you are limited on time at the change of ends. You have likely seen players using ice towels when playing in hot conditions. This study is looking to compare the methods of ice towels, ice slushy, and cold-water, to assess if one is more effective at reducing heat stress than the others.

What impact will the research have?

This research aims to identify effective and practical cooling strategies, which, may be beneficial to both players' wellbeing and performance.

Who may participate?

Male tennis players aged between 18 and 40 years, regularly training (at least once per week) and competing (at least once per month). They will also have to undertake a health check through the SHU medical screening questionnaire prior to being allowed to partake in the study.

Participants must not have any known: cardio, respiratory, haematological or renal disorders; blood carried infections (Hepatitis, HIV); anal haemorrhoids, fissures or bleeding.

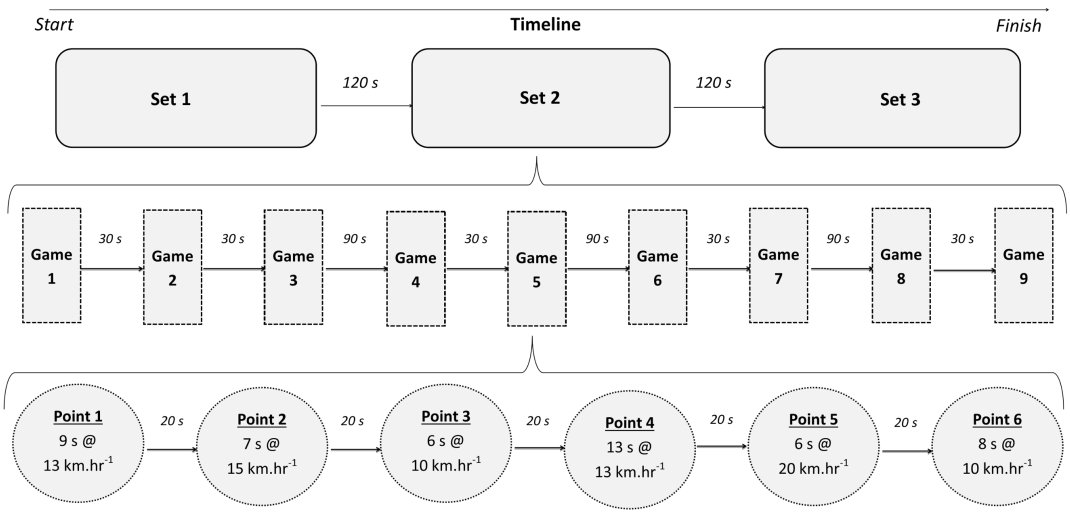
Where is it?

Exercise Physiology Lab (A001) and Environmental Chamber (A105), Sport Science Laboratories, Sheffield Hallam University, Collegiate Hall, Collegiate Crescent, Sheffield, S10 2BP

What do I have to do?

You will need to come to the labs on 6 occasions. The first visit will be around 2 hours during which some familiarisation of the protocol and the heat chamber will follow a maximal aerobic capacity test (on a treadmill), along with some basic measures such as height, weight and body fat percentage.

The remaining 4 sessions will involve running the tennis-specific treadmill protocol (see image below) in the environmental chamber at 36°C and 50% Relative Humidity, similar to conditions at the US Open. A different cooling method or control will be utilised in each session (cold-water, ice towels [as seen on the tour], ice slushy, ice slushy + ice towel combined, and a control).



What measures will be taken during the trials?

- **Body fat %:** This will be estimated using bioelectrical impedance on the In-Body machine.
- **Hydration status:** A urine sample (in privacy) will be required at the start of each testing visit to monitor hydration levels.
- **Capillary blood sampling:** Fingertip blood samples (~100 μL) will be taken at rest and certain periods throughout the testing for the measurement of blood lactate.
- **Perception of effort, thermal sensation and thermal comfort scales:** These perceptual measures will be determined before and during the testing sessions using numerical scales.
- **Core temperature:** University ethics require all participants entering the heat chamber to have their core temperature monitored for your own safety. The most common method for this is through a rectal thermometer, these are flexible with a thickness less than a pencil, pain-free and pose no health risk, though may cause slight discomfort.
- **Skin temperature:** Measured through 4 small thermocouples taped on to the skin at the chest, tricep, thigh and calf.
- **Expired air:** An online system connected to a mouthpiece or mask. This will be worn continuously during the maximal aerobic test but, intermittently throughout the tennis-specific treadmill test.

- **Sweat rate:** This will be calculated using clothed body mass and nude body mass (in privacy) pre and post-protocol to assess sweat loss and sweat absorbed in clothes. This also informs us how much you need to rehydrate after the trial.
- **Heart rate:** A heart rate strap will be worn around the chest and paired with a watch, allowing monitoring throughout the protocol.

What is expected of me?

- ❖ Attend Sheffield Hallam's laboratories for 6 sessions with at least 48 hours between each session.
- ❖ Refrain from consuming alcohol in **24 hours** prior and no caffeine for **12 hours** prior to each session.
- ❖ Prepare for each session as though a competitive match e.g. easy training in the **48 hours** prior to testing.
- ❖ Please be aware of eating habits in the 24 hours before the initial session and attempt to replicate a similar diet for each subsequent session.
- ❖ Please arrive for your testing session **well hydrated** as dehydrated participants will not be allowed in the chamber, leading to delays. Hydration is achieved through regular drinking but, please ensure 500 ml of water is consumed 1-1.5 hours before attending or, the night before if testing is early the next morning).
- ❖ Maintain **normal** diet and activity/training patterns throughout the study.
- ❖ Following each session, you should **rehydrate** by drinking little and often throughout the day, following your trial.
- ❖ If you are ill or encounter a situation where you cannot attend a session, simply phone the lead investigator. For extended illness, you may withdraw as a participant or postpone testing until fully recovered.

What are the benefits of participating?

You will learn how you cope when exercising in hot conditions and discover various ways of keeping yourself cool. It is intended for the study to be published in a scientific journal and you are entitled to a copy of the final manuscript, upon request. You will also be enabling us to identify methods of countering ill effects of the heat, helping to inform tennis governing bodies and tournaments for recommendations to their heat policies.

Are there any risks?

There is a very minor risk of infection due to the blood taking procedures, however, this risk will be minimised by using sterilised equipment at all times. As with all exercise there is a small risk of musculo-skeletal injury which will be minimised through the use of a standardised warm up. Heat exposure may lead to heat illness such as heat exhaustion; however, participants will be monitored at all times and removed from the chamber if a health risk is posed. Participants are free to withdraw at any point throughout each session if they so wish. Due to the risks associated, exclusion criteria are in place (see who may participate) and a brief medical questionnaire will be used to assess suitability to participate in the research. The lead investigator is first aid trained and the laboratories are equipped with first aid kits.

Will my information remain confidential?

Your responses and measures will be confidential. No individuals will be identifiable from any collated data or any written report of the research whether published or not. All data will be kept on a password secure computer or in a locked office on the University premises where by only the experimenter or supervisors can access.

This study relies on volunteers like yourselves and you are reminded that you are free to withdraw from the study at any time, without justification and with no subsequent prejudice.

Please feel free to ask any questions you may have and ensure you fully understand what is required of you as a participant.

10.4.4 *Study 4*

SURVEY INSTRUCTION

What is the purpose of the questionnaire?
The purpose of this questionnaire is to investigate the current cooling* strategies used during tennis matches played in hot conditions, the way that players, coaches, practitioners, and tournaments use or offer these strategies, and to explore these people's perceptions of the different methods available. The results from this study will provide a more detailed insight into cooling practice and advice in the tennis community. They will also inform advice to governing bodies and other stakeholders on future directions for heat policy at tournaments and advice given to players/coaches etc. It is hoped that the responses will guide future research into the effectiveness of various cooling methods, too.**

***Cooling: Refers to any practice that makes you feel cooler when competing in hot conditions.**
****Hot conditions: Temperatures above 25°C**

Who is doing the research and why?
The research is being conducted by Matthew Debney, a PhD student at Sheffield Hallam University; his PhD is looking at ways of reducing heat stress in tennis. This research aims to 'bridge the gap' between researchers and practitioners to find out current practice, compare this to the literature and inform future research and advice for cooling in tennis. The data will be published in a peer-reviewed scientific journal and may be used in educational presentations. Supervisors for this project are: Dr Alison Purvis (Sheffield Hallam University); Dr Alan Ruddock (Sheffield Hallam University); and Dr Ciara O'Hagan (Institute of Technology Carlow).

Legal basis for research for studies
The University undertakes research as part of its function for the community under its legal status. Data protection allows us to use personal data for research with appropriate safeguards in place under the legal basis of public tasks that are in the public interest. A full statement of your rights can be found at https://www.shu.ac.uk/about-this-website/privacy-policy/privacy-notices/privacy-notice-for-research. However, all University research is reviewed to ensure that participants are treated appropriately and their rights respected. This study was approved by University Research Ethics Committee with Converis number ER15495719. Further information at https://www.shu.ac.uk/research/ethics-integrity-and-practice

You should contact the Data Protection Officer if:	**You should contact the Head of Research Ethics (Professor Ann Macaskill) if:**
· you have a query about how your data is used by the University · you would like to report a data security breach (e.g. if you think your personal data has been lost or disclosed inappropriately) · you would like to complain about how the University has used your personal data DPO@shu.ac.uk	· you have concerns with how the research was undertaken or how you were treated a.macaskill@shu.ac.uk

Postal address: Sheffield Hallam University, Howard Street, Sheffield S1 1WBT Telephone: 0114 225 5555

Will my taking part in this study be kept confidential and will the data be secure?
The data from the questionnaire will be password protected and only accessible to the research team. Your email address will be asked for; you will only be contacted if the research team feel they need to clarify a point you have made and/or you have agreed to fill out the questionnaire again for reliability purposes.

What do I need to do?
You will be asked a number of questions about which cooling practices you might have used previously (and how, if relevant), and your perceptions towards them. Please be assured that your responses will not be linked to you in any way in any future publication or presentation of the data; only the research team have access to the raw data. The questionnaire should take you 20-30 minutes to complete.

10.5 Study 4 Survey

SURVEY INSTRUCTION

What is the purpose of the questionnaire?

The purpose of this questionnaire is to investigate the current cooling* strategies used during tennis matches played in hot conditions**, the way that players, coaches, practitioners, and tournaments use or offer these strategies, and to explore these people's perceptions of the different methods available. The results from this study will provide a more detailed insight into cooling practice and advice in the tennis community. They will also inform advice to governing bodies and other stakeholders on future directions for heat policy at tournaments and advice given to players/coaches etc. It is hoped that the responses will guide future research into the effectiveness of various cooling methods, too.

*Cooling: Refers to any practice that makes you feel cooler when competing in hot conditions.

**Hot conditions: Temperatures above 25°C

Who is doing the research and why?

The research is being conducted by Matthew Debney, a PhD student at Sheffield Hallam University; his PhD is looking at ways of reducing heat stress in tennis. This research aims to 'bridge the gap' between researchers and practitioners to find out current practice, compare this to the literature and inform future research and advice for cooling in tennis. The data will be published in a peer-reviewed scientific journal and may be used in educational presentations. Supervisors for this project are: Dr Alison Purvis (Sheffield Hallam University); Dr Alan Ruddock (Sheffield Hallam University); and Dr Ciara O'Hagan (Institute of Technology Carlow).

Legal basis for research for studies

The University undertakes research as part of its function for the community under its legal status. Data protection allows us to use personal data for research with appropriate safeguards in place under the legal basis of public tasks that are in the public interest. A full statement of your rights can be found at https://www.shu.ac.uk/aboutthis-website/privacy-policy/privacy-notices/privacy-notice-for-research. However, all University research is reviewed to ensure that participants are treated appropriately and their rights respected. This study was approved by University Research Ethics Committee with Converis number ER15495719. Further information at https://www.shu.ac.uk/research/ethics-integrity-and-practice

You should contact the Data Protection Officer if:

· you have a query about how your data is used by the University

· you would like to report a data security breach (e.g. if you think your personal data has been lost or disclosed inappropriately)

· you would like to complain about how the University has used your personal data DPO@shu.ac.uk

You should contact the Head of Research Ethics (Professor Ann Macaskill) if:

· you have concerns with how the research was undertaken or how you were treated

a.macaskill@shu.ac.uk

Postal address: Sheffield Hallam University, Howard Street, Sheffield S1 1WBT Telephone: 0114 225 5555

Will my taking part in this study be kept confidential and will the data be secure?

The data from the questionnaire will be password protected and only accessible to the research team. Your email address will be asked for; you will only be contacted if the research team feel they need to clarify a point you have made and/or you have agreed to fill out the questionnaire again for reliability purposes.

What do I need to do?

You will be asked a number of questions about which cooling practices you might have used previously (and how, if relevant), and your perceptions towards them. Please be assured that your responses will not be linked to you in any way in any future publication or presentation of the data; only the research team have access to the raw data.

The questionnaire should take you 20-30 minutes to complete.
Informed Consent
Welcome to the research questionnaire!
Your participation in this research is voluntary. You have the right to withdraw at any point whilst completing the questionnaire, for
any reason, and without any prejudice. If you would like to withdraw or you have any queries, please contact the Principal Investigator by e-mailing m.debney@shu.ac.uk. If your browser crashes or you run out of time, you will be able to start from where
you finished by clicking the link again. THIS IS ONLY POSSIBLE IF YOU USE THE SAME DEVICE AND BROWSER, AND HAVE NOT
CLEARED YOUR COOKIES.
By clicking the button below, you acknowledge the information provided above.
Please note this questionnaire has been optimised as much as possible for use on a mobile device, however, it will be best displayed on a laptop or desktop computer.
I consent, begin the questionnaire
I do not consent, I do not wish to participate
Player
Tennis Coach
Science Practitioner (performance scientist/physiologist/S&C coach/physio etc)
Medical Practitioner
Under 18
18 - 24
25 - 34
35 - 44
45 - 54
Male
Female
Email Address
Please indicate your primary role
PLAYER CHARACTERISTICS
What is your age?
What is your nationality?
Where was your main residence up to the age of 16?
e.g. Lived in England but trained in Spain for 2 years; answer would be England
Where is your current residence?
What is your sex?
Please indicate which levels of male competition you have competed at within the last 2 years. Select all that apply
Olympics ITF 25s+
Davis Cup ITF 15s
Grand Slam ITF Juniors
Junior Grand Slam National Competition
Masters 1000 Regional or County Competition
ATP 500 Junior Regional or County Competition
ATP 250 Other (please specify)
Challenger Tour
Yes
No
Please indicate which levels of female competition you have competed at within the last 2 years. Select all that apply
Olympics WTA 125k
Fed Cup ITF 25s+
Grand Slam ITF 15s
Junior Grand Slam ITF Juniors
WTA Premier Mandatory National Competition
WTA Premier 5 Regional or County Competition
WTA Premier Junior Regional or County Competition
WTA International Other (please specify)
What are your current rankings for doubles and singles?
Complete the boxes which apply to your highest ranking level e.g. Do not fill in ITF and WTA, just WTA.
If not sure, please estimate as precisely as you can. Or leave blank if unknown.
National ITF ATP WTA
Junior singles
Junior doubles
Do you also have senior rankings?
What are your current rankings for doubles and singles?
Complete the boxes which apply to your highest ranking level e.g. Do not fill in ITF and WTA, just WTA.
If not sure, please estimate as precisely as you can. Or leave blank if unknown.
National ITF ATP WTA
Senior singles
Senior doubles
PLAYER COOLING USES AND VALUES
From a broad perspective on your ability to compete at your very best in hot conditions.
*Cooling: Refers to an attempt to cool down when competing in hot conditions. Cooling could be anything from cold drinks at fridge
temperature, to ice towels, fans, or using an umbrella for shade.
Do you think cooling is...
Extremely useful Moderately useful Slightly useful
Neither useful nor

useless Slightly useless Moderately useless Extremely useless
Where and from whom have you sought or received advice about cooling? Please tick all that apply.
Never had or sought any advice Tournament official
Read about it myself Tour supervisor
Fellow Players Commercial supplier
Personal coach Academic
Another coach Parents
Team captain Home nation institute practitioner
Yes
No
Under 18
18 - 24
25 - 34
35 - 44
45 - 54
Male(s)
Female(s)
Male(s) and Female(s)
NGB medical staff Other (please specify)
Tour medical staff
The following questions will find out which methods you have used, asking more detail for those that you have.
We are trying to identify the specifics of how these methods are used when playing tennis in hot conditions. If the options available
do not a suitable answer to how you use the method, please either choose the closest answer, or provide specific details in the text
box provided.
SUPPORT STAFF CHARACTERISTICS
When answering the following questions (and the rest of the questionnaire), please consider the player or group of players that you
work with the most.
Have you ever competed as a player?
What age are the player(s) you work with?
What is their nationality?
Where is your current training base?
What is the sex of your player or players?
Please indicate which levels of male competition you have coached/supported players at within the last 2 years. Select all that apply
Olympics Challenger Tour
Davis Cup ITF 25s+
Grand Slam ITF 15s
Junior Grand Slam ITF Juniors
Masters 1000 Regional or County Competition
ATP 500 Junior Regional or County Competition
ATP 250 Other (please specify)
Please indicate which levels of female competition you have coached/supported players at within the last 2 years. Select all that
Yes
No
apply
Olympics WTA 125k
Fed Cup ITF 25s+
Grand Slam ITF 15s
Junior Grand Slam ITF Juniors
WTA Premier Mandatory Regional or County Competition
WTA Premier 5 Junior Regional or County Competition
WTA Premier Other (please specify)
WTA International
What are the current junior rankings (for doubles and singles) for the player you work with the most, or your highest ranked player if
you work with a number of players equally.
Complete the boxes which apply to their highest ranking level e.g. Do not fill in ITF and WTA, just WTA.
If not sure, please estimate as precisely as you can. Or leave blank if unknown.
National ITF ATP WTA
Junior singles
Junior doubles
Do they also have senior rankings?
What are the current senior rankings (for doubles and singles) for the player you work with the most, or your highest ranked player if
you work with a number of players equally.
Complete the boxes which apply to their highest ranking level e.g. Do not fill in ITF and WTA, just WTA.
If not sure, please estimate as precisely as you can. Or leave blank if unknown.
National ITF ATP WTA
Senior singles
Senior doubles
SUPPORT STAFF COOLING USES AND VALUES
Answer the following block of questions from a broad perspective and consider how you enable your players to compete at their
best in hot conditions.

*Cooling: Refers to an attempt to cool down when competing in hot conditions. Cooling could be anything from cold drinks at fridge
temperature, to ice towels, fans, or using an umbrella for shade.
Do you think cooling is...
Extremely useful Moderately useful Slightly useful
Neither useful nor
useless Slightly useless Moderately useless Extremely useless
Where and from whom have you sought or received advice about cooling? Please tick all that apply.
Never had or sought any advice Tour supervisor
Read about it myself Commercial supplier
Players Academic
Coaches Parents
Team captain Home nation institute practitioner
NGB medical staff Own research
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Tour medical staff Other (please specify)
Tournament official
The following questions will find out which methods you have used, asking more detail for those that you have.
We are trying to identify the specifics of how these methods are used when playing tennis in hot conditions. If the options available
do not provide a suitable answer, please either choose the closest answer, or provide specific details in the text box provided.
PLAYER ICE TOWELS
ICE TOWELS
Ice towels are ice wrapped in a towel (see picture), placed around the neck or on the lap, possibly used at the same time as cold
damp towels.
Do you use ice towels during competitive matchplay in hot conditions?
In which conditions have you used ice towels?
When do you use ice towels during a match? (please select all that apply)
When do you start using ice towels?
When you are too hot (reactive)
Before you get too hot (preventative)
Ice towel around the neck
Ice towel around neck and cold wet towel on lap
Ice towel around neck and cold wet towel on head
Ice towel around neck and cold wet towels on lap and head
Other (please specify)
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Do you start using ice towels:
How do you use ice towels?
Do you use ice towels in combination with another cooling method?
If yes, please select all that apply.
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF ICE TOWELS
ICE TOWELS
Ice towels are ice wrapped in a towel (see picture), placed around the neck or on the lap, possibly used at the same time as cold
damp towels.
Do you advise using ice towels during competitive matchplay in hot conditions?
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends

The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
When you are too hot (reactive)
Before you get too hot (preventative)
Ice towel around the neck
Ice towel around neck and cold wet towel on lap
Ice towel around neck and cold wet towel on head
Ice towel around neck and cold wet towels on lap and head
Other (please specify)
Yes
No
In which conditions would you advise using ice towels?
When would you advise using ice towels during a match? (please select all that apply)
When would you advise to start using ice towels?
Would you advise to start using ice towels:
How do you advise to use ice towels?
Do you advise to use ice towels in combination with another cooling method?
If yes, please select all that apply.
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
PLAYER ICE SLURRY
ICE SLURRY
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
When you are too hot (reactive)
Before you get too hot (preventative)
Volume
Based on body mass
Based on sweat rate
Whatever I feel is necessary
0 - 49 ml
50 - 99 ml
This section is about your use of ice slurries. Ice slurries are a drink with blended ice (see picture)
Do you drink ice slurries during competitive matchplay in hot conditions?
In which conditions have you drank ice slurries?
When do you consume ice slurry during a match? (please select all that apply)
When do you start drinking ice slurries?
Do you start drinking ice slurry:
How do you decide how much you should consume?
How much ice slurry do you consume at each change of ends?
100 - 149 ml
150 - 199 ml
200 - 249 ml
> 250 ml
0 - 0.4 g/kg
0.5 - 0.9 g/kg
1 - 1.4 g/kg
1.5 - 1.9 g/kg
2 - 2.4 g/kg
> 2.5 g/kg
0 - 5%
6 - 10%
11 - 15%
16 - 20%
21 - 25%
Yes
No

Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
In relation to body mass, how much ice slurry do you consume at each change of ends?
What percentage of sweat rate do you consume at each change of ends?
Do you use this method in combination with another?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF ICE SLURRY
ICE SLURRY
This section is about the use of ice slurries. Ice slurries are a drink with blended ice (see picture)
Do you advise drinking ice slurries during competitive matchplay in hot conditions?
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
When you are too hot (reactive)
Before you get too hot (preventative)
Volume
Based on body mass
Based on sweat rate
Whatever they feel is necessary
I don't advise
0 - 49 ml
50 - 99 ml
100 - 149 ml
150 - 199 ml
200 - 249 ml
> 250 ml
0 - 0.4 g/kg
0.5 - 0.9 g/kg
1 - 1.4 g/kg
1.5 - 1.9 g/kg
2 - 2.4 g/kg
In which conditions would you advise drinking ice slurries?
When would you advise to drink ice slurries during a match? (please select all that apply)
When would you advise to start drinking ice slurries?
Do you advise to start drinking ice slurry:
How do you advise how much the player should consume?
How much ice slurry would you advise to consume at each change of ends?
How much ice slurry would you advise to consume at each change of ends?
> 2.5 g/kg
0 - 5%
6 - 10%
11 - 15%
16 - 20%
21 - 25%
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
What percentage of sweat rate would you advise to consume at each change of ends?
Do you use advise using this method in combination with another?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
PLAYER ICE VEST
ICE VEST
This section is about your use of ice vests. These are garments with frozen sections (see picture)

Do you use ice vests during competitive matchplay in hot conditions?
In which conditions do you use an ice vest?
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Yes
No
When do you drink ice slurries during a match? (please select all that apply)
When do you start using an ice vest?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF ICE VEST
ICE VEST
This section is about the use of ice vests. These are garments with frozen sections (see picture)
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Yes
No
Do you advise using ice vests during competitive matchplay in hot conditions?
In which conditions do you advise using an ice vest?
When do you advise using ice vests during a match? (please select all that apply)
When do you advise to start using an ice vest?
Do you advise to use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Fans Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
PLAYER FANS
FANS
This section is about your use of fans (see picture) during competitive matchplay
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
In front of you
To the side of you

Behind you
No specific placement
Yes
No
Do you use fans during competitive matchplay in hot conditions?
In which conditions have you used a fan?
When do you use ice vests during a match? (please select all that apply)
When do you start using fans?
Where do you place the fan when you're sitting down?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF FANS
FANS
This section is about the use of fans (see picture) during competitive matchplay
Do you advise using fans during competitive matchplay in hot conditions?
In which conditions have you advised using a fan?
When do you advise to use fans during a match? (please select all that apply)
When do you advise to start using fans?
In front of them
To the side of them
Behind them
No specific placement
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
Where do you advise the fan be placed when the player is sitting down?
Do you advise to use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Water spray Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
PLAYER WATER SPRAY
WATER SPRAY
This section is about the use of a water spray during competitive matchplay. This would most likely be on any exposed skin.
Do you use a water spray during competitive matchplay in hot conditions?
In which conditions have you used a water spray?
When do you use a water spray during a match? (please select all that apply)
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Yes
No

Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
When do you start using a water spray?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF WATER SPRAY
WATER SPRAY
This section is about the use of a water spray during competitive matchplay. This would most likely be on any exposed skin.
Do you advise using a water spray during competitive matchplay in hot conditions?
In which conditions have you advised using a water spray?
When do you advise using a water spray during a match? (please select all that apply)
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
When do you advise to start using a water spray?
Do you advise to use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Cold drinks (fridge) Accepting the extended 10 minute break
Seeking shade Other (please specify)
PLAYER COLD DRINKS
COLD DRINKS FOR COOLING
This section is about your use of cold drinks as a deliberate attempt to cool you down, in addition to drinking for hydration. Cold
drinks might be water, an isotonic drink or any other drink that is fridge temperature.
Do you use cold drinks to cool during competitive matchplay in hot conditions?
In which conditions have you used cold drinks?
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Volume
Based on body mass
Based on sweat rate
Whatever I feel is necessary
0 - 49 ml
50 - 99 ml
100 - 149 ml
150 - 199 ml
200 - 249 ml
> 250 ml
0 - 0.4 g/kg
0.5 - 0.9 g/kg
1 - 1.4 g/kg
1.5 - 1.9 g/kg

2 - 2.4 g/kg
> 2.5 g/kg
0 - 5%
6 - 10%
11 - 15%
16 - 20%
21 - 25%
When do you consume cold drinks during a match? (please select all that apply)
When do you start drinking cold drinks?
How do you decide how much you should consume?
How much do you consume at each change of ends?
How much do you consume at each change of ends?
What percentage of sweat rate do you consume at each change of ends?
Do you use this method in combination with another cooling method?
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Seeking shade Other (please specify)
SUPPORT STAFF COLD DRINKS
COLD DRINKS FOR COOLING
This section is about the use of cold drinks as a deliberate attempt to cool down, in addition to drinking for hydration. Cold drinks
might be water, an isotonic drink or any other drink that is fridge temperature.
Do you advise using cold drinks to cool during competitive matchplay in hot conditions?
In which conditions have you advised using cold drinks?
When do you advise to consume cold drinks during a match? (please select all that apply)
When do you advise to start drinking cold drinks?
In the middle of the match
Towards the end of the match
Volume
Based on body mass
Based on sweat rate
Whatever they feel is necessary
I don't advise
0 - 49 ml
50 - 99 ml
100 - 149 ml
150 - 199 ml
200 - 249 ml
> 250 ml
0 - 0.4 g/kg
0.5 - 0.9 g/kg
1 - 1.4 g/kg
1.5 - 1.9 g/kg
2 - 2.4 g/kg
> 2.5 g/kg
0 - 5%
6 - 10%
11 - 15%
16 - 20%
21 - 25%
Yes
No
How do you advise how much the player should consume?
How much would you advise to consume at each change of ends?
How much would you advise to consume at each change of ends?
What percentage of sweat rate would you advise to consume at each change of ends?
Do you advise to use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself

Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Seeking shade Other (please specify)

PLAYER SEEKING SHADE

Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Between points
Between games (not changing ends)
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Under an umbrella or shelter (e.g. attached to the chair)
Wearing a cap/hat
Shade created by court permanent structures, stadium or stands
Yes

SEEKING SHADE

This section is about you seeking shade (no direct sunlight) on the court during matchplay.
Do you seek shade during competitive matchplay in hot conditions?
In which conditions would you seek shade ?
When would you seek shade during a match? (please select all that apply)
When in the match do you start seeking shade?
Where or how do you seek shade?
Do you use this method in combination with another cooling method?

No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Between points
Between games (not changing ends)
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match

If yes, please select all that apply.

Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)

SUPPORT STAFF SEEKING SHADE

SEEKING SHADE

This section is about seeking shade (no direct sunlight) on the court during matchplay.
Do you advise seeking shade during competitive matchplay in hot conditions?
In which conditions would you advise seeking shade ?
When would you advise seeking shade during a match? (please select all that apply)
When in the match do you advise to start seeking shade?

The start of the match
In the middle of the match
Towards the end of the match
Under an umbrella or shelter (e.g. attached to the chair)
Wearing a cap/hat
Shade created by court permanent structures, stadium or stands
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both

Where or how do you advise to seek shade?
Do you advise using this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Cold water immersion (bath)
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
PLAYER COLD WATER IMMERSION AND SHOWERS
COLD WATER IMMERSION AND SHOWERS (CWI)
This section is about you immersing yourself in cold-water or having a cold shower during matchplay (see example picture). It could
just be cold-water or could include some ice as well.
Do you use cold-water immersion or showers (CWI) during competitive matchplay in hot conditions?
In which conditions would you use CWI?
Before the match
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
On court
In the changing / locker rooms
Somewhere else (please specify)
0-5 mins
6-10 mins
11-15 mins
16-20 mins
Definitely yes
Probably yes
Might or might not
Probably not
Definitely not
Yes
No
When do you use CWI during a match? (please select all that apply)
When do you start using CWI?
Where do you use CWI?
How long do you stay immersed for?
Do you put ice in the water with you?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Before the match
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
On court
In the changing / locker rooms
Cold drinks (fridge) Other (please specify)
SUPPORT STAFF COLD WATER IMMERSION AND SHOWERS
COLD WATER IMMERSION AND SHOWERS (CWI)
This section is about immersing in cold-water or having a cold shower during matchplay (see example picture). It could just be cold
water or could include some ice as well.
Do you advise cold-water immersion or showers (CWI) during competitive matchplay in hot conditions?

In which conditions would you advise using CWI?
When do you advise using CWI during a match? (please select all that apply)
When do you advise to start using CWI?
Where do you advise to use CWI?
Somewhere else (please specify)
0-5 mins
6-10 mins
11-15 mins
16-20 mins
Definitely yes
Probably yes
Might or might not
Probably not
Definitely not
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
How long do you advise staying immersed for?
Do you advise putting ice in the water (if a bath)?
Do you advise using this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Pouring water on yourself
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
PLAYER WATER POURING
POURING WATER ON YOURSELF
This is as simple as just pouring cold-water over you to actively cool yourself (see picture).
Do you pour water on yourself during competitive matchplay in hot conditions?
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible
Before the match
The start of the match
In the middle of the match
Towards the end of the match
Over head
Upper body only
Lower body only
Whole body
Yes
No
In which conditions would you pour water over yourself?
How often do you pour water over yourself during a match? (please select all that apply)
When do you start pouring water over yourself?
How do you pour water over yourself?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
SUPPORT STAFF WATER POURING
POURING WATER ON YOURSELF
This is as simple as just pouring cold-water over you to actively cool yourself (see picture).
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every change of ends
Every other change of ends
The end of a set
During the extended break
When feeling particularly hot
Whenever possible

Before the match
The start of the match
In the middle of the match
Towards the end of the match
Over head
Upper body only
Lower body only
Whole body
Yes
No
Do you advise players pouring water on themselves during competitive matchplay in hot conditions?
In which conditions would you advise pouring water over yourself?
How often do you advise pouring water over yourself during a match? (please select all that apply)
When do you advise to start pouring water over yourself?
How do you advise to pour water over yourself?
Do you advise using this method in combination with another cooling method?
If yes, please select all that apply.
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Top half (T-shirt etc)
Bottom half (Shorts/trousers/leggings etc)
Accessories (sweat bands/caps etc)
Clothing material (cotton/polyester etc)
Other (please specify)
End of set 1
End of set 2
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Clothing choices
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
PLAYER CLOTHING CHOICES
CLOTHING CHOICES
This section is about whether you make different clothing choices or changing clothes during matches in hot conditions (>25°C)
compared to a temperature of around 20°C / 68°F.
Do you make different clothing choices during competitive matchplay in hot conditions?
In which conditions have you made different clothing choices?
What do you wear differently to usual when competing in hot conditions?
When do you change into fresh clothes during a match in hot conditions? (please select all that apply)
End of set 3
End of set 4
I do not change
When needed to stay comfortable
Other (please specify)
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
SUPPORT STAFF CLOTHING CHOICES
CLOTHING CHOICES
This section is about whether you make different clothing choices or changing clothes during matches in hot conditions (>25°C)
compared to a temperature of around 20°C / 68°F.
Do you advise different clothing choices during competitive matchplay in hot conditions?
In which conditions have you advised making different clothing choices?
Top half (T-shirt etc)
Bottom half (Shorts/trousers/leggings etc)
Accessories (sweat bands/caps etc)
Clothing material (cotton/polyester etc)
Other (please specify)

End of set 1
End of set 2
End of set 3
End of set 4
I would not advise changing
When needed to stay comfortable
Other (please specify)
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
What do you advise wearing differently to usual when competing in hot conditions?
When do you advise to change into fresh clothes during a match in hot conditions? (please select all that apply)
Do you advise using this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Taking longer (than 25 s) between points
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
PLAYER EXTENDED BETWEEN-POINT REST
PLAYER EXTENDED BETWEEN-POINT REST
This section is about you taking a longer rest, between points, than the 25 s stipulated in the rules. This could be before or after the
introduction of a shot clock, if that applies at your level.
Do you take a longer between-point rest during competitive matchplay in hot conditions?
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every point
After a long rally
When feeling particularly hot
Whenever possible
Tactically to slow down the opponent
Other (please specify)
The start of the match
In the middle of the match
Towards the end of the match
Yes
No
Sometimes
There is no shot clock at my competitions
Yes
No
Yes
No
In which conditions would you increase your between point rest length?
How often do you increase your between-point rest length? (please select all that apply)
When in the match do you start taking more time between points?
Are you still able to take longer between breaks since the introduction of the shot clock?
Do you feel umpires are more lenient with time violations in hot conditions?
Do you use this method in combination with another cooling method?
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
SUPPORT STAFF EXTENDED BETWEEN-POINT REST
PLAYER EXTENDED BETWEEN-POINT REST
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Every point
After a long rally
When feeling particularly hot
Whenever possible
Tactically to slow down the opponent
Other (please specify)
The start of the match
In the middle of the match
Towards the end of the match
Yes

No
Sometimes
There is no shot clock at my competitions
Yes
No
This section is about taking a longer rest, between points, than the 25 s stipulated in the rules. This could be before or after the
introduction of a shot clock, if that applies at your level.
Do you advise taking a longer between-point rest during competitive matchplay in hot conditions?
In which conditions would you advise increasing your between point rest length?
How often would you advise increasing your between-point rest length? (please select all that apply)
When in the match do you advise to start taking more time between points?
Are players still able to take longer between breaks since the introduction of the shot clock?
Do you feel umpires are more lenient with time violations in hot conditions?
Do you advise using this method in combination with another cooling method?
Yes
No
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Stay on court
The changing/locker rooms
The court building
The closest convenient place to cool down
Other (please specify)
If yes, please select all that apply.
Ice towels Seeking shade
Ice slurry / slushy Cold water immersion (bath)
Ice vest Pouring water on yourself
Fans Clothing choices
Water spray Accepting the extended 10 minute break
Cold drinks (fridge) Other (please specify)
PLAYER 10 MINUTE EXTENDED BREAK
10 MINUTE EXTENDED BREAK
This section is about the 10 minute extended break that might be offered after set 2, 3 or 4 depending on the tournament and their
governing heat policy.
Image result for 10 minute break
Do you accept the 10 minute extended break during competitive matchplay in hot conditions?
In which conditions would you take up the extended break?
Where do you go during the 10 minute break?
Do you use any cooling methods during this period? (including air conditioning)
Yes
No
Ice towels
Ice slurry / slushy
Fans
Water spray
Cold drinks
Seeking shade
Cold water immersion (bath)
Pouring water on yourself
Air conditioning
Other (please specify)
Never used and never will
Have not used, but would consider in the future
Have used previously but not anymore
Use currently (within the last 2 years)
Hot & dry (e.g. desert conditions; Australian Open)
Hot & humid (e.g. sub-tropical conditions; US Open)
Both
Stay on court
The changing/locker rooms
The court building
The closest convenient place to cool down
Other (please specify)
Which cooling method do you use? (please tick all that apply)
SUPPORT STAFF 10 MINUTE EXTENDED BREAK
10 MINUTE EXTENDED BREAK
This section is about the 10 minute extended break that might be offered after set 2, 3 or 4 depending on the tournament and their
governing heat policy.
Image result for 10 minute break
Do you advise accepting the 10 minute extended break during competitive matchplay in hot conditions?
In which conditions would you advise taking up the extended break?

Where do you advise to go during the 10 minute break?
Yes
No
Ice towels
Ice slurry / slushy
Fans
Water spray
Cold drinks
Seeking shade
Cold water immersion (bath)
Pouring water on yourself
Air conditioning
Other (please specify)
Yes
No
Yes
No
Do you advise using any cooling methods during this period? (including air conditioning)
Which cooling method do you use? (please tick all that apply)
PAUSE 1
Thank you very much for taking part in this questionnaire up to this point, your participation has helped us understand how players
cool down when competing in the heat!
The next section explores your perceptions of cooling containing a number of statements which you rate on a scale from strongly
agree to strongly disagree. This should take no more than 5 minutes.
Your answers to these statements will help improve and tailor future advice to tennis players on cooling interventions.
Are you willing to continue to the next section on your perceptions of cooling?
Would you be willing to answer two more questions on benefits and drawbacks of cooling before finishing?
PLAYER (USER) PERCEPTIONS
Perceptions
Please give an indication of how you feel about each of the following statements when you think about cooling (rather than no
cooling) during a match in hot conditions. Everyone feels differently about cooling so there are no right or wrong answers, we are
interested in your opinions. Do not spend too long on any one statement and give the response that best describes your feelings.
(All are rated from strongly agree to strongly disagree)
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
I understand how cooling increases my
ability to compete in hot conditions
I am able to last longer before tiring
when using cooling
When cooling, I can have more
negative thoughts on court
Cooling decreases my ability to hit the
ball where I want
My body is still fatigued when I am due
to play my next match after using
cooling
I typically try out cooling methods
during training prior to using in a match
When I use cooling methods, my heart
rate is higher
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
I tire more quickly when I use cooling
I have been made aware of strategies
to counter the effects of the heat
I have not received any advice about
ways to keep cool when competing in
hot conditions
I feel cooling is beneficial and would
use it again
Feeling hot is more uncomfortable for
me when I am using cooling
I feel more refreshed after change of
ends due to cooling
I don't think that cooling helps me in
matches and am not interested in using
it again
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
My accuracy improves when I use
cooling
I feel cooler whilst playing when using
cooling methods

I don't sweat as much when I am using cooling
I need more time to recover in between points because of cooling
When I use cooling, I do not feel as quick around the court
I feel I move faster around the court when I cool myself down
I am unable to generate as much power when using cooling
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
I do not practice cooling methods before using them during a match
I do not know how cooling is beneficial to me when playing in the heat
When cooling, I don't recover as quickly during change of ends
Cooling makes me feel hotter whilst playing
I feel like I sweat more when using cooling
I am able to maintain a positive attitude when using cooling
I feel more physically ready for my next match after using cooling
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
I feel like cooling reduces my heart rate
When I use cooling strategies I can hit the ball harder
I find I recover quicker between-points when I am cooling
I find cooling means I am more comfortable with feeling hot

SUPPORT STAFF (USER) PERCEPTIONS

Perceptions

Please give an indication of how you feel about each of the following statements when you think about cooling (rather than no cooling) during a match in hot conditions. Everyone feels differently about cooling so there are no right or wrong answers, we are interested in your opinions. Do not spend too long on any one statement and give the response that best describes your feelings.
(All are rated from strongly agree to strongly disagree)

Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
Players are less comfortable with the sensation of feeling hot when they are using cooling
Cooling decreases my player's ability to hit the ball where they want
I find cooling means players are more comfortable with feeling hot
I feel players move faster around the court when they cool themselves down
When players use cooling strategies they can hit the ball harder
I feel like cooling reduces my players' heart rates
My players' bodies are still fatigued when they are due to play their next match after using cooling
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
I understand how cooling increases my player's ability to compete in hot conditions
Players need more time to recover in between points when cooling
I feel my players sweat more when using cooling
Players are unable to generate as much power when using cooling
I do not practice cooling methods with my players before using them during a match
My players don't sweat as much when using cooling
I feel cooling is beneficial and would advise using it again

Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
Cooling makes players feel hotter
whilst playing
When cooling, players can have more
negative thoughts on court
When cooling, players don't recover as
quickly during change of ends
Players tire more quickly when I use
cooling
My player's accuracy improves when
using cooling
Players are able to last longer before
tiring when using cooling
I find players recover quicker betweenpoints
when they are cooling
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
Players report feeling cooler whilst
playing when using cooling methods
I do not know how cooling is beneficial
for my player when playing in the heat
I have not given any advice about ways
to keep cool when competing in hot
conditions
When players use cooling, I do not feel
they are as quick around the court
Players are able to maintain a positive
attitude when using cooling
I don't think that cooling helps my
players in matches and am not
interested in advising its use again
I typically try out cooling methods with
my players during training prior to
using in a match
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
When my player(s) use cooling
methods, their heart rate is higher
Players feel more physically ready for
their next match after using cooling
I have made my players aware of
strategies to counter the effects of the
heat
Players look and feel more refreshed
after change of ends due to cooling

PLAYER (NON-USER) PERCEPTIONS

Perceptions

Please give an indication of how you feel about each of the following statements when you think about cooling. Everyone feels
differently about cooling so there are no right or wrong answers, we are interested in your opinions. Do not spend too long on any
one statement and give the response that best describes your feelings.
(All rated from strongly agree to strongly disagree)

Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
I don't want my opponent to think I am
weak because I use cooling
My support staff do not think I should
use cooling
Cooling requires specialist equipment,
which I do not have
I think I'd feel better and be more likely
to win matches if I used cooling
strategies
Cooling is quite simple and straight
forward to use
I think that cooling is too complicated,
and is not worth the effort
Cooling doesn't affect how my
opponent thinks I am coping physically
Strongly agree Somewhat agree
Neither agree nor
disagree Somewhat disagree Strongly disagree
The hot conditions don't make me feel
any hotter, I play the same as any
other tournament
I am aware that other players cool
themselves when playing
I have been made aware of strategies

to counter the effects of the heat
When playing in the heat, I feel hotter which can affect my game
Cooling won't affect my ability to cope in the heat or my performance
I do not know how cooling is beneficial to me when playing in the heat
I would be willing to spend time to see if cooling is beneficial for me
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
I understand how cooling increases my ability to compete in hot conditions
The equipment I need for cooling is accessible to me, if I want it
I have not heard of other players using cooling methods
I have heard positive things about cooling from my support staff
I do not have time to try out different cooling methods
I have not received any advice about ways to keep cool when competing in hot conditions

SUPPORT STAFF (NON-USER) PERCEPTIONS

Perceptions

Please give an indication of how you feel about each of the following statements when you think about cooling. Everyone feels differently about cooling so there are no right or wrong answers, we are interested in your opinions. Do not spend too long on any

Yes
No

one statement and give the response that best describes your feelings.
(All rated from strongly agree to strongly disagree)

Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
Cooling is quite simple and straight forward to use
I understand how cooling increases my players' ability to compete in hot conditions
Cooling requires specialist equipment, which we cannot offer to players
I have not heard of other players receiving advice about cooling methods
I have heard positive things about cooling from my colleagues or support network
I think that cooling is too complicated, and is not worth the effort
The hot conditions don't make my players feel any hotter, I play the same as any other tournament
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
Cooling doesn't affect how an opponent thinks my player is coping physically
I do not have time to try out different cooling methods with my players
I have made my player(s) aware of strategies to counter the effects of the heat
I am aware that other players are advised to cool themselves when playing
I have not given any advice about ways to keep cool when competing in hot conditions
I would be willing to spend time to see if cooling is beneficial for my players
When playing in the heat, players feel hotter which can affect their game
Strongly agree Somewhat agree
Neither agree nor disagree Somewhat disagree Strongly disagree
I don't want my player's opponent to think they are weak because they use cooling
I think my players would feel better and

be more likely to win matches if I used
cooling strategies
The equipment needed for cooling is
accessible to my players, if they want it
I do not know how cooling is beneficial
to my players when playing in the heat
My colleagues or support network do
not think I should advise my players to
use cooling
Cooling won't affect my players' ability
to cope in the heat or their
performance

PAUSE 2

Thank you very much for telling us your perceptions of cooling. This will help us tailor future guidance and advice for cooling during
tennis in the heat.

The final section offers you an opportunity to comment on your opinion of the main benefits and drawbacks of cooling, in general.

This will provide more clarity on the perceptions of cooling, again improving future advice to players, coaches etc.

Are you willing to answer two more questions on benefits and drawbacks of cooling?

Yes
No
Yes
No

BENEFITS AND DRAWBACKS

In your opinion and experience, what do you consider the main benefits of cooling during tennis in hot conditions? Please be as
specific or as broad as you wish to be. If you think there is no benefit then say so; if you think there are a lot of benefits then please
also say so.

What do you consider the main drawbacks of cooling during tennis in hot conditions? Please be as specific or as broad as you wish
to be.

CONTACT AND RELIABILITY

Are you willing to be contacted by the research team if they need to clarify something you have said in this survey?

Would you be willing to complete this survey again, at a later date for us to assess its reliability?

Thank you very much for your time. Please move on to the next page to finish the questionnaire.