The Effect of Environmental Temperature on Health Outcomes and Match Play Characteristics in Professional Tennis Matchplay

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Certificate of authorship and originality of thesis

I, Matthew Smith declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Health at the University of Technology Sydney. This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution. This research is supported by the Australian Government Research Training Program.

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It’s been real -
Cheers

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Publications resulting from this thesis

Smith MT, Reid M, Kovalchik S, Woods TO, Duffield R. Heat stress incident prevalence and tennis matchplay performance at the Australian Open. *Journal of Science and Medicine in Sport*. 2018;21(5):467-72.

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Abbreviations, Symbols and Subunits

ACSM	American College of Sports Medicine
ATP	Association of Tennis Professionals
AO	Australian Open
BoM	Bureau of Meteorology
EHP	Extreme Heat Policy
GLM	Generalised Linear Model
ITF	International Tennis Federation
WBGT	Wet Bulb Globe Temperature
WTA	Women's Tennis Association
VO_2	Oxygen consumption
VO_{2max}	Maximal Oxygen consumption
HR	Heart Rate
RPE	Rating of Perceived Exhaustion
MVC	Maximal Voluntary Contraction
ME	Match Exposures
USA	United States of America
^oC	Degrees Celsius
>	Greater Than
<	Less than
±	plus or minus
=	equal
s	seconds
m	meter
m/s	meters per second
km/h	kilometres per hour
$mL \cdot kg^{-1} \cdot min^{-1}$	millilitre of oxygen per kilogram of body mass per minute
~	approximately
L/h	litre per hour
L/min	litre per minute
mMol/L	millimoles per litre
cm	centimetres
%	percentage
RH	relative humidity
GT	globe temperature
NWB	natural wet bulb
DB	dry bulb
↑	increase
↓	decrease

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Abstract

This thesis examines the relationship between estimated wet bulb globe temperature (WBGT) and heat-related medical consults, the occurrence of heat illness and changes in matchplay performance at the Australian Open (AO).

To do this, whole match and set-by-set match characteristics data from the first four rounds of the 2014 - 2016 AO men's and women's main draw was collated. From this data set, whole match characteristics, change in first to last set performance, and the set-to-set standard deviation of match characteristics were collected and collated in to WBGT zone according to the American College of Sport Medicines (ACSM) extreme heat policy (EHP). Individual generalised linear models (GLM) were conducted to assess the effect of estimated WBGT zones on heat related events/medical outcomes, matchplay characteristics, within match changes in matchplay characteristics and the set-to-set standard deviation of matchplay characteristics. Further, medical events were also assessed as a rate per 1000/h of matchplay per WBGT zone.

The key findings from these studies were:

- There were 3 heat illness retirements in the men's competition at the AO between 2014 and 2016, and no heat illness retirements in the women's competition.
- Each increase in match estimated WBGT was significantly ($p<0.05$) associated with increases in post-match heat related consultations with doctors (87% men; 68% women), and total on court heat-related events (55% men; 56%

women). Further, conditions >32°C estimated WBGT had the greatest increase in heat related events, when examined as a rate per 1000h of matchplay.

- Increased estimated WBGT resulted in a significant reduction in net approaches in both the men's (7.6% ± 0.01; p<0.001) and women's (8.4 ± 0.02%; p<0.001) competition.
- Matchplay in hot conditions significantly affected whole-match serve performance in both the men's and women's competition; with men increasing the number of aces (5.0 ± 0.018; p=0.003), while women increased their number of double faults (13.8 ± 0.029; p<0.001) per WBGT zone.
- Increased match estimated WBGT lead to an increase in set duration (3.31 ± 1.02%; p=0.001) and unforced errors (0.16 ± 0.37%; p=0.002) from the first to last set of matchplay in the heat in the women's competition, while there was also a reduction in the percentage of points won on first serve (-2.17 ± 1.07%; p=0.04). In the men's competition, there was no significant (p>0.05) change in performance from the first to last set of matchplay in the heat.
- Matchplay in hotter conditions (increased WBGT) lead to a reduction in the set-to-set consistency (standard deviation) of set duration (0.910 ± 0.43%; p=0.033), total points won (1.52 ± 0.58%; p=0.008) and net approaches (1.21 ± 0.58%; p=0.049) in the men's competition. With the women's competition showing a reduction in the set-to-set consistency of set duration (2.16 ± 1.89%; p=0.05) and conversion of break points won (3.65 ± 1.89%; p=0.05) during matchplay in the heat.

The above-mentioned findings suggest that during Grand Slam matchplay in conditions above 32^{o}C estimated WBGT tournaments medical staff should be vigilant and prepared for an increase in heat related consultations. Tournament organisers should also look to avoid matchplay in such conditions by scheduling matches outside the hottest periods of the day if hot conditions are expected.

The above-mentioned findings also suggest that matchplay in extreme heat will result in subtle changes to matchplay performance in both the men's and women's competition, with the whole match reduction in the use of net approaches in both the men's and women's competition showing the most significant change. The reduction in the use of net approaches suggest that competitors were attempting to reduce the use of aggressive matchplay tactics, likely an attempt to reduce match intensity or selectively conserve effort for select passages of play. The increase in whole-match aces in hot conditions in men suggests either risker serving strategies, or reduced pressure from the returner. In either case, matchplay tactics for the serve likely attempted to reduce point durations in the heat. In the women's competition, there was an increase in the whole match double fault count, and a progressive reduction in the percentage of points won on first serve during matchplay in the heat. This alteration to points won on first serve suggests a reduced dominance during service games and/or an increase in fatigue throughout matchplay in the heat.

Chapter One

Introduction

1.1 Introduction and Overview

The Australian Open (AO) is one of the 4 major professional tennis tournaments (known as Grand Slams) played each year on the world tour; with considerable prize money and ranking points attached to these tournaments. Further, the AO conducted during the Australian summer is regularly impacted by extreme heat. For example, 8% of the days in which competition occurred between 2009 and 2019 the ambient air temperature exceeded 40°C (179). Due to this potential for extreme heat, the AO has an Extreme Heat Policy (EHP) to safeguard player wellbeing and ensure the competitive integrity of the tournament. Prior to 2019, this EHP stated matchplay could be suspended once the Wet Bulb Globe Temperature (WBGT) reached 32.5°C and ambient air temperature of 40°C (2). Further, the Women's Tennis Association (WTA) has an additional heat rule which provides the women's draw competitors with a 10-minutes break between the 2nd and 3rd set in conditions >28°C WBGT. However, the temperatures at which these EHP's are implemented have been the source of significant debate by competitors, the media and tournament organisers (2, 48, 115). Further, due to the limited available literature examining the effect of extreme heat on heat illness occurrence and matchplay performance within professional tennis, these EHP's have drawn criticism in the literature (44, 129, 150, 157); and thus the effects of professional tennis in the heat requires further examination.

The physical demands of Grand Slam matchplay are substantial (63, 110, 163, 165), largely owing to matches having no fixed duration, whereby typical match duration can be between 1 to 5 h (110, 163). Men's matches at Grand Slams are typically longer in duration than women's matches due to the best of 5 set format, where women play best of 3 sets (63, 64). During such matchplay, male players can hit an average of 3 shots/point (63) with racket speeds of up to 130-160 km/h (116), while also repeatedly moving 8-12m/point at peak speeds of up to 20km/h (163). These high within-point physical demands lead to competitors making over 500 high intensity efforts (110, 146) and covering 2110 ± 839m/match in the men's competition, and 1232 ± 440m/match in the women's competition (165). In hot conditions it has been reported that these high physical demands will increase physiological strain (64, 154) resulting in additional heat induced fatigue. This heat induced fatigue has previously been demonstrated to reduce tennis ground stroke accuracy (54). Further, the increased demands of matchplay in the heat may expose competitors to an increased risk of heat illness occurrence due to the extended nature of tennis matchplay in Grand Slam events (7).

1.2 Heat Incidents in Tennis

Previously it has been suggested that heat illness occurrence in tennis may be related to a number of factors including; environmental conditions, intensity of matchplay, duration of matchplay, dehydration and potential abnormal physiological markers (189). However, the US Open provides the only available data to describe heat illness occurrence in Grand Slam competition. The event's medical report shows a heat illness occurrence rate of 1.42/1000h of match exposure in women and 2.84/1000h in men (173). Of note, this work demonstrated no significant association between the environmental conditions and heat illness occurrence (173). The absence of association between WBGT and heat illness at the US Open was unexpected, though could be explained through the incorporation of doubles matchplay in the analysis reducing the exposure rate. Despite this limitation, such findings represent the best evidence for the extent, rate and type of heat illness in Grand Slam tennis.

While the aforementioned data is useful in providing a broad understanding of the occurrence of heat illness in Grand Slam competition, there are substantial differences in the physical demands of singles and doubles competition (130). As such the combining of doubles and singles competitions when assessing the occurrence of heat illness within professional tennis limits the ability to determine heat illness occurrence in specific competitions. Further, there is no available evidence examining the heat related medical consultation usage during Grand Slam competition. Accordingly, the impact of extreme heat on the occurrence of heat illness in professional tennis remains under-investigated and has led to calls for greater peer reviewed scrutiny (44, 157). On a practical level, more comprehensive and relevant insight from the AO examining the incidence of heat illness and its relationship with environmental conditions would assist medical staff in appropriately planning, preparing and preventing heat illness events during professional matchplay in the heat.

1.3 Effect of Extreme Heat on Tennis Performance

In addition to the limited peer reviewed literature reporting the occurrence of heat illness in Grand Slam tennis, limited literature examining the impact of extreme heat on tennis performance during professional Grand Slam matchplay exists. It has previously been reported that during simulated matchplay in the heat (33.6 ± 0.9°C WBGT) aces, double faults, total games and points played are unaffected in comparison to cooler conditions (154). However, an increase in rest duration during matchplay in the heat is observed, and thought to be a tactic to reduce match intensity (94, 154), and thus potentially increase match duration (154). In Grand Slam tennis though, rest periods are more closely monitored, likely limiting the systematic and strategic manipulation of rest periods observed in simulated studies (99), heightening the need for competitors to find alternative methods of coping and/or reducing match intensity i.e. alterations to stroke outcomes or within-match tactics. In support, Hornery et al. (2007) found that hot conditions impacted the technical performance of male tennis players' serve performance during professional tournament matchplay (94).

The heat-induced changes to the match demands of tennis suggest that professional tennis matchplay performance may be reduced in hot conditions (54, 94, 154). However, while the potential for extreme heat to regularly impact professional tennis matchplay at the AO exists, there is limited peer-reviewed literature to inform how extreme heat may impact professional tennis performance. Further, there is almost no evidence examining the impact of extreme heat in women's tennis. Accordingly, tournament organisers would be better placed to justify and/or modify current EHP's, and improve match scheduling with improved clarity on the relationship between these environmental conditions and the performance characteristics of professional matchplay. Additionally, this analysis may benefit coaching staff in understanding and adjusting performance expectations during tournament matchplay in the heat.

1.4 Thesis Aims

Given the relevance of extreme heat in professional tennis, from both medical and performance points of view, this thesis aims to:

1. Investigate the association between WBGT and the occurrence of heat related events, medical consultations and requests for cooling devices and water in the AO's main draw competition (study's 1 and 2).
2. Assess the impact of increased estimated WBGT on whole-match changes to tennis performance of professional men's and women's players during main draw tournament matchplay at the AO (study's 1 and 2)
3. Investigate the implications of increased estimated WBGT on the within-match changes to performance by examining 1) the change in match characteristics from the first to last set of matchplay, and 2) the within match consistency of tennis performance during main draw matchplay at the AO (study 3 and 4).

1.5 Justification of Thesis

Due to the regular potential for extreme heat to affect professional tennis tournaments, there is often debate among the media, competitors, spectators and tournament organisers surrounding the implications of extreme heat on player welfare and performance. This debate often intensifies during the AO due to the importance of the event in the tennis world calendar and the regular potential for conditions in excess of 40^{o}C dry bulb. While a number of competitors have suggested that they believe these conditions are not appropriate for competition (2, 48, 115), this opinion is often countered with suggestions that the conditions are just part of the sport (48). While significant debate exists surrounding the impact of extreme heat on competitor welfare and performance, there is limited peer-reviewed literature at the professional level to inform this debate (44, 157). For these reasons, there have been calls for further investigation into the impacts of extreme heat on professional tennis performance and the occurrence of heat illness (44, 157).

With a greater understanding of the occurrence rate of heat illness within tennis, tournament organisers will be able to better plan tournament schedules to safeguard competitor wellbeing in the event of extreme heat affecting matchplay. Further, medical staff at the AO would benefit from a deeper assessment of the occurrence of heat illness at the AO to better prepare resources for changes in treatment demands during matchplay in the heat. Tournament organisers would also benefit from ongoing assessment of the performance implications of extreme heat during tennis matchplay as to ensure the competitive integrity of the tournament is not affected by extreme heat.

1.6 Limitations

Several limitations are present in this course of studies, including;

- Within these studies the use of estimated WBGT from an off-court location likely reduced the accuracy of assessing on-court WBGT, as off-court WBGT recordings can underreport on-court WBGT (159). Further, the use of a fixed black globe temperature in the estimation of WBGT (in the absence of black globe temperature) likely reduced the accuracy in estimating the thermal stress experienced by competitors during matchplay. However, the binning of matches into WBGT zones and using zonal assessment to determine the relationship between estimated WBGT and match variables, rather than individual match estimated WBGT's, likely reduced the impact of potential inaccuracies in the estimation of on court WBGT. Additionally, the retrospective data set, and the use of WBGT at the time of data collection for the implementation of EHP at the AO made the use of estimated WBGT the most logical and available heat index.

- The use of a retrospective data set also needs to be highlighted as a limitation. This meant that there was no control or opportunity to determine the type of data captured to describe on-court medical consultations. This prevented an understanding of issues like the potential tactical usage of medical consultations in the slowing down of matchplay.
- Due to the EHP in place at the AO, some matches in the current study were suspended in extreme conditions. This meant that the more extreme thermal conditions that may occur at the AO were not examined; nevertheless, players are unlikely to be required to compete in such extreme conditions.
- As competitors at the AO in the current data set were from over 45 different countries it is not possible to account for the level of heat acclimatisation by competitors prior to the AO. However, due to the significant travel requirements of the tennis world tour, competitors spend a large proportion of the year in similar climates. Additionally, prior to the AO, a large proportion of competitors in the current data set would have competed in prior events in Australia providing a level of heat acclimatisation.
- Due to the elite level of competition and the high volume of matches, it was not possible to collect physiological measures such as hydration status, core

temperature and lactate concentration prior to, during or after matchplay. Further, it was also not possible to ascertain perceptual measures, such as RPE, or rating of thermal conditions by competitors prior to, throughout and after competition.

1.7 Delimitations

Several known delimitations are present in this sequence of studies, including;

- The use of an elite population during a live competitive environment where significant prize money and ranking points were on offer ensured that competitors had significant motivation to perform.
- All matches were officiated by professional officials ensuring similar match conditions across all matches.
- Both male and female competitors were assessed separately, due to the significantly different physiological and match demands of respective competitions.
- All medical assessments were conducted by WTA, Association of Tennis Professional's (ATP), Tennis Australia approved medical staff, and all performance data was collected by well trained staff ensuring similar and accurate data across the data set.
- The use of a large data set likely reduced the potential of outlying results to skew results related to player performance or the incidence of heat illness.

Chapter Two

Literature Review

2.1 Overview

The effect of extreme heat on performance and athlete health is a contentious topic within tennis, as much speculation fills mainstream media discussions of the "disastrous" effects of extreme heat on player welfare and the integrity of the competition (2, 44, 54, 185). Despite this regular debate among competitors, tournament organisers and the media, relatively little peer-review literature exists to inform these debates (44, 64, 157). This limited volume of peer-reviewed literature has made it difficult for tournament organisers, medical staff, coaching staff, competitors and the media to make informed decisions surrounding professional matchplay in the heat, particularly in Grand Slam events. Conversely, in light of this absence of evidence, it is also difficult for tournament organisers to justify EHP's to safeguard player wellbeing and protect the competitive integrity of the AO.

Given the regular speculation surrounding the impact of extreme heat on Grand Slam tennis, this literature review will describe the current evidence examining the effect of extreme heat on heat illness occurrence within tennis, and the implications of matchplay in extreme heat on tennis performance. Specifically, the review will start by describing the physical and physiological demands of tennis to set the scene, before exploring the changes to the physiological and performance responses during exercise more generally, and then tennis specifically in hot conditions. Further, this literature review will then examine the occurrence of heat illness within tennis, and the available evidence examining EHP's within sport. Finally, this literature review will also examine the use of WBGT and its current limitations.

2.2 Literature Review Methods

Inclusion Criteria

Studies that were eligible for inclusion within this literature review were those that examined the impact of environmental conditions on the occurrence of heat illness during tennis matchplay. In addition, studies examining the impact of heat on changes in tennis performance, inclusive of physiological and physical changes during tennis matchplay in the heat were also included. Due to the limited number of available published studies examining the effect of hot conditions on tennis performance, studies using all playing levels of participants were included.

Studies were excluded from the current literature review if they were:

- Non-English articles
- The full text was not available
- Magazine or newspaper articles

Information sources

Databases searched for the above literature topics included CINAHL, SPORTdiscus, and Pubmed. Reference lists of included articles were also searched for further articles.

Search strategy's

The search strategy employed consisted of search terms including:

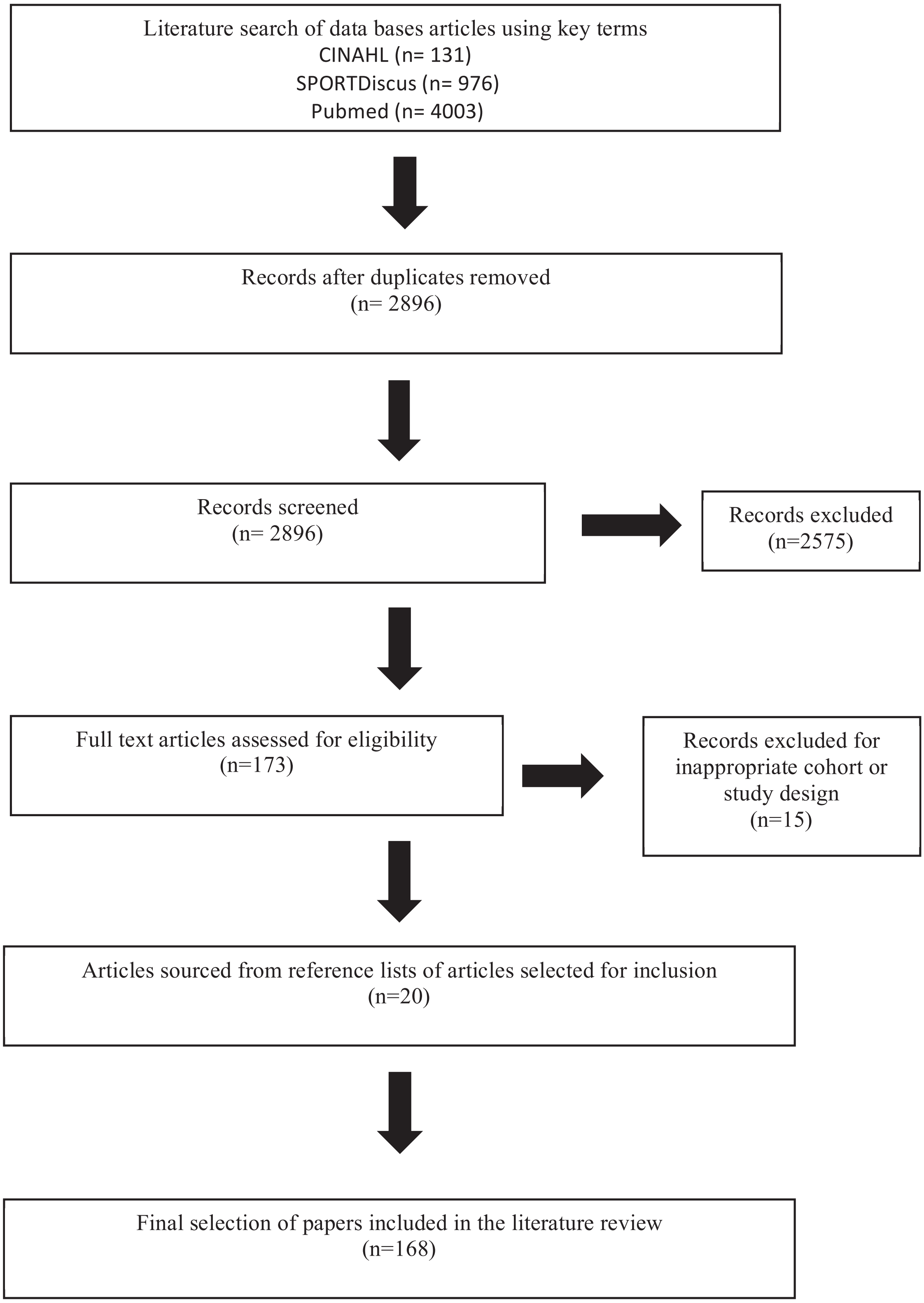
- Thermoregulation and exercise
- Tennis and heat illness
- Tennis and heat and match characteristics
- Tennis and Wet Bulb Globe Temperature

- Wet Bulb Globe Temperature
- WBGT limitations

Study collection and data collection process

Titles and abstracts were screened for eligibility and all duplicates were removed. Methods, results and discussions were then assessed and synthesized in a narrative review for those articles selected for inclusion. The initial search generated 5110 articles, which after a process of review, elimination and hand searching, were reduced to 168 articles for inclusion. See Figure 2.1 for PRISMA flow diagram outlining the inclusion and exclusion of data throughout the review process

Figure 2.1: PRISMA flow diagram describing the literature search process.



2.3 Physical and Perceptual Demands of Professional Tennis

Prior to examining the impact of extreme heat on tennis performance it is important to understand the physical demands of tennis in temperate environments to provide context to matchplay in the heat. Tennis has previously been described as a physically demanding sport, particularly at the pinnacle of Grand Slam events (110, 163). Such demands at Grand Slam events are largely due to unrestricted match durations, where men's matches have been reported at over 5h in duration (163). Further, tennis players have been reported to make on average 300-500 high intensity efforts in a best of 3 set match (63). Competitors move an average of 8-12m per point with an average of 4 changes of direction, at speeds up to 20km/h during professional competitive matchplay (163). These within-point movement demands lead to competitors moving ≈ 2110 ± 839m per match in the men's competition, and 1232 ± 440m per match in the women's competition at the AO (165). Though court coverage during men's AO singles matches has been recorded as high as 6625m (163). Within such distances, this court coverage consists of explosive accelerations and decelerations, further increasing the physical demands of movement during tennis matchplay (63, 64, 77).

Pointplay within tennis has previously been described as having anaerobic work periods with aerobic based recovery periods (110, 163). Within this general description it has been reported that work to rest ratios within professional tennis are 1:2 – 1:4 (109), though the actual ball in play proportion of the match (known as effective playing time), may only account for ≈15% of the total match duration (165). The point to point demands of tennis matchplay are also physically demanding, with point duration in professional tennis commonly reported on average to be 6-8s (110, 163) and often extending to beyond 15s (110). Competitors will make ≈3 shots per point (63), with racket speeds of up to 130-160 km/h (116). Additionally, competitors will move ≈3m per shot (Table 2.1) (163) while making tactical adjustments to court positioning in response to ball and opponent movement to optimise hitting position on court (63).

The physical movement demands during professional tennis matchplay create pronounced physiological responses. For example, professional tennis results in oxygen consumption ($\dot{V}O_2$) during pointplay ranging from 60-75% of maximal oxygen consumption (VO_{2max}), (107, 110) (Table 2.1). Further, the mean heart rate (HR) during professional tennis pointplay has also been reported at 82-86% of maximal HR (Table 2.1) (76, 110, 128), with serving games having significantly higher HR than when receiving serve (76, 110, 128). However, it has also been suggested that HR should be used with caution to describe match intensity due to the intermittent nature of tennis workloads meaning that HR will not always accurately reflect VO_2 (63). Additionally, core temperatures during professional tennis matchplay in cooler conditions have been reported at ≈38.7°C (154) indicating moderate and sustained increases in core temperature during matchplay.

Table 2.1: Summary of the physical demands of professional tennis.

Measure	Measured ranges
Point duration	3.0 - 14.9s
Match duration	1 - 6h
Effective playing time	16 - 26%
Total balls hit per match	<727
Total serves hit per match	85 - 157
Distance covered per set	553 - 572
Changes of direction per point	1 - 8
Mean first serve speed	155 - 184 km/h
Mean ground stroke speed	106 - 111 km/h
% of max heart rate	60 - 80%
% of maximal oxygen consumption	54 - 70%
Rating of perceived exertion (Borg 6-20 scale)(33)	11 - 15
Estimated energy expenditure	213 - 343 kcal/min
Blood lactate	<5.5 mmol/L

(63, 64, 74, 109, 110, 119, 132, 163, 165, 195)

While it has been demonstrated that the physical demands of tennis are significant, there are also pronounced perceptual demands during tennis matchplay. It has been reported that tennis matchplay in cooler conditions can be rated as a 12-13 on the 6-20 Borg's rating of perceived exertion scale (RPE) (62, 63). Additionally, serving games have a significantly higher RPE (13.5 ± 1.9) than receiving games (12.0 ± 2.0) (62), which would agree with the reported increased physiological demands of service games (76, 110, 128). Furthermore, throughout tennis matchplay RPE has been reported to significantly increase over the course of the match (154), with match RPE also being aligned with match duration (77). In addition, significant correlations between RPE and muscle soreness ($r=0.99$, $p<0.001$) have also been reported during tennis matchplay (77). Interestingly, RPE and muscle soreness in previous research were not associated directly with workload, as HR near the end of the matchplay has been reported to decrease, while RPE and muscle soreness increased (77). This dissociation between workload and RPE in tennis has been attributed to the high levels of muscle damage and fatigue caused by the number of eccentric contractions due to braking, flexion and stretch shortening actions in addition to the length of matchplay (77).

2.4 Gender Differences in the Physical Demands of Tennis

Although men's and women's tennis competition are conducted under similar rules, the demands of matchplay between the two competitions can vary significantly, particularly at the Grand Slam level (63). The largest contrast in physical demands between men's and women's matchplay at Grand Slam events is that men's main draw competitors compete a best of 5 set match format, with women's main draw competition being a best of 3 set format (99). This difference in competition format will typically results in longer matches in the men's draw, and consequently, greater volumes of distances covered, points played, shots taken and resulting physiological and perceptual demands (77, 110, 165).

In addition to the difference in match format between the two competitions, there are also significant differences between the style of matchplay and tactics employed within men's and women's competitions (63). One of the largest differences in matchplay tactics between the men's and women's draw is the heavy reliance on the serve by male competitors to win uncontested points or set up an advantage within the point (65). As evidence, a higher proportion of points in the men's competition are won or lost based on the serve or the return of serve compared to the women's competition (145, 165). While in the women's competition there tends to be more double faults (65, 165), and fewer points decided by the serve or return, alongside a greater number of points lasting >3 shots (145). The increased reliance on the serve in the men's competition is further highlighted by the lower percentage of points won while returning (29 ± 5%) in comparison to women's draw (41 ± 6 %) (91). The reliance in the men's competition to use to serve to win uncontested points, or to dictate points is largely due to the significantly higher serve speed in the men's game in comparison to the women's competition (91, 165). However, in both the men's and women's competition first serve percentage and points won on first serve significantly correlated with match outcome (65). These findings clarify that serve performance is highly important in professional tennis matchplay for both male and female competitors.

While there are significant gender differences to the application of serving tactics in professional men's and women's tennis, there are also significant differences to the use of net approaches. Previous evidence demonstrates a significantly greater number of net approaches in the men's game compared to the women (65, 145). The increased use of net approaches in the men's draw could be explained based on the consequence of the aforementioned reliance on the serve to create dominant point positioning and control the rally (145), and may suggest a more aggressive style of matchplay (163). In comparison women's draw competitors appear to prefer to rally's and finish points from the baseline (145). However, in both the men's and women's competition the percentage of points won at the net during Grand Slam matchplay was correlated with match outcome (65), suggesting that net approaches are important in both competitions.

Such differences in the tactical use of the serve and net approaches in respective men's and women's matchplay has an impact on ensuing rally lengths. The reduced reliance on the serve to win uncontested points in the women's game is likely the cause of the increased rally length in the women's game in comparison to the men's game (63, 91, 145). This was demonstrated at the AO with the mean rally times in the women's draw reported as ~7s, while in the men's draw rally lengths were reported at ~6s (145). While rally length in the women's game have been reported as longer, the speed of rally was significantly faster in the men's game, with a faster stroke rate in the men's competition (145, 165). This faster rate of shot likely lead to the increased movement demands in the men's competition, with men hitting fewer shots while recording similar distances covered per set to the women's competition (165).

The physical and physiological demands of professional tennis matchplay are pronounced even in cooler conditions (63, 110, 163, 165). Accordingly, the effects of hot environmental conditions on tennis matchplay may result in significant challenges to player performance and thermoregulatory outcomes. Additionally, there are significant differences in the physical and tactical demands of men's and women's competition, particularly in Grand Slam events (65, 165). As such the challenges of extreme heat to tennis performance and occurrence of heat related events are likely to differ between the men's and women's competition. Accordingly, the implications of extreme heat on tennis performance and health outcomes within men's and women's tennis should be assessed independently.

2.5 Thermoregulation During Exercise in the Heat

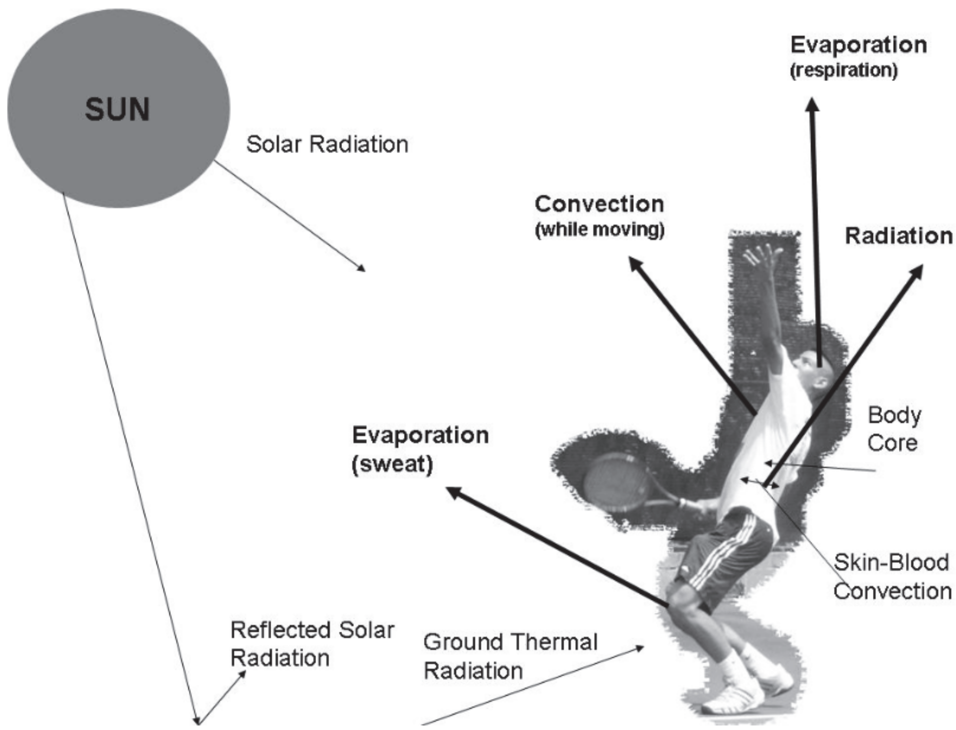
Whilst this thesis does not focus on physiological responses to tennis in the heat, it is nonetheless important to provide a short context to the thermoregulatory demands of tennis in the heat. During exercise the regulation of core temperature is placed under significant burden, with metabolic heat output increasing by up to 20 times that of resting levels (34, 134). This increase in metabolic heat output has been reported to increase core temperature to $\approx 38.7 \pm 0.2^{o}C$ during professional tennis matchplay in cool conditions (154). However, with greater exercise intensity and duration an increased stress is placed on the thermoregulatory ability to maintain safer core temperatures (46, 168).

In cooler conditions core temperature will be hotter than that of the skin, allowing for heat to transfer from the core to the skin, where it can then transfer to the environment and allow effective thermoregulation (7, 17, 34, 46). However, during exercise in the heat, air temperature may surpass that of the skin, disrupting this heat gradient and leading to exacerbated increases in core temperature (168). As example, during tennis matchplay in the heat core temperatures have been recorded at 39.4 ± 0.5°C compared to the reported <38.5°C in cooler conditions (154). Given core temperature >40°C are typically considered a sign and symptom of heat illness (7, 17, 34, 50), avoiding uncontrolled increases in core temperature is paramount.

There are four main methods of heat transfer between the human body and the environment for human thermoregulation, which are, conduction, radiation, convection, evaporation (7, 17, 34, 111). Conductive thermoregulation occurs through making physical contact with objects such as the ground; however, in tennis conductive thermoregulation regularly results in heat gain due to court surfaces usually being hotter than that of the skin (Figure 2.2) (111). Further, radiant heat transfer is the non-contact transfer of electromagnetic energy, and will also typically results in heat gain within tennis due to the absorption of solar radiation (111). Convective thermoregulation is the result of heat transfer from gas or fluid movement such as air (46, 128). Convective heat loss during exercise in cooler conditions is a key component of thermoregulation due to wind and air movement over the skin as locomotion occurs (46, 111, 128). However, evaporative cooling through the absorption of sweat into the air from the skin is typically the most effective form of heat loss both in hot and cool conditions (20).

While conduction, convection, evaporation and radiation will typically satisfy thermoregulatory needs in a majority of exercising conditions, there are a number of factors that can inhibit or limit thermoregulation. As previously mentioned, high environmental temperature will stress thermoregulation efficiency (43, 168), though dehydration is also often associated with increase heat storage and reduce thermoregulatory capabilities (46, 108, 124). This is largely due to effective thermoregulation requiring the maintenance of adequate blood volume (46), with adequate blood volume required to disperse excess heat throughout the body (124). Further, adequate blood volume is required to maintain functions such as sweating for evaporative cooling (124, 133), and allowing blood to be drawn to the skin for cooling while maintaining blood pressure (83, 124). However, sweat rates during extended exercise in the heat, such as tennis, will often be greater than the rate of replenishment (43, 81, 111). As such, dehydration can have a significant impact on thermoregulation during exercise in the heat (43, 168). Further, due to the extended nature of tennis matchplay it has previously been reported that tennis matchplay can lead to significant dehydration in competitors (111).

Figure 2.2: Heat exchange during tennis matchplay. (111)



In addition to dehydration, the fabric type and amount of clothing worn by an individual has been demonstrated to significantly impact thermoregulation (71, 90). As clothing creates a barrier for the transfer of heat from the skin to the air, this is particularly evident in evaporative cooling (40). As such the permeability and surface area coverage of clothing has a significant impact on thermoregulation (71). However, clothing has also been reported to reduce thermal stress by shading the body from solar radiation, particularly when wearing light coloured clothing (71). Additionally, professional tennis players at the AO are typically provided with highly permeable, fast drying, well ventilated clothing from major sporting company's reducing the impact of clothing on the impediment of thermoregulation (71, 90). Moreover, during tennis matchplay the constant adjusting of court position by competitors will reduce the barrier impact of clothing on thermal stress by increasing air movement over skin aiding thermoregulation, and improving evaporative cooling (168).

2.6 Effect of Extreme Heat on Exercise Performance and Physiology

The increase in muscle temperature during exercise in the heat has previously been reported to improve short sprint based activities due to an increase in metabolic process, nerve conduction, and the conformational changes required during muscular contraction (140). However, extreme heat has been demonstrated to negatively impact longer lasting exercise performance; with significant increases in core (82, 89, 140, 144, 168) and skin temperatures (10, 58, 125) associated with reductions in aerobic performance. For example, exercise from 3 min (10, 82, 156) to greater than an hour in duration (59, 84, 102, 141) has previously been demonstrated to be negatively impacted by increased environmental temperatures (43, 168). Further, at the point of exhaustion HR (hot ~175bmp; cool ~165 bmp), core (hot ~40^{o}C; cool ~39.5^{o}C) and skin (hot ~35^{o}C; cool ~25^{o}C) temperature are significantly elevated after prolonged cycling in hot conditions compared to cooler conditions (70). These reductions in performance and exacerbation of physiological responses are historically suggested to be due to reduced cardiovascular efficiency and drawing of blood to the skin for cooling (82, 89, 140, 144, 168).

Reductions in cardiovascular function during exercise in the heat have been associated with skin temperature irrespective of core temperature (10, 58, 125). With increased skin temperature resulting in an increase in blood flow to the skin for cooling (34), reducing the volume of blood and available oxygen for metabolism (82, 89). In addition increased sweat rates during exercise in the heat will likely result in dehydration, as rehydration practices are rarely able to match the rate of fluid loss (43, 111, 168). Dehydration compounds the cardiovascular insufficiency's of exercise in the heat, with decreases in total blood volume, reducing the blood available for cooling at the skin and for oxygen delivery (43, 168). This reduction in oxygen delivery caused by dehydration and the drawing of blood to the skin for cooling results in reduced exercise performance as a result of increased peripheral fatigue (82, 89). Further, the reduced delivery of oxygen increases the use of anaerobic energy metabolism within the exercising muscles (82, 89). These reductions in cardiovascular function during exercise in the heat have been suggested to have the most significant impact on high intensity exercise, where blood flow to exercising muscles can be reduced by 2-4 L/min (82, 84). With reductions in blood flow affecting VO_{2max} and oxygen transportation during high intensity exercise (86, 151) however, at low intensity VO_2 may remain unaffected with increased heart rate compensating for decreases in stroke volume (43, 85).

While reductions in exercise performance have been recorded with increases in skin temperature alone (10, 58, 125), increases in core temperature have been demonstrated to further reduce aerobic exercise performance in the heat (84, 142). Further, increased core temperature has been demonstrated to significantly impact central nervous system function (84, 136, 140, 142). It has previously been proposed that increased core temperatures will result in CNS down-regulation in an attempt to reduce exercise intensity to reduce increases in core temperature and the occurrence of heat illness (84, 139, 142, 168, 169). This change in CNS function may have significant implications for tennis performance in the heat due to the prolonged intermittent-sprint nature of the sport. However, reductions in muscular force due to reductions in central activation are progressive in nature and are not the result of a distinct core temperature threshold inhibiting performance (131). Although speculative, this gradual reduction in central activation in the heat may have implications for tennis, particularly in the men's competition due to the extend duration of matchplay. Further, reductions in torque and voluntary muscular activation are only impaired by core temperature, with no association between muscle temperature and reduction in contractile performance (190). Thus, the above-mentioned reductions in exercise performance during exercise in the heat has the potential to significantly impact professional tennis matchplay performance in the heat. With the combination of extended match durations at Grand Slam events and the potential for extreme heat to impact the AO it is important to understand how extreme heat may impact professional tennis performance.

2.7 Effect of Extreme Heat on Tennis Performance

The regular occurrence of professional tennis matchplay in hot conditions often results in discussion surrounding the performance implications of matchplay in these conditions. However, Périard et al. (152) has previously demonstrated that there was no association between number of points played, number of games played, or percentage of aces or double faults hit within simulated competitive matchplay in extreme heat (33.6 ± 0.9^{o}C WBGT) compared to cooler conditions (19.4 ± 0.3^{o}C WBGT) (Table 2.2). From these findings the authors suggested that extreme heat had no impact on tennis matchplay performance (154). Separately, it has also been demonstrated that during professional tennis tournament matchplay in moderately hot conditions (32 ± 4.5^{o}C dry bulb), there was no change to serve velocity, serve accuracy, the percentage of points won on first or second serve, or the number of unforced errors made in comparison to cooler conditions (25.4 ± 3.8^{o}C dry bulb) (94). Nevertheless, it was reported that matches in hot conditions lead to a significant reduction in the technical performance of the serve, although the specifics as to what or why this reduction in technical performance of the serve existed were not reported (94). Further, these authors stated that reductions in the technical performance of the serve had no implications on service outcome (94). However, the data within this study were collected from two different competitions and on different court surfaces; as matches in hot conditions were on hard courts and matches in cool conditions on clay.

Table 2.2: Summary of studies examining the impact of environmental temperature on tennis.

AUTHOR	COHORT (n)	PURPOSE	TEMPERATURE	CORE TEMPERATURE	MEASURES	KEY FINDINGS
PÉRIARD, ET AL. (153)	Low level Professional men (10)	Investigate the impact of dehydration on matchplay characteristics, physical performance and physiological markers	36.8±0.03°C 33.3±3.8% RH 34.2±0.04°C WBGT	39.4±0.5°C	**Physiological** USG, Body mass, Fluid intake, sweat sodium content, core and skin temperature, HR, RPE, thermal comfort **Performance** Match characteristics, Neuromuscular Function, 15m Sprint, Vertical jump	Hydration status had no impact on match characteristics, neuromuscular fatigue, physical performance, blood lactate or skin temperature. ↑ Hydration status initially ↓ core temperature and thermal sensation, although were similar by match end ↑ hydration status ↓ heart rate
PÉRIARD, ET AL.(154)	Low level Professional men (12)	Investigate the impact of extreme heat on tennis performance along with thermal, physiological and perceptual measurements	**Hot:** 36.8±1.5°C, 36.1±11.3% RH, 33.6±0.9°C WBGT **Cool:** 21.8±0.1°C, 72.3±3.2% relative humidity, 19.4±0.3°C WBGT	**Hot** 39.4±0.5°C **Cool** 38.7±0.2°C	**Physiological** Core and skin temperature Heart rate RPE Thermal comfort Thermal sensation **Performance** Match characteristics	↑ temperature lead to ↑core and skin temperature, HR, and RPE ↑ temperature lead to ↑ rest durations WBGT had no impact on aces, double faults, or total points or games played
PÉRIARD, ET AL.(152)	Low level	Examine impairments in neuromuscular	**Hot:**	**Hot** 39.4±0.5°C	**Physiological** 5s MVC	↑ temperature during matchplay resulted in ↓ knee

	Professional men (12)	function integrity in lower limbs	36.8±1.5°C, 36.1±11.3% relative humidity **Cool:** 21.8±0.1°C 72.3±3.2% relative humidity	**Cool** 38.7±0.2°C	stimulated MVC 20s MVC	extensor force production, and voluntary activation, ↑ peripheral fatigue, central fatigue post match
HORNERY ET AL. (94)	Low Level Professional Men (14)	Describe the physiological responses to professional tournament tennis and the influence of physiology on match notation and performance variables	**Hot:** 32.0±4.5°C 38±14% relative humidity **Cool** 25.4±3.8°C 32±5% relative humidity	**Hot** 38.9±0.3°C **Cool** 38.5±0.6°C	**Performance measures** serve speed (km/h), serve accuracy, % of points won on first and second serve, unforced errors, Serve kinematics **Physiological** core temperature hydration status heart rate blood variables	Similar peak core temperatures and average heart rate between hot and cool conditions no impact of heat on performance on measures, however serve technique was reported to deteriorate during matchplay in the heat Time between points was longer during matchplay in the heat (25.1±4.3s) vs cool (17.2±3.3s)

KENZ ET AL. (107)	Low level Professional men (10)	examine the impact of match-play tennis in HOT and COOL conditions in high-level players, on oxidative stress and antioxidant potential during play and into the recovery period	**Hot:** 36.7±1.6°C 35.9±11.9% RH, 33.6±0.9°C WBGT **Cool:** 21.8±0.1°C 73.3±2.9% RH 19.5±0.3°C WBGT	**Hot** 39.3±0.5°C **Cool** 38.7±0.2°C	**Physiological** Core temperature, body mass and indirect markers of oxidative stress and antioxidant status	WBGT had no impact on oxidative status in match-play or recovery Match-play in the heat ↑ antioxidant status.
GIRARD ET AL. (78)	Low level Professional men (12)	assess the immediate and pro- longed alterations in rapid muscle force/torque characteristics of the KE and PF in response to match-play tennis in temperate and hot environments	**Hot:** 36.8±1.5°C 36.1±11.3% RH 33.6±0.9°C WBGT **Cool:** 21.8±0.1°C 72.3±3.2%RH, 19.4±0.3°C WBGT	**Hot** 39.4±0.5°C **Cool** 38.7±0.2°C	Performance rates of torque development and electromyography activity within the entirety of the torque-time curve	↓ Knee Extinction Max Voluntary Contraction post matchplay in heat, also at 24 hours' post.
GIRARD ET AL. (76)	Low level Professional men (12)	Assess the within and post-match changes in physical performance in response to match-play tennis in cool and hot environments.	**Hot:** 36.8±1.5°C 36.1±11.3% RH 47.5±3.5°C GT 33.6±0.9°C WBGT **Cool:** 21.8±0.1°C 72.3±3.2% RH 22.3±0.2°C GT 19.4±0.3°C WBGT	**Hot** 39.4±0.5°C **Cool** 38.7±0.2°C	**Performance** Repeated-sprint, Change of Direction sprint, squat and countermovement jump, leg stiffness	No significant difference in physical performances decreases between conditions. All measures returned to baseline with 24 hours with no difference between conditions.

BERGERON ET AL. (27)	elite junior players (8)	Assess the impact of hydration status on thermal strain and heat stress	WBGT 29.6±0.4°C	38.7±0.3°C	**Physiological** USG **Performance** Match results	↓ pre-match hydration status strongly associated with ↑ post match core temperature.
TIPPET ET AL. (191)	Professional women (10)	Assess the effect the 10-minute heat rule break on core temperature in professional female tennis players during live tournament play in the heat	30.3±2.3°C WBGT	39.13°C±0.34°C	**Physiological** Core temperature Fluid intake Sweat response	The 10-minute suspension of matchplay ↓ core temperature by 0.25±0.20°C
MORANTE ET AL. (129)	Non-professional players (6)	Examine the thermological and physiological response to tennis matchplay in comparison to steady state running	Wide verity of environments	--	**Physiological** Core and skin temperature, skin temperature and heart rate	Core temperature took longer to reach plateau then steady-state exercise, and was well controlled in conditions of 30.3°C. Skin temperature during tennis varied widely depending on environmental air temperature, and was ↓ than that of running at the same air temperature.
MORANTE ET AL. (128)	Non-professional men (19) women (6)	Assess the Autonomic and behavioural thermoregulation during tennis matchplay in the heat	25.0±5.4°C 50.7±14.3 % RH 22.5±4.3°C WBGT	38.45±0.36°C	**Physiological** Core and skin temperature, Body mass, fluid intake, subjective rating of thermal comfort, sweatiness and RPE **Performance** Match, game and point duration, effective playing time.	Sweat rate ↑ with ↑ air, rectal and skin temperature. Thermal comfort was ↓with ↑ rectal and skin temperature. Point duration and effective playing time were ↓ when conditions were rated ↑difficult.

MORANTE ET AL. (127)	Non-professional Men (19) Women (6)	Assess the thermoregulatory and subjective responses to singles tennis in a wide range of thermal environments.	Wide verity of environments 14.5-38.4^{o}C	**Men** 38.5±0.4°C **Women** 38.4±0.3°C	**Physiological** Core and skin temperature, Heart rate, Body mass, fluid intake Subjective measures of thermal comfort, sweatiness and RPE	Core temperature demonstrated no association with air temperature or WBGT Skin temperature and sweat rate ↑ with ↑ air temperature, HR showed no association with air temperature. All subjective responses ↑ with ↑ air temperature.
COYLE ET AL. (53)	elite junior players (1334)	Assess the impact of accumulative heat load on tennis performance.	31.9±1.3°C	--	**Performance** Match result	Hometown heat stress zone, body surface area, body mass index, total tournament degree-minutes of heat stress, day-before plus day-of degree minutes had no impact on match outcome. Player competition seed and same-day degree-minutes had a significant correlation with match out come.

In contrast to the findings of Hornery et al. (94), it has been demonstrated that after a treadmill fatiguing protocol in the heat, tennis shot accuracy is significantly decreased when compared to cooler conditions (54). Crew et al. (54) found that after completing a fatiguing protocol replicating tennis workloads on a treadmill in a heat chamber shot accuracy was reduced from 57.5% to 33.4% in a custom-designed shot accuracy test. However, while assessing the impact of extreme heat on shot accuracy is relevant to understanding the implications of extreme heat on tennis performance, assessing shot accuracy in a closed environment does not truly reflect Grand Slam matchplay demands. As such, assessing the implications of extreme heat on changes to match characteristics in professional competition is vital to understand how Grand Slam tennis performance is affected by extreme heat.

It has previously been demonstrated that simulated tennis matchplay in the heat by lower ranked professional tennis players had minimal impact on physical performance (76) (Table 2.2). With no significant change in the pre, mid and post-match testing of 20m sprint, repeat 15m sprint, change of direction, squat jump, countermovement jump and leg stiffness existed between matchplay in hot (33.6 ± 0.9°C WBGT) and cool conditions (19.4 ± 0.3°C WBGT) (76). Further, post-match reductions in these physical performance tests were completely recovered within 24 h (76). However, the use of simulated matchplay may have impacted match involvement by participants with the absence of ranking points or prize money on offer impacting motivation (75, 123). This absence of additional heat induced fatigue after simulated matchplay in the heat is in contrast to previous evidence from team sports (57, 121, 186).

While the effect of extreme heat on elite tennis match characteristics is limited (76, 94, 154), it has been reported that competitors will adjust work to rest ratios as a method of behavioural thermoregulation (76, 94, 128, 154). Périard et al. (154) reported that during simulated matchplay in the heat (33.6 ± 0.9°C WBGT) lower ranked professional male tennis players would extend between point rest periods to 27.2 ± 4.2s, in comparison to 17.3 ± 4.0s in cooler conditions (19.4 ± 0.3°C WBGT). These increases in rest periods reduced work to rest ratios from 1:3 in temperate conditions to 1:4 during matchplay in hotter conditions (154). Further, Hornery et al. (94) also reported increases in rest periods from 17.2 ± 3.3 in cooler conditions (25.4 ± 3.8°C), to 25.1 ± 4.3s during matchplay in hot conditions (32.0 ± 4.5°C) at a lower tier professional men's tournament. While it has previously been reported that armature tennis players will decrease point duration during matchplay in hot conditions, evidence from lower ranked professional tennis players reported no significant adjustment to point duration during matchplay in hot conditions (94, 154). The increased rest durations between points were suggested to be due to competitors attempting to reduce match intensity (94, 154) as a result of reductions in $\dot{V}O_2$ during matchplay in the heat (106, 154, 167, 175). Further, Périard et al. (154) also reported that the increased duration of rest periods resulted in an additional 17.1 ± 12.6 min of matchplay being required to reach 20 min of effective playing time (accumulation of total time the ball is in play). These increased rest durations may in part explain the absences of significant change to match characteristics and physical fitness performance in the heat (76, 94, 154). However, ITF rules limit between point rest periods to 20s, and at Grand Slam competitions rest periods are routinely monitored by elite officiating teams with the regular (excessive) extension of between point rest periods likely met with penalties

(99). As such, without examining the impact of extreme heat on live tournament matchplay it is difficult to understand the impact of extreme heat on Grand Slam tennis performance.

While previous studies have examined the impact of extreme heat on a handful of match characteristics and shot accuracy, no studies have explicitly examined the impact of extreme heat on both whole-match and within-match changes to matchplay characteristics. Further, of the available studies, none have used Grand Slam level competition data, as evidence primarily exists from matchplay between lower-ranked players. Furthermore, of particular note there is no available evidence examining the impact of extreme heat on tennis performance in professional women tennis players. With the significant differences in the physical and tactical demands of women's tennis matchplay in comparison to the men's competition, particularly at Grand Slams (65, 165), further investigation is timely.

2.8 Physiological and Perceptual Responses of Tennis Matchplay in the Heat

Whilst not a thesis based on the physiology of tennis in the heat, such topics sit underneath the consequence of medical concerns regarding playing tennis in the heat and require some exploration. Tennis presents unique thermoregulatory challenges to competitors, with extended match duration which have been reported in excess of 5 h in the men's competition at the AO. Additionally, professional tennis matchplay occurs on a number of surfaces, primarily hard court, grass and clay. The use of hard court tennis surfaces, such as those used at the AO, have previously been suggested to reflect a significantly higher level of solar radiation and ground thermal radiation then grass surfaces (111, 159). This increased radiant heat and reflected solar radiation adds to the thermal stress placed on competitors at the AO that must be expelled from the body (111).

As previously discussed the physiological demands of tennis matchplay in temperate conditions are substantial (100, 109, 163), and in the heat these demands become exacerbated (127-129, 154). For example, significant increases in heart rate (76, 154, 186), core temperature (94, 152, 154), and anaerobic energy pathway utilisation (154) are evident. One such study has reported an increase in heart rate by 18 ± 11 bpm during matchplay in 33.6 ± 0.9°C WBGT, in comparison to matchplay in 19.4 ± 0.4°C WBGT (154). The increase in HR during matchplay in the heat has been suggested to be the result of the increased relative intensity of matchplay, as a result of reduced cardiac output reducing VO_{2max} (151, 154).

While the thermoregulatory demands of tennis matchplay in the heat have been suggested to be pronounced (7, 111) the impact of hot conditions on core temperature responses in professional tennis players has been mixed (94, 127, 128, 154, 191). During tournament and simulated matchplay in mildly hot conditions, tennis players core temperatures showed no significant association with dry bulb temperatures (94, 127-129). However, previous evidence showed significant elevations in core temperature (39.4 ± 0.5°C hot vs 38.7 ± 0.2°C cool) during simulated matchplay (20 min of effective playing time) in professional male tennis players in extreme heat (33.6 ± 0.9°C WBGT) compared to cooler conditions (19.4 ± 0.3°C WBGT) (154). Further, within professional women's tournament matchplay in the heat (30.3 ± 2.3°C WBGT) peak core temperatures of 39.13 ± 0.34°C were recorded (191). Additionally, core temperatures during matchplay in apparently uncompensable conditions were demonstrated to steadily increase throughout matchplay until the completion of play (154, 191). With the potential for extended match durations at Grand Slam tennis, particularly in the men's competition, core temperatures have the potential to be significantly elevated for extended periods of time increasing the risk of heat illness occurrence (154).

Evidence has suggested that the increased relative intensity of tennis matchplay in the heat resulted in an increase in blood lactate concentration (63, 154). However, these increase in blood lactate were mild and still within normal exercise-induced ranges (63, 154). The mild elevation in blood lactate even during matchplay in extreme heat was likely due to the intermittent format of tennis matchplay allowing for frequent rests for blood lactate levels to recover. Furthermore, as previously discussed, during matchplay in the heat competitors may increase rest period duration further allowing time for blood lactate levels to reduce (94, 152, 154). However, when these increases in blood lactate are accompanied by the reported increases in heart rate it is evident that matchplay in the heat resulted in a significantly elevated physiological strain (151, 154).

While the reported impact of extreme heat on tennis matchplay and physical performance are limited, there have also been reports of the impact of tennis matchplay in extreme heat on neuromuscular fatigue (78, 152). With pervious studies demonstrating that matchplay in extreme heat reduced knee extensor maximal voluntary contraction (MVC) torque (−22.0±10.9%) more so then matchplay in cooler conditions (−9.5±6.9%) (78). Further, 24 hours post match knee extensor MVC torque was still reduce after matchplay in hot conditions (−10.6±7.3%) when compared to cool (−11.2 ±9.1%) conditions (78). Authors have suggested that the loss in torque strength for knee extensors was a combination of peripheral and central fatigue (152). This reduction in torque production suggests that extreme heat impacts the neuromuscular system both peripherally and centrally. However, while these studies are novel, they do not directly inform as to how extreme heat directly impact tennis performance.

During matchplay in the heat tennis players have recorded significantly elevated rates of sweating (127-129), as evaporative cooling becomes the primary method of cooling for the body (111). Sweat rates of up to 2.5 L/h (20) have been recorded during tennis matchplay in the heat, while in cooler conditions sweat rates of only 0.9 ± 0.2 L/h have been reported (154). The significant elevation in sweat rates in combination with the extended duration of matchplay may lead to significant hypo- or dehydration during tennis matchplay (43, 111). With previous evidence showing that significant dehydration will significantly impact aerobic exercise performance in the heat and increase the risk of heat illness occurrence (43, 168, 189). However, within the literature there have been mixed reports surrounding the occurrence of significant dehydration during tennis matchplay in the heat (21, 23, 24, 79, 94, 111, 127, 153, 154, 191). With a number of have studies reported only minimal dehydration as a result of increased sweat rates due to an increase in fluid intake during matchplay in the heat (127, 154, 191). It has also been reported that tennis players often start matchplay in a dehydrated state (153, 180, 189). Further, it has also been demonstrated that pre-match hydration status impacts within match core temperature, regardless of good in match hydration practices (153, 180). As such the pre-match hydration practises of professional tennis players may expose competitors to an increased risk of heat illness occurrence (50, 153, 180).

Along with increased physiological demands of tennis matchplay in the heat there are accompanying increases in the perceptual demands of matchplay in the heat (128, 129, 154). With previous evidence suggesting that thermal comfort is linked with core and skin temperature (60, 66) which in turn may drive modifications in behaviour (68, 128, 154). Within tennis this was highlighted by Morante et al. (127) who demonstrated a significant association between skin and air temperature and thermal comfort. A similar finding was demonstrated in an association between air temperature and RPE, suggesting competitors felt they were working harder in matches played in hotter conditions (127). These increases in perceptual demands of tennis matchplay in hot conditions may also drive the previously reported increases in rest periods between points, as competitors attempt to reduce match intensity (94, 154). Further, it has also been demonstrated that RPE, thermal comfort, and thermal sensation will rise in both cool and hot conditions. However, in hot conditions these measure will continuously rise until the completion of play; while in cooler conditions these measures will plateau (77, 154). Interestingly, the initial hydration status of competitors did not impact on the thermal comfort and thermal sensation during matchplay in professional tennis players, even with increases in core temperature for those who started the match in a euhydrated state (153). This increase in RPE during matchplay in the heat has also been found in a number of other sports (26, 171, 186) and is suggested to be caused by the higher relative intensity of exercise due to the reduced VO_2 during exercise in the heat (151).

2.9 Heat Illness and Heat Illness Incidence in Tennis

2.9.1 Heat illness

The increased metabolic heat generation during exercise in combination with the reduced efficiency of thermoregulation in hot environments can result in significant increases in the risk of heat illness development (7, 43, 168). As situations where the production of heat outweighs the ability of the body to remove excess heat the body core temperatures will begin to rise (50). If this rise in core temperatures becomes uncontrolled it will place the athlete at risk of developing heat illness (7, 34, 50). Heat illness can present in a number of different way (as outlined in Table 2.3), with the four most common and milder forms of heat illness consisting of heat oedema, heat cramps, heat syncope and heat exhaustion (7, 50). While, core temperatures above 40.5^{o}C have previously been reported as a sign and symptom of heat stroke (7, 17, 34, 50) evidence has also reported core temperatures >40.5^{o}C in elite cyclists without adverse health affects (161). Exertional heat stroke is less common than minor heat illness conditions, although is considered the most severe of heat illness classifications (50, 95, 138). Heat stroke is considered a medical emergency due to the uncontrolled elevation of core temperature having the ability to cause significant central nervous system dysfunction and permanent organ and tissue damage if exposure is prolonged (97). These organ system failures are caused by the increased core temperature damaging cell membranes, and disrupting energy pathways (61), disturbances to the cell can lead to cell death and organ failure if left untreated (7). Further, heat stroke is also considered a medical emergency as the body can often lose the ability cool itself and will require external cooling (7). In the occurrence of heat stroke ice baths have been suggested as the most effective method of cooling (7, 47). Symptoms of heat stroke can include hypotension, tachycardia, tachypnoea, syncope, coma, and acute renal failure (Table 2.3) (50). Although heat stroke is of serious concern there are only limited mentions of heat stroke during tennis matchplay in the literature (189).

Table 2.3: Heat illness symptoms, signs and treatments (50).

Illness	Symptoms	Signs	Treatment
Heat Oedema	None	Peripheral oedema	Rest, elevate extremities, acclimatisation
Heat Cramps	Painful muscle cramps	Palpable muscle spasm	Stretch, ice massage, oral fluids
Heat Syncope	Syncope	Loss of consciousness	Rest, supine with feet up, monitor vital signs.
Heat Exhaustion	Fatigue, Inability to continue exercise, mild confusion, nausea, vomiting, syncope, 'chills' to heat and neck	Hypotension, elevated core temperature up to 40.5°C, syncope	Monitor airways, breathing and circulation, cool rest, monitor temperature and vital signs, oral fluids.
Heat Stroke	Altered mental status, fatigue, nausea, vomiting, syncope	Elevated core temperature above 40.5°C, Hypotension, tachycardia, tachypnoea, syncope, possibly stop sweating, coma, acute renal failure, disseminated intravascular coagulation	Monitor airways, breathing and circulation, cool, call emergency services, monitor vital signs and intravenous fluids if available.

Heat exhaustion is a milder manifestation of heat stroke in which core temperatures remain below 40°C (6, 50). Further, heat exhaustion symptoms are milder than those of heat stroke, but may include dizziness, weakness, headaches and can lead to a physical collapse (Table 2.3) (80, 95). Further, heat exhaustion does not result in central nervous system dysfunction as typically observed during heat stroke (80). Intense exercise in hot and humid environments has been suggested to most likely result in heat exhaustion, due to decreased efficiency of evaporative cooling (39, 170). However, the increase in blood flow to the skin may also result in hypotension and cardiac insufficiency's leading to central failure (39, 50, 170). The occurrence of central failure may also lead to the development of heat syncope and a feeling of dizziness due to reduced blood flow to the brain (50). Further, dizziness is commonly reported within anecdotal reports from competitors during matchplay in hot conditions in tennis (48), though larger reporting of heat illness in tennis remains minimal.

Exertional heat cramps are the mildest, yet most commonly reported form of heat illness within tennis (19, 22, 50, 155). Heat cramps are painful muscle spasms of skeletal muscles, most commonly affecting the muscles of the legs, arms and abdomen, usually after long strenuous exercise and most commonly during exercise in hot environmental conditions (19, 24, 113, 187). The physiological cause of heat cramps are still the source of debate within the literature (7); although is commonly suggested that significant depletion of whole-body sodium stores and dehydration play a significant role in their development (18, 19, 22, 24, 96, 113). That said, the role of dehydration in the occurrence of cramping is becoming increasingly questionable (35, 120). Additionally, exercise induced muscle and neuromuscular fatigue have also been suggested to play a significant role in the development of heat cramps, particularly when in combination with dehydration and significant sodium loss (18, 120). As such tennis players are at high risk of the development of exertional heat cramps during matchplay in the heat, with previously reporting increased neuromuscular fatigue after matchplay in the heat (78, 152), and tennis players often becoming dehydrated during tennis matchplay in the heat (20, 21, 111).

2.9.2 Heat illness incidence in tennis

Tennis has been highlighted as a sport that predisposes athletes to a high risk of developing exertional heat cramps due to the duration of competition and potential for hot environmental conditions (7, 22-24). Further, competitors often have growing neuromuscular and physiological fatigue from both extended match durations and congested competition schedules (74, 163). Hot environments, such as those often encountered at the AO (44), expose players to significant cumulative heat load, which can significantly increase the risk of heat illness occurrence (9). The potential risk of heat illness due to the high accumulation of heat load is further exacerbated by the high density of extended matches making it difficult for athletes to ensure hydration and sodium replenishment is adequate to sufficiently recover between matches (7, 50, 153). Collectively, tennis players regularly compete in hypohydrated states with multiple matches in warm to hot environmental conditions; all of which can predispose players to an increased risk of heat illness development (7, 50).

The US Open is the only event to have previously reported the occurrence of heat illness rates in professional tennis. The authors reported that the US Open competition had a rate of heat illness of 2.14/1000 match exposures (ME) (173). Further, when examined according to gender, the women's competition had a heat illness occurrence rate of 1.42/1000 ME, while the men's competition reported a rate of 2.84/1000 ME (173). For context, over the same time period the occurrence rate of musculoskeletal injuries at the US Open was significantly higher (33.38/1000 ME in women; 47.74/1000 ME in men) (174). Regardless, there was no association between environmental conditions and the occurrence of heat illness (173). Interestingly, the authors suggested that the occurrence of heat illness was likely related to high levels of air pollution due to the close proximity of the US Open venue to New York city (173). This aligns with previous evidence also suggesting that air pollution can significantly impact exercise performance and heat outcomes, particularly in hot environments (28, 42).

Despite limited evidence examining the occurrence of exertional heat cramps in tennis, Therminarias et al. (189) provided an explorative analysis of the physiological markers in professional tennis players who suffered cramps and heat exhaustion/stroke during simulated matchplay in warm conditions (28.3 ± 0.7^{o}C) with restricted fluid intake. The authors found match intensity and dehydration levels did not differ significantly between those with and without symptoms of heat illness. However, there were significant differences in specific biological markers of women who suffer heat cramps; including anaemia, significant dehydration and deficiency in plasma magnesium and calcium both pre and post-match (189). Regardless, it was concluded that a number of factors combine to cause heat illness during tennis, including exercise duration, intensity, environmental conditions, dehydration and the pre-existing abnormalities in biological markers prior to matchplay (189). Further, a case study within tennis has also reported that frequent exertional heat cramps were prevented with an improvement in hydration strategies and daily sodium intake (22).

While the rate of heat illness occurrence for the US Open has been reported (173), there has been no analysis of the occurrence of heat related events, and the frequency of heat related medical consultations. Further, the US Open is notoriously for having a humid heat, whilst the AO is often impacted by extreme dry heat which may impact the occurrence of heat illness between the events (17, 50, 95). By assessing the implication of extreme heat at the AO on the occurrence of heat related events including the use of medical consultations it would better prepare medical staff and tournament organisers for matches played in these hot conditions.

2.10 Extreme Heat Policies (EHP)

Sports with the potential for matchplay to occur in hot conditions will often employ EHP's to dictate the modification or suspension of competition in order to safeguard competitors wellbeing and competition integrity (7, 15, 87, 135). Tennis is not unique in dealing with difficulties in determining the suspension of play due to extreme heat, with many summer sports often faced with this dilemma (87). Indeed early approaches to this issue were developed by the United States Army during World War II, and were among the first to implement an EHP in order to reduce the occurrence of heat illness during training camps (41). Initial forays into development of an EHP proved successful in reducing the occurrence of heat illness during military training camps from 12.4 per 10,000 trainees to 4.7 per 10,000 trainees (31, 41). The success of this initial EHP and continual issues surrounding sports training and competition in the heat lead the

ACSM to provide and revise their own EHP (7). Within the current ACSM Position Statement there are guidelines for event organisers, medical staff, athletes and coaches for the management of exercise in the heat and reducing the risk of developing of heat illness (as shown in Table 2.4). Within these guidelines temperature thresholds for suspension or modification of exercise are included; which have been widely adopted or slightly modified globally across many sports and governing bodies (7, 11, 15, 25, 31, 87, 99, 196), including tennis and the AO (11, 14, 99, 196).

Table 2.4: ACSM's extreme heat policy guidelines (7).

WBGT			Training and Noncontinuous Activity	
-F	-C	Continuous Activity and Competition	Nonacclimatized, Unfit, High-Risk Individuals [c]	Acclimatized, Fit, Low-Risk Individuals [c,d]
e50.0	e10.0	Generally safe; EHS can occur associated with individual factors	Normal activity	Normal activity
50.1–65.0	10.1–18.3	Generally safe; EHS can occur	Normal activity	Normal activity
65.1–72.0	18.4–22.2	Risk of EHS and other heat illness begins to rise; high-risk individuals should be monitored or not compete	Increase the rest:work ratio. Monitor fluid intake.	Normal activity
72.1–78.0	22.3–25.6	Risk for all competitors is increased	Increase the rest:work ratio and decrease total duration of activity.	Normal activity. Monitor fluid intake.
78.1–82.0	25.7–27.8	Risk for unfit, nonacclimatized individuals is high	Increase the rest:work ratio; decrease intensity and total duration of activity.	Normal activity. Monitor fluid intake.
82.1–86.0	27.9–30.0	Cancel level for EHS risk	Increase the rest:work ratio to 1:1, decrease intensity and total duration of activity. Limit intense exercise. Watch at-risk individuals carefully	Plan intense or prolonged exercise with discretion[f]; watch at-risk individuals carefully
86.1–90.0	30.1–32.2		Cancel or stop practice and competition.	Limit intense exercise[f] and total daily exposure to heat and humidity; watch for early signs and symptoms
>90.1	>32.3		Cancel exercise.	Cancel exercise uncompensable heat stress[e] exists for all athletes[f]

[a] revised from reference (38).
[b] wet bulb globe temperature.
[c] while wearing shorts, T-shirt, socks and sneakers.
[d] acclimatized to training in the heat at least 3 wk.
[e] internal heat production exceeds heat loss and core body temperature rises continuously, without a plateau.
[f] Differences of local climate and individual heat acclimatization status may allow activity at higher levels than outlined in the table, but athletes and coaches should consult with sports medicine staff and should be cautious when exceeding these limits.

Due to the lack of literature examining heat illness occurrence in tennis, EHP's at the AO prior to 2019 were guided by the ACSM EHP (7). The AO EHP prior to 2019 stated that at the tournament referee's discretion matchplay is to be suspended at 32.5^{o}C WBGT and 40^{o}C ambient air temperature (2, 14). Once matchplay has been suspended the tournament referee may opt to close the roof on courts with retractable roofs where play may then continue. However, there is limited peer review literature to support the use of this EHP at the AO and within tennis more generally. Thus suggestions in the literature call for a greater scientific backing for EHP within tennis (15, 44). As such the limited available literature examining the impact of extreme heat on tennis performance and heat illness occurrence in professional tennis makes it difficult for the justification or modification of EHP's within tennis. In addition to this EHP the AO up holds the WTA own heat rule, were at 28^{o}C WBGT women's and junior's matches receive a 10-minute break between the 2nd and 3rd set, if a 3rd set is to be played (196). However, this heat rule has been criticised in the literature for the limited available evidence within tennis to support its implementation at 28^{o}C WBGT (129, 157). Separately, Tippet et al. (191) demonstrated that this 10-min break in play was sufficient to significantly reduce core temperature (-0.25°C ± 0.20°C) during professional women's tournament matchplay in the heat (30.3°C ± 2.3°C). Consequently, implementation of the heat rule in tennis may be appropriate to reduce core temperatures during matchplay however, the temperature at which EHP should be implemented within professional tennis is still the source of significant debate (44, 129, 150, 157).

The ACSM's EHP is largely based on literature examining the impact of extreme heat on long distance running (7, 127), which has then been used to inform the historical AO EHP (7, 127). This use of long distance running evidence to inform EHP in elite tennis players has led concerns over the appropriateness of the current EHP's for tennis (127). Previous authors (127) have suggested that the percentage of VO_{2max} of tennis matchplay results in metabolic heat output that is significantly lower than the long distance running used for determining the EHP (127). As evidence, estimated tennis matchplay would have a metabolic heat rate of 850 W (estimation of work rate at 64% VO_{2max}), while long distance running has been shown to produce a metabolic heat output of approximately 1200 W (working at 80% VO_{2max}) (51, 56, 127, 137). While these are estimations, they do highlight a limitation with the current justification of EHP's within tennis. With significant differences in metabolic heat output potentially suggesting that the EHP in tennis is implemented to early, and as such limiting the advantages of players which appropriately acclimatised for the potential heat faced at the AO.

As a case study for similar concerns over the appropriateness of the use of the ACSM's EHP for professional athletes competing in intermittent sport have also been raised in relation to professional Beach Volleyball (15). Previous evidence reports a low rate of heat illness incidences over the course of a number of world tour seasons, even when competition was regularly played in conditions above the threshold temperature for all exercise according to the ACSM guidelines (32.3^{o}C WBGT) (15). Within this study the authors suggested that the low incident rate of heat illness even when competing in extreme heat was due to competitors being well acclimatised due to the world tour following the summer conditions around the world. They also suggested that Beach Volleyball is an intermittent sport so players were provided ample opportunities for rest, and hydration allowing for increased thermoregulation due to the lower work to rest ratios (15). Consequently, this led the authors to suggest that the ACSM EHP is too conservative for Beach Volleyball and the resultant cancelation of events when there was limited risk of heat illness for competitors would have grave consequence for the sport. Recognising the different duration and physical demands, the above arguments could theoretically apply to tennis with athletes being considered extremely fit (109, 110, 165), and are also provided ample opportunities for rest and hydration due to the scoring format. However, without completing a large-scale analysis at an event such as the AO, is it not possible to determine the appropriateness of the current EHP's within tennis.

Due to the limited peer-reviewed literature examining the appropriateness of current EHP's within tennis it is difficult for policy makers and tournament organisers within tennis to justify or adjust current EHPs (15, 44, 157). Furthermore, the significantly different physical and tactical demands of women's tennis in comparison to men's tennis (65, 165), in combination with the limited literature examining the impact of extreme heat in professional women's tennis provides additional challenges for tournament organisers in the formulation and adjustment to EHP within professional tennis. As such, analysis of the impact of extreme heat on professional tennis at the AO is required to provide a platform for future decision making surrounding the modification to professional matchplay in the heat at the AO.

2.11 Wet Bulb Globe Temperature (WBGT)

2.11.1 History of WBGT and calculation

Fundamental to many EHP's, including tennis is the use of the WBGT to guide decisions on the environmental conditions of play (7, 15). Historically the WBGT gained popularity after its innovation in the 1950's and was implemented by the US army due to the large number of heat illness events during training camps in the 1940's (41). The WBGT replaced the Effective Temperature index, due to its ease of calculation, and ability to account for the 4 major environmental factors affecting human thermoregulation. These four major environmental factors being solar radiation, humidity, air temperature and wind, of which the effective temperature calculations did not include solar radiation (4, 41). The WBGT index is currently the most widely implemented heat indices for estimating environmental conditions and human comfort both within industrial and sporting settings (4, 25, 36, 41). Further, the WBGT is extensively used for determining the implementation of EHP's in a wide variety of sports including Soccer (135), Tennis (14, 196), Olympic Sports (25), and Field hockey (87); however, most notability the WBGT index is used in the implementation of the ACSM's EHP (7).

The WBGT is calculated as a single number to determine the heat stress index. This is achieved by the weighted average of the dry bulb temperature, black globe temperature and natural wet bulb temperature (4, 36, 41). The black globe temperature is measured at the centre of a sealed matte-black globe exposed to the ambient solar radiation; the black globe primarily informs the amount of solar radiation (4, 36, 41). The natural wet bulb indicates the relative humidity of the environment, it is measured by a wet bulb thermometer that is naturally ventilated and is exposed to ambient thermal radiation (41). It has previously been suggested that measuring black globe and naturally wet bulb will also measure air movement, with wind cooling black globe and naturally wet bulb temperature down impacting on the end WBGT (4, 41). However, it is often criticised that these indirect measures of air movement do not appropriately reflect the impact of air movement on thermoregulation (41).

Additionally, dry bulb temperature is also measured to assess the ambient air temperature and must be shielded from the ambient solar radiation during measurement. In turn, black globe temperature, naturally wet bulb temperature and ambient air temperature are then weighted to calculate WBGT;

$$WBGT = 0.7NWB + 0.2GT + 0.1DB$$

NWB = natural wet bulb

GT = black globe

DB = dry bulb

Due to the limited measurement of the black globe temperature the ACSM has previously provided a formula to estimate WBGT for when black globe temperature is not available (1). The formula for the calculation of estimated WBGT is:

$$\text{Estimated WBGT} = 0.567 \times Ta + 0.393 \times e + 3.94$$

where:
Ta = Dry bulb temperature (°C)
e = Water vapour pressure (hPa) [humidity]

Vapour pressure is calculated from the temperature and relative humidity using the equation:

$$e = rh / 100 \times 6.105 \times \exp (17.27 \times Ta / (237.7 + Ta))$$

where:
rh = Relative Humidity [%]

The above estimation of black globe temperature provides a fixed weighting of the black globe temperature expected during a mostly sunny day with light wind (13). This fixed estimation of black globe temperature may lead to the underestimation of conditions in hot sunny days with little wind, or overestimation in cloudy days with significant wind, or night (4, 36, 41, 72, 114). Regardless, estimated WBGT has frequently been utilised in a number of peer reviewed studies in situations where black globe temperature was not available (30, 72, 87, 88, 104, 105, 148, 149, 197). The use of estimated WBGT within the peer-reviewed literature has included large scale meta-analysis, where estimated WBGT was used to include studies that only provided dry bulb temperature and relative humidity (88). Furthermore, estimating WBGT is also widely utilised in sporting contexts for the implementation of EHP's (5, 72, 87), and by the Australian Bureau of Meteorology (13). Further, the Australian Bureau of Meteorology provides the environmental conditions for the AO, with estimated WBGT having previously been used for determining the implementation of the EHP at the AO. Due to the potential for underestimation of hot sunny conditions by estimated WBGT and the regular occurrence of hot conditions at the AO an analysis is required to assess the association of heat related events and performance adjustments at the AO in response to increased estimated WBGT.

2.11.2 Limitations of WBGT

Despite the wide-spread use of WBGT index to establish thresholds for exercise modification in hot environments, there are significant limitations to the WBGT index that need to be recognised. Firstly, it has been suggested that the fixed weighting of the naturally wet bulb temperature leads to significant underestimated of the thermal strain placed on an exercising individual in hot conditions where evaporation is restricted (4, 36, 41). With evaporation being the only method of cooling once air temperature surpasses skin temperature (17, 34), as such restriction of evaporative cooling by sweeting in hot conditions will place the body under significant strain in hotter environments, particularly when there is little air movement (17). This under estimation of thermal strain in restricted evaporative environments is due to the fixed weighting of the natural wet bulb of 0.7 within the WBGT formula (41). It has also been suggested that this weighting of the neural wet bulb is excessively high in lower temperatures, with the body relying more heavily on radiant heat loss in cooler temperature (41). Arguments have been made for a sliding scale for humidity based on ambient temperature, by which to properly weight the importance of evaporative cooling depending on the ambient air temperature. However, this would essentially provide similar problems as the effective temperature scale (41) which lead to the creation of the WBGT index. Although, with modern technology the issues surrounding the effective temperature scale are likely reduced.

The WBGT has also been cited for its limitations surrounding its ability to account for the impact of air movement on thermal strain (36, 41, 114). With WBGT indirectly accounting for wind speed through the black globe and naturally wet globe temperature, while it has been suggested that these do not adequately account for the impact of wind on the thermoregulation in humans (36, 41, 114). As wind and air movement during locomotive sports, such as tennis, is a major contributor to thermoregulation in humans. Further, it has been suggested that the indirect measurement of air movement does not truly account for the importance of air movement in human thermoregulation (41, 114). Additionally, wind also improves the efficiency of evaporation, which increases the importance of wind in evaporation restricted environments, particularly in hotter temperatures (37, 38).

Issues have also been raised surrounding the way in which the WBGT accounts for clothing within its calculation, with the original weightings of the WBGT used to take into account the olive drab uniforms of the US army at the time (4). While the use of the WBGT has extended well beyond use by the US army and the WBGT has not yet been adjusted to take into account changes to clothing. This is particularly imperative in sport due to the significantly improved technology in sporting clothing, which have increased ventilation and reduced heat storage (29, 36, 41). However, it may be argued that rather than adjusting WBGT to account for clothing, that heat policy's should adjust to account for clothing variation.

While the aforementioned limitations exist with the use of WBGT and estimated WBGT (4, 36, 41); the wide spread use of WBGT with substantial historical records makes the measurement the most easily comparable measure between various sporting and industrial setting. Further, the wide spread use of WBGT and estimated WBGT within tennis makes the use of these measures the most practically relevant for retrospective analysis of the impact of extreme heat on tennis performance.

2.12 State of the Literature

The rationale behind the current literature review was to investigate and highlight the available literature examining the impact of extreme heat on tennis performance and heat illness occurrence in professional tennis matchplay. While the impact of extreme heat on exercise performance and heat illness occurrence has gained a significant amount of attention in the literature, there is a substantial gap when specifically examining tennis. With only a small number of studies specifically examining the impact of extreme heat on tennis performance found (54, 94, 154), with even fewer examining heat illness (22, 155, 173) occurrence during professional tennis matchplay. Of these available studies, very few examined high level professional tennis players in live Grand Slam competition.

The reporting of heat illness occurrence within professional tennis is significantly limited with only the US Open previously reporting the rate of heat illness at their event (173). Outside of this report a handful of case studies have document treatment and symptoms of heat illness occurrence within elite tennis players (22, 155). However, this significant gap in the literature makes it challenging to determine the appropriateness of heat policies within professional tennis. Further, the absence of comprehensive analysis of the occurrence of heat illness and heat related events during professional tennis at the AO or other Grand Slam events makes the justification of adjustment of EHP within tennis challenging.

The impact of extreme heat on tennis performance has only been examined in a handful of studies, utilising only a small number of match characteristics in men (54, 154), further only one study examined sanctioned professional tournament matchplay (94). However, it has been suggested that extreme heat had no impact on matchplay performance, although there were significant adjustments to work to rest ratios (94, 154). Further, the use of simulated matchplay may have significant implications on the motivation and effort of players within the study, potentially altering the implications extreme heat on matchplay performance. Without examining the performance implications of tennis matchplay in hot conditions during Grand Slam tournament matchplay it is not possible to gain a deeper understanding as to how professional tennis matchplay performance may be impacted by extreme heat.
Consequently, this significant gap in the literature surrounding the occurrence of heat illness and changes to performance in response to extreme heat during professional tennis matchplay makes it difficult for tournament organisers and medical staff to appropriately prepare for professional tennis events where hot conditions may occur. However by developing a deeper understanding of how extreme heat affects the occurrence of heat illness during professional tennis tournament matchplay organisers will be able to make informed decisions for the scheduling of matches and match suspension when extreme heat is predicted during matchplay. Further, understanding the effect of extreme heat on match performance will help tournament organisers to consider the impact of extreme heat on matchplay quality and integrity of the

competition. Finally, coaching staff and competitors would value understanding how performance may change during matchplay in the heat, as to better prepare match tactics and understand how their own game may be impacted. As such, the current thesis will in part fill the current gaps in the literature by examining the effect of estimated WBGT on professional tennis performance and heat related incidents during live tournament matchplay in both the men's and women's AO.

Chapter Three

Study 1

As based on publication:

Smith MT, Reid M, Kovalchik S, Woods TO, Duffield R. Heat stress incident prevalence and tennis matchplay performance at the Australian Open. *Journal of Science and Medicine in Sport*. 2018;21(5):467-72.

3.1 Abstract

Objective: To examine the association of wet bulb globe temperature (WBGT) with the occurrence of heat-related incidents and changes in behavioural and matchplay characteristics in men's Grand Slam tennis.

Methods: On-court calls for trainers, doctors, cooling devices and water, post-match medical consults and matchplay characteristic data were collected from 360 Australian Open matches (first 4 rounds 2014-16). Data were referenced against estimated WBGT and categorised into standard zones. GLM's assessed the association of WBGT zone on heat-related medical incidences and matchplay variables.

Results: On-court calls for doctor (47% increase per zone, p=0.001), heat-related events (41%, p= 0.019), cooling devices (53%, p<0.001), and post-match heat-related consults (87%, p=0.014) increased with each rise in estimated WBGT zone. In WBGT's >32^{o}C and >28^{o}C, significant increases in heat-related calls (p=0.019) and calls for cooling devices (p<0.001), respectively, were evident. The number of winners (-2.5 ± 0.006% per zone, p<0.001) and net approaches (-7.1 ± 0.008%, p<0.001) reduced as the estimated WBGT zone increased, while return points won increased (1.750 ± 0.459, p<0.001). When matches were adjusted for player quality of the opponent (Elo rating), the number of aces (5 ± 0.018%, p=0.003) increased with estimated WBGT zone, whilst net approaches decreased (7.6 ± 0.013%, p<0.001).

Conclusions: Increased estimated WBGT increased total match doctor and trainer consults for heat related-incidents, post-match heat-related consults (>32^{o}C) and cooling device callouts (>28^{o}C). However, few matchplay characteristics were noticeably affected, with only reduced net approaches and increased aces evident in higher estimated WBGT environments.

3.2 Introduction

The Australian Open (AO), one of the four Grand Slam tennis tournaments, is held during the Australian summer with matchplay regularly occurring in high (>28^{o}C) and sometimes extreme (>32^{o}C) WBGT. In such conditions the risk of heat illness (7, 50, 160) and reduced performance (57, 188) is of concern; though evidence from professional tennis matchplay remain scarce (127). The protection of players, officials and spectators necessitates the existence and implementation of EHP's, which guide continuation or suspension of play. The current AO policy is guided by the WBGT index, which is widely deployed (98, 99, 135) as a measurement of thermal stress (126). Indeed, it is instructive that the American College of Sports Medicine (ACSM) has used the WBGT to derive general guidelines for exercise in the heat. For example, exercising strenuously in conditions >28^{o}C (WBGT) is considered "high risk" while exercise is suggested to be stopped >32^{o}C (8, 50). However, such conditions are regularly encountered at the AO, and much debate exists regarding the fair implementation of the EHP to ensure player wellbeing without compromising the tournament's integrity.

Strenuous exercise in hot environmental conditions increases the potential for developing heat illnesses (34, 160) such as, heat cramps, heat exhaustion and heat stroke (34, 50). Limited literature of heat illness exists in professional tennis, though the US Open (between 1994 and 2009) has previously documented heat illness occurrence rates of 2.84 per 1000-match exposures in men's matches (173); despite the recorded environmental conditions appearing too temperate (26-33^{o}C ambient temperature) to pose a high risk (173). Regardless, these data confirm the presence of heat illness in tennis, yet provide little insight into player discomfort. Accordingly, a focus on other indicators of player distress, such as calling for additional water or cooling devices, would help to further clarify the level of environmental stress experienced *insitu* by professional tennis players.

In the absence of specific heat stress data measurement of core temperature responses to matchplay in the heat are used as evidence of the inferred risks (76, 127). During matchplay in a range of ambient temperatures (14.5 - 38.4^{o}C dry bulb) core temperatures remain stable and commonly reported between 37.0 to 39.0^{o}C, however core temperatures have been reported ~39.5^{o}C (27, 128). Evidence of changes in match characteristics due to increased temperature are largely anecdotal, suggesting reductions in ball velocity and court movement speed. However, repeated-sprint, change of direction and vertical jump following matchplay in hot temperatures appear unaffected when compared to cooler temperatures (76). Further, the number of games, points, aces, double faults, or the length of points have also been shown to be unaffected between hot and cool playing conditions (154). In part, the maintenance of normal core temperatures and lack of reduction in physical capacities may be attributed to modifications in on-court behaviour, such as increased between-point rest duration to manipulate work-to-rest ratios (154). However, these studies are not representative of the cohort or performance context of Grand Slam competitions, with participants in these studies having much lower professional rankings than most Grand Slam competitors.

The risk of heat illness and reduction in performance during Grand Slam matchplay remains relatively poorly understood and the effect of extreme heat on player wellbeing and performance is speculative. Accordingly, to determine the effect of environmental conditions on Grand Slam tennis, this study retrospectively examined the association between estimated WBGT and markers of heat-related trainer and doctor consults, on court requests for water and cooling devices, and match characteristics at the men's Australian Open. It was hypothesized that increased estimated WBGT would result in increased heat-related trainer/doctor consults and alter player behaviour (i.e. calls for water and cooling devices) with minimal changes to match characteristics.

3.3 Methods

Data were obtained from all 360 matches in the first four rounds of the 2014, 2015 and 2016 AO Men's Main Draw, made up of 189 participants with a mean ± standard deviation (SD) age of 27.8 ± 3.8 years, from 54 countries and an Association of Tennis Professionals rank of 66 ± 69. Consent for the use of data for research purposes was gathered from all participants upon entry to the tournament via tournament conditions of entry. This study was approved by the University of Technology Sydney Human Research Ethics Committee (UTS REF: 2015000126).

Descriptive point level data and player rank information were collected from the AO tournament organisers. Point level data were generated in real time via match umpires and/or tennis match coding professionals. These coding professionals were extensively trained and used a platform that is widely deployed. While no reliability data is available on the coding professionals, tennis match statistics have been shown to have very high levels of inter- and intra-tester reliability (91). Point level data of all match characteristics outlined in Table 3.1 were collected and aggregated to the match level. Match averaged estimated WBGT was calculated from weather data retrospectively collated from half-hourly recordings from an Australian Bureau of Meteorology weather station located within 100m of the venue. Due to the Australian Bureau of Meteorology not explicitly measuring globe temperature, an estimated WBGT is provided instead to categorise matches based on: WBGT = 0.567 x Ta + 0.393 x e + 3.94, where Ta= dry bulb temperature (^{o}C) and e = Water vapour pressure (hPa) [humidity]. This formula is recommended by the ACSM for estimating WBGT without black globe temperature (5, 7), and has been successfully used in large scale meta-analysis of physical performance in hot environments (88), and in studies where black globe temperature was not available (87). Despite WBGT being one of several measures of thermal stress and its limitations related to potential underestimation of the stress of restricted evaporation(41), it is the primary measure of heat stress throughout international tennis (14, 196).

Table 3.1: Descriptors of match characteristics data collected.

Measure	Description
Medical and Behavioural Characteristics	
On court trainer calls	A call by the on court umpire for a trainer to the court for a specific player.
On court doctor calls	A call by the on court umpire for a doctor to the court for a specific player.
If on court doctor or trainer call was heat related incident	If the nature of the on court consult was recorded as heat related
Post match consults with Doctor for heat related incident	The number of post match doctor heat related incident consults made by athletes
Retirements	The number of athletes that retire from a match
Heat Stress Retirement	The number of athletes that retire from a match due to heat stress
On court calls for cooling devices	If the on court match umpires made a court call for any cooling devices including, ice, ice towels or ice vests.
On court calls for water	If the on court match umpires made a court call for any water or sports drinks
Match Characteristics	
Match Duration (min)	Length of the match in minutes
First serve (%)	The percentage of first serves made
Number of Aces	Total number of aces
Double Faults	Total number of double faults
Unforced Errors	Total number of unforced errors
Winners	Total number of winners
Winning on first serve (%)	Percentage of points won when first serve was made
Winner on Second Serve (%)	Percentage of points won when second serve was made
Break point conversion (%)	Percentage of break points won
Return points won	Percentage of return points won
Total points won	Total number of points won by the player in the match
Total match points	Total number of points in the match
Number of net approaches	Total number of net approaches
Net approaches won (%)	Percentage of net approach points won
Fastest serve (km/h)	Speed of the fastest serve in the match
Average first serve speed (km/h)	Average speed of all first serves by the athlete in the match
Average second serve speed (km/h)	Average speed of all second serves by the athlete in the match

Time stamped tournament communication logs were used to inform the timing of on-court calls for medical consults and flagged as heat-related by presiding physician, alongside calls for cooling devices/water (Table 3.1). Post-match heat-related consults were collated from the AO medical database, which captures all athlete-doctor consultations during the event. Matches were excluded from analysis if they were missing data (i.e., WBGT, on-court calls, or large amounts of match data) (n=22), suspended for rain or played under a closed roof (n=4). Matches that were suspended due to EHP were separated into pre-EHP and post-EHP and reintroduced into the data set as separate matches (n=3) and treated as individual matches in differing temperature zones. This was to ensure all data from matches in hotter conditions were included and to include all available performance data for players who had played in some of the hottest conditions. All data from court call logs, medical consults, match statistics and Australian Bureau of Meteorology recordings were collated into Microsoft Excel and classified into a WBGT zone according to the ASCM classification (1), zone 5: >32.3^{o}C, zone 4: 30.1-32.2^{o}C, zone 3: 27.9-30^{o}C, zone 2: 22.3-27.9^{o}C , zone 1: <22.2^{o}C (with ACSM's zones <10 and 10.1-22.2^{o}C being combined to form zone 1, and zones 22.3-25.6^{o}C and 25.7-27.8^{o}C being combined to form zone 2).

Analyses for the present study were completed in RStudio version 0.99.902 (RStudio: Integrated Development for R. RStudio, Inc., Boston, MA). Generalised linear models (GLM) were used to assess zone associations study outcomes. Count outcomes were modelled with a Poisson distribution and continuous outcomes with a Gaussian distribution. Medical and behavioural outcomes were considered per match and per 1000 match hours. Odds ratios were calculated for medical call outs and behavioural characteristics in each WBGT zone. In these comparisons, zone 5 was the WBGT reference group and, being the reference group, we report the baseline odds of an event rather than the odds ratio. The odds for zone 5 were obtained by exponentiation of the intercept term of the logistic model while the odds ratios were obtained by exponentiation of the model coefficients corresponding to each comparison WBGT zone.

Performance outcomes were assessed without adjustment for player quality ("unadjusted" models) and with adjustment for player quality ("adjusted" models). In the adjusted analyses, players were defined as being of *similar* quality if their pre-match Elo ratings, a metric that accurately captures a player's ability at the time of the match, were within 50 points of each other (112). Elo ratings are based on the strength of their career wins rather than just ranking. The unadjusted analyses compared performance outcomes of all matches in each zone. Since by chance, these groups could have a different distribution of quality of players that could confound the assessment of the association with zone. As such, the adjusted analyses matched each player and opponent in matches in the extreme zone group (5-3) to a match in a normal zone condition whose player and opponent were of similar quality (1-2). Confidence intervals are reported at the 95% level and statistical significance was defined as an effect of 5% significance or less.

3.4 Results

With each increase in estimated WBGT zone there was an increase in total doctor calls (47% increase per zone; p=0.001), trainer calls for heat-related incidents (41%; p=0.019), post-match heat-related incident consults (87%; p=0.014), total heat-related incident consult (55%; p<0.001), and total calls for cooling devices (53%; p<0.001). When medical and behavioural events were examined as a rate per 1000 hours, the largest increases in total heat-related incidents and total trainer calls occurred from zone 4 to zone 5 (76.5% and 22.6% increases, respectively; Table 3.2). In contrast, non-heat related trainer calls decreased from zone 4 to 5 (58.9, 76.4 calls /1000h respectively), whilst zone 5 had the lowest rate of non-heat related trainer consults. Of note, the number of retirements significantly increased in zone 5 (29.44/1000h), with 2 of those retirements being heat incident related, whereas zone 4 had no heat-related retirements.

Table 3.2 Medical and behavioural characteristics as a rate per 1000 hours (absolute occurrence) according to ACSM WBGT zones in men.

Variable	Zone 5 >32.3°C	Zone 4 30.1-32.2°C	Zone 3 27.9-30°C	Zone 2 22.3-27.9°C	Zone 1 <22.2°C
Total match play time in minutes (number of matches)	8152 (30)	8642 (29)	5572 (18)	58954 (203)	16992 (60)
Retirement	29.4 (4)	13.9 (2)	0 (0)	12.2 (12)	3.5 (1)
Heat Stress Retirement	14.7 (2)	0 (0)	0 (0)	1.0 (1)	0 (0)
Trainer Call	80.7(11)	62.5 (9)	53.8 (5)	69.2 (68)	70.6(20)
Doctor Call	22.1 (3)	27.8 (4)	21.5 (2)	4.1 (4)	0 (0)
In match Heat Stress Call	29.4 (4)	6.9 (1)	0 (0)	3.1 (3)	7.1 (2)
Non Heat Stress Call	58.9 (8)	76.4 (11)	75.4 (7)	68.2 (67)	63.6 (18)
Post Match Heat Stress Call	29.4 (4)	6.9 (1)	0 (0)	0 (0)	0 (0)
Cooling Device Call	103.0 (14)	69.4 (10)	43.1 (4)	16.3 (16)	0 (0)
Water Calls	22.1 (3)	27.8 (4)	10.8 (1)	25.4 (25)	21.2 (6)

Table 3.3 summarises the odds ratio of medical and behavioural characteristics when compared to zone 5. The odds of a player calling for trainers during the match did not significantly change when each compared to zone 5 ($p>0.05$). For the odds of a doctor being called during a match, only zone 2 showed significant change with an 81% ($p=0.032$) decrease in likelihood when compared to zone 5; though zone 1 had no occurrences, and thus no comparison was made. The odds of a trainer/doctor call being a heat-related incident was only significantly different with zone 2, with a decrease compared to zone 5 (90%; $p=0.004$). Cooling device call outs decreased by 86% ($p<0.001$) in zone 2 when compared to zone 5, without significant differences to other zones ($p>0.05$). Non-heat related trainer/doctor on court calls, water call outs and post-match heat-related incident consults were statistically comparable between zones ($p>0.05$).

Table 3.3 Odds for medical and behavioural characteristics according to ACSM WBGT zone in men.

	Zone 5 Reference Group[a]	Odds ratio compared to zone 5			
	Zone 5 >32°C	**Zone 4 30-32°C**	**Zone 3 28-30°C**	**Zone 2 22-28°C**	**Zone 1 <22°C**
Player calling for trainer during match	0.22 ± 0.33 (<0.001)	0.82 ± 0.49 (0.684)	0.72 ± 0.59 (0.573)	0.90 ± 0.36 (0.760)	0.89 ± 0.41 (0.780)
Player calling for Doctor during match	0.05 ± 0.59 (<0.001)	1.407 ±0.79 (0.664)	1.12 ± 0.94 (0.906)	0.19 ± 0.78 (0.032)*	0 (0)
Call for trainer or doctor was Heat stress related	0.07 ± 0.52 (<0.001)	0.25 ± 1.13 (0.216)	0 (0)	0.10 ± 0.78 (0.004)*	0.24 ± 0.88 (0.103)
Post match heat stress consultation	0.07 ± 0.51 (<0.001)	0.25 ± 1.13 (0.216)	0 (0)	0 (0)	0 (0)
Non heat stress trainer or doctor call	0.15 ± 0.38 (<0.001)	1.52 ± 0.51 (0.407)	1.57 ± 0.57 (0.427)	1.29 ± 0.40 (0.534)	1.15 ± 0.46 (0.764)
Cooling device called for	0.304 ± 0.31 (<0.001)	0.69 ± 0.46 (0.413)	0.41 ± 0.61 (0.146)	0.14 ± 0.40 (<0.001)*	0 (0)
Water called for	0.053± 0.59 (<0.001)	1.41 ± 0.79 (0.664)	0.54 ± 1.17 (0.603)	1.14 ± 0.63 (0.834)	0.83 ± 0.75 (0.798)

Odds ratio for medical and behavioural characteristics when compared to zone 5: odd ratio ± standard error (p value). *=(p<0.05)
a The effect shown for the reference category are the odds of the outcome for zone 5 matches

Table 3.4 shows the match characteristics per estimated WBGT zone and their change without adjustment for player Elo quality. The number of points won on return of serve increased by 1.8 ± 0.4 ($p<0.001$) points per increase in estimated WBGT zone, although the large standard error may make this result of modest practical significance. Further, both the number of winners (2.5 ± 0.01%, $p<0.001$) and net approaches (7.1 ± 0.008%, $p<0.001$) decreased for every increase in estimated WBGT zone. No other match characteristics showed significant differences between estimated WBGT zones ($p>0.05$).

Table 3.4: Match characteristics and association of change per ACSM WBGT zone in Non-ELO adjusted matches in men.

	WBGT 5 >32.3°C	WBGT 4 30.1-32.2°C	WBGT 3 27.9-30°C	WBGT 2 22.3-27.9°C	WBGT 1 <22.2°C	Association of change to WBGT zone
Match Duration (min) ø	143.6±41.7	152.8±54.3	155.7±42.2	145.2±44.5	141.6±43.0	-0.38±1.54ø(0.804)
1st Serve Percentage (%)ø	61.8±7.7	59.6±6.9	61.6±7.2	61.2±7.2	62.1±6.0	+0.31±0.24ø (0.193)
Aces (count) ≠	11.0±6.8	10.9±10.9	13.8±9.4	10.8±7.3	9.5±7.0	+0.011± 0.01¥ (0.27)
Double Faults (count) ≠	4.5±2.8	5.3±3.6	5.3±3.9	4.4±2.9	4.0±2.7	+0.042±0.016¥ (0.008)*
Winning on 1st Serve (%)ø	72.3±9.6	73.8±8.5	74.9±8.3	73.0±9.4	72.1±72.1	+0.148±0.315ø (0.639)
Winning on 2nd Serve (%)ø	49.8±10.9	51.3±11.9	53.0±9.3	51.2±10.5	51.5±11.4	-0.191±0.373ø (0.609)
Unforced Errors (count) ≠	31.2±19.5	32.9±21.2	38.7±17.7	32.8±18.3	32.5±18.9	-0.191±0.373¥ (0.609)
Breakpoint Conversation (%)ø	44.9±14.4	43.2±43.2	42.3±20.6	42.2±19.4	43.4±20.4	+0.543±0.711ø (0.445)
Return Points Won (%)ø	36.3±8.7	35.5±35.5	33.4±8.2	35.6±9.0	35.9±9.3	+1.750±0.459ø (<0.001)*
Total Points Won (count) ø	105.9±30.1	114.3±40.5	118.3±31.7	111.1±32.8	109.6±36.9	-1.476±1.166ø (0.206)
Total points (count) ø	211.7±55.8	228.7±77.7	236.6±59.8	222.1±61.7	219.2±69.6	-2.952±2.206ø (0.181)
Winners (count) ≠	32.8±17.6	32.4±20.9	39.9±17.6	33.9±17.4	32.9±17.1	-0.025±0.006¥ (<0.001)*
Net Approaches (count) ≠	20.5±9.7	22.5±14.9	24.8±14.3	23.3±13.5	24.7±12.3	-0.071±0.008¥ (<0.001)*
Net Approaches Won (%)ø	66.1±14.8	66.6±15.3	64.2±12.3	66.3±13.3	66.0±13.8	+0.230±0.521ø (0.66)
Fastest Serve (km/h) ø	205.1±10.5	206.9±10.7	210.4±11.7	205.7±16.7	205.1±11.2	+0.251±0.635ø (0.693)
Average 1st Serve Speed (km/h) ø	180.9±7.8	183.4±9.5	187.0±11.7	185.1±10.1	184.1±9.1	+0.716±0.428ø (0.095)
Average 2nd Serve Speed (km/h) ø	148.9±10.3	148.3±8.5	151.6±13.5	151.4±10.7	149.6±10.3	+0.523±0.464ø (0.261)

Match characteristics: match characteristics average ±SE. Table gives match characteristics average across each temperature zone in from ELO adjusted matches characteristics and the association of change per change in WBGT zone as calculated through GLM analysis. –or+ indicates the direction of slope (- = decrease in hotter condition, + = increase in hotter conditions). ø denotes continuous data, data displayed as a change of the mean. ≠ denotes count data, data displayed as a rate ratio. *=(p<0.05).

Table 3.5 shows the match characteristics per estimated WBGT zone and change per zone when adjusted for differences in player Elo quality. Analysis suggests that aces increased by 5 ± 0.018% ($p=0.003$) per increase in estimated WBGT zone, while net approaches decreased by 7.6 ± 0.013% ($p<0.001$) per zone. No other match characteristics showed significant differences between estimated WBGT zones ($p>0.05$).

Table 3.5: Match characteristics and association of change per ACSM WBGT zone in ELO adjusted matches in men.

	WBGT 5 (ELO) >32°C	WBGT 4 (ELO) 30-32°C	WBGT 3 (ELO) 28-30°C	WBGT 2 (ELO) 22-28°C	WBGT 1 (ELO) <22°C	Association of change to WBGT zone
Match Duration (min) ø	144.8±49.9	144.8±50.1	142.5±47.1	140.8±41.7	137.0±42.1	+2.04±2.51 (0.418)
1st Serve Percentage (%)ø	60.8±7.1	60.5±7.3	61.3±7.8	62.6±7.2	62.5±7.1	-0.442±0.413 (0.286)
Aces (count) ≠	10.2±7.4	10.2±7.3	10.1±7.5	8.5±6.7	8.2±6.5	+0.05±0.018 (0.003)*
Double Faults (count) ≠	4.6±3.3	4.7±3.4	4.1±3.2	3.6±2.7	3.7±3.1	+0.045±0.027 (0.091)
Winning on 1st Serve (%)ø	72.3±9.1	72.7±9.1	73.0±8.5	72.0±9.4	71.6±9.7	-0.442±0.413 (0.286)
Winning on 2nd Serve (%)ø	50.5±10.9	50.8±11.1	52.2±10.5	50.9±10.5	51.0±10.5	-0.328±0.618 (0.596)
Unforced Errors (count) ≠	31.1±20.9	30.9±20.4	31.5±18.2	27.7±20.9	28.2±21.0	-0.001±0.010 (0.915)
Breakpoint Conversation (%)ø	44.8±17.9	44.5±18.1	45.4±20.3	44.6±18.2	46.0±18.5	+0.865±1.114 (0.439)
Return Points Won (%)ø	36.1±8.5	35.9±8.6	34.3±10.1	34.5±12.3	34.4±12.9	+0.808±0.607 (0.185)
Total Points Won (count) ø	108.0±36.9	107.6±36.2	106.2±33.6	108.3±32.4	105.1±32.8	+0.455±1.889 (0.81)
Total points (count) ø	216.1±70.7	215.2±69.2	212.4±32.9	216.6±61.8	210.1±62.5	+0.910±3.558 (0.798)
Winners (count) ≠	30.9±2.1	30.9±19.6	32.2±18.3	29.0±17.5	28.1±16.6	+0.007±0.010 (0.48)
Net Approaches (count) ≠	15.9±14.0	15.9±13.7	18.6±15.2	18.9±16.1	18.0±15.3	-0.076±0.013 (<0.001)*
Net Approaches Won (%)ø	66.6±14.8	60.5±15.5	67.0±13.6	65.9±14.6	65.8±15.0	+0.588±0.876 (0.503)
Fastest Serve (km/h) ø	206.2±9.9	206.3±16.4	206.5±11.5	203.4±13.0	202.7±13.7	+0.164±0.995 (0.869)
Average 1st Serve Speed (km/h) ø	181.9±9.1	182.3±9.4	183.7±11.4	182.0±8.0	181.8±7.9	-1.254±0.733 (0.09)
Average 2nd Serve Speed (km/h) ø	148.6±10.2	148.7±10.1	150.0±11.8	147.6±9.1	147.5±8.8	-0.532±0.782 (0.498)

Match characteristics: match characteristics average ±SE. Table gives match characteristics average across each temperature zone in from ELO adjusted matches characteristics and the association of change per change in WBGT zone as calculated through GLM analysis. –or+ indicates the direction of slope (- = decrease in hotter condition, + = increase in hotter conditions). ø denotes continuous data, data displayed as a change of the mean. ≠ denotes count data, data displayed as a rate ratio. *=(p<0.05).

3.5 Discussion

This study represents the first examination of the association of estimated WBGT and heat-related incidents, behavioural and matchplay characteristics in Grand Slam tennis. As expected, higher WBGT zones resulted in increased occurrence of heat-related incidents, which was particularly evident >32^{o}C WBGT, and increased cooling device call outs >28^{o}C WBGT. Regardless, there was minimal association between higher WBGT and most matchplay characteristics; with only net approaches and aces shown to decrease and increase in higher temperatures zones.

Although heat illness is caused by a number of factors, high environmental stress as represented by high WBGT, has been cast as a significant risk factor (7). From the present study, it was demonstrated that estimated WBGT in professional men's Grand Slam tennis was positively associated with heat-related incidence. More specifically, Grand Slam matchplay in conditions >32^{o}C WBGT were characterised by the highest number of heat-related retirements (14.7/1000 h in zone 5) and ensuing post-match heat related medical consults (87%; p=0.014). Previously, the US Open reported heat-related incidence rates of 2.84 per 1000 match exposures, without association to environmental temperature (173). While the present study shows a significant association between estimated WBGT and heat related incidents with an in-match heat related incident rate of 14.7 per 1000 match exposures over the 3-year data set. Thus the current study highlights the extent of heat-related incidents relative to WBGT zone for Grand Slam tennis, these results generally align with the ACSM position stance (7) and the current AO heat policy (14), whereby matchplay can be suspended in temperatures above 32.5^{o}C WBGT.

While the incidence of heat-related events increased >32°C WBGT, this study also demonstrated an increased number of calls for cooling devices, particularly from zone 2 to 3 (>28°C WBGT); suggesting athletes began to find the conditions thermally challenging (68). Surprisingly there was no significant increase in calls for water, although this may be due to high courtside availability of fluid. There are limited, if any, previous accounts of player behaviour during Grand Slam matchplay in the heat. Consequently, this paper provides initial evidence that player discomfort becomes evident in temperatures beyond 28°C WBGT, although it must be noted that our use of WBGT zones precludes the determination of an explicit inflection point for increased player discomfort.

In the present study neither mean match duration nor total number of points per match differed with increased estimated WBGT zones. This finding contrasts with previous research, in lower-ranked professional tennis players, which suggests match duration increases in the heat because of increased rest periods (154). It is important to note that previous research was conducted on timed simulated matchplay, possibly reducing participant's motivation given career success was not determined by match outcome. The similarity in match duration between estimated WBGT zones in the current study may also relate to the ITF ruling that a maximum of 20 sec is allowed between points in professional tennis, thus preventing manipulation of rest period durations (99). However, it cannot be discounted that the increase in trainer/Doctor call outs with increasing estimated WBGT zone may indicate an attempt by players to slow the match down to reduce effective play percentage by using a medical time out (99).

The impact of extreme heat on tennis matchplay characteristics is relatively unknown, with suggestions of negligible influence on number of games, points, aces, double faults, or the point duration (154). In the present study, most markers of matchplay did not significantly differ between estimated WBGT zones. However, an increase in return points won, decrease in the number of winners and the number of net approaches were evident as WBGT increased. It is important to note that the increase in return points won with each increase in estimated WBGT zone may be confounded by the high standard error, and the relatively small association. The 2.5% decrease in winners with each increase in estimated WBGT zone may relate to a decrease in the court coverage and a change of court position by players in hotter conditions, confounding their balance and ability to execute winners (163). It may also be a case of winners or preceding shots to set up winners requiring more physical, technical or mental effort, meaning that a reduction in the number of attempted winners may also form a component of an overarching pacing strategy. Finally, the decrease in winners may have been explained by an increase in forced errors on the part of opponents; but, unfortunately, forced error data was not available to test this hypothesis. The significant decrease in the number of net approaches during hotter conditions (-7.1%, $p<0.001$) also infers that players adopted baseline oriented game styles to conserve energy and/or assume a more conservative approach to winning points (163).

The examination of match characteristics when match quality was statistically controlled revealed that the number of aces increased with each increase in estimated WBGT zone. Thus with increased WBGT, players seemingly attempted more decisive or riskier serves to shorten points and reduce the chances of extended matchplay, whereas during baseline rallies a more conservative approach is evident due to the decreased number of winners. Hence, players selectively choose when to be aggressive or conservative during matchplay in increased WBGT. Or, in other words, they're constantly evaluating risk and reward, where in this context the potential reward associated attempting to end the point quickly with the serve appears greater than that on offer when attempting to hit a groundstroke winner. This adoption of a more aggressive approach to serving appears to be further reflected in trend for an increase in the number of double faults as estimated WBGT zones increase ($p=0.091$). This may provide some preliminary evidence of tennis players adjusting their serve tactics to cope with increased WBGT's. Indeed, calls for players to adjust (the riskiness of) their serve strategy in accordance with the context of matches as well as their individual serving prowess is common in tennis (158). As with the non-Elo adjusted matches, there was a significant decrease in the number of net approaches as temperatures increased. Again this implies that players altered their tactics to some extent, be that because of the physical exertion of net play, their reduced precision on approach or the perceived elevated risk associated with this tactic. With the lack of available data describing elite tennis in the heat, comparisons to other sports performed in the heat are instructive. For example, in various football codes players have been observed to cover reduced distances in high speed running zones under increasing WBGT (12, 135). While our data do not directly describe player movement, the noted decrease in net approaches and winners may be indicative of altered movement profile in tennis matchplay at the Grand Slam level.

Debate over the use of WBGT as a heat stress index (41) is common, yet still widely used in international tennis for determining implementation of EHP's (14, 196), and thus it is the most practically relevant for this study. That said, there are limitations of WBGT index related to equipment calibration and standardization (41) and lack of accounting for air movement or clothing within its calculation (4). The current study also used estimated WBGT using moderate solar radiation with light wind, potentially underestimating "true" environmental stress (13). While use of non-court side, estimated WBGT does reduce the accuracy of determining the true heat stress index, the wide ranging data set and use of zone-based analysis should reduce these limitations. Further, this study did not account for prior heat exposure on previous days; although Grand Slam formats result in limited singles matches on consecutive days.

3.7 Conclusion

In conclusion this was the first study to examine the association of estimated WBGT and heat-related incidents, behavioural and matchplay characteristics in men's professional Grand Slam tennis. As hypothesised, increased estimated WBGT increased total match doctor and trainer consults for heat related-incident, post-match heat-related incident consults (>32^{o}C) and calls for cooling devices (>28^{o}C). However, few matchplay characteristics were noticeably affected, with some signs of altered matchplay tactics mainly evident in reduced net approaches and increased aces, respectively. Finally, heat related incidence and behavioural characteristic markers in men's Grand Slam tennis appear to first increase in temperatures above 28^{o}C WBGT, although the most significant increases occur in temperatures above 32^{o}C WBGT.

3.8 Practical Implications

- Tennis match play in conditions over 28°C is associated with altered behavioural characteristics markers indicating reduced environmental comfort, while conditions above 32°C WBGT showed an increase in heat related incidents.
- Medical staff at tennis tournaments that are at risk of high temperatures should be aware of the risks associated with heat illness and tennis match play in conditions above 32.3°C WBGT.
- In high environmental temperatures coaching staff should also be aware of the potential changes to athlete’s performance, particularly the decreased number of winners and net approaches, and an increase in the number of aces.

Chapter Four

Study 2

As based on publication:

Smith MT, Reid M, Kovalchik S, Wood T, Duffield R. Heat stress incidence and matchplay characteristics in Women's Grand Slam Tennis. *Journal of Science and Medicine in Sport*. 2018;21(7):666-70.

4.1 Abstract

Objective: To explore the relationship of wet bulb globe temperature (WBGT) on heat-related incidents and alterations in matchplay and behavioural characteristics in women's tennis at the Australian Open.

Methods: From 360 main draw Australian Open women's matches (2014-2016), data describing on-court calls for trainers, doctors, cooling devices and water, post-match medical consults and matchplay characteristics were collated. Data were referenced against estimated WBGT and categorised into standard zones (zone 5: >32.3°C, zone 4: 30.1-32.2°C, zone 3: 27.9-30°C, zone 2: 22.3-27.9°C, zone 1: <22.2°C). GLM's assessed the association of WBGT zone on heat-related medical incidences, court call-outs and match characteristics.

Results: With an increased estimated WBGT zone, there was an increase in total trainer calls (+19.5%/zone; p=0.019), total doctor calls (+54.1%; p<0.001), total calls for heat related incidents (+55.9%; p<0.001), and cooling devices (+31.4%; p<0.001) calculated from the regression slope. When match characteristics were adjusted for match quality, significant decreases (p<0.001) in the number of winners and net approaches and increase in double faults were associated with increased estimated WBGT zone.

Conclusion: An association between higher estimated WBGT and medical callouts (heat and non-heat related) was evident, with an increased call rate >32°C WBGT, despite no heat-related retirements. As estimated WBGT increased, the number of winners and net approaches were reduced, while double faults increased, particularly >30°C WBGT. Accordingly, the manner in which female players manage and play in the heat during women's Grand Slam tennis appears to change at ≈30°C WBGT.

4.2 Introduction

As the Australian Open (AO) is played each year during the Southern Hemisphere summer, tennis matchplay during extreme heat and its potential implications for athlete wellbeing and performance is a constant source of discussion. This scrutiny exists against the backdrop of the American College of Sports Medicine (ACSM) stating that exercise in temperatures >28^{o}C WBGT places individuals at high risk for heat illness (7). In turn, the Women's Tennis Association (WTA) introduced an EHP that allows players to receive a 10-min rest period between the second and third set (if a third set is to be played) in conditions >28^{o}C WBGT (196). Notwithstanding the lack of publicly available evidence surrounding the effect of extreme heat on player wellbeing and performance in women's tennis, the logic was that this rest allows for core temperature reductions (191). The AO has followed the WTA's lead, providing players with this choice prior to commencing the deciding set.

Heat illness is a multi-factorial occurrence, yet prolonged or high-intensity exercise in hot/humid environments is a significant contributor (7). In professional women's tennis, the prevalence of heat illness remains poorly reported. Of the limited literature available, the 1994-2009 US Open reported a heat illness rate of 1.42 per 1000 match exposures in women, although no association with ambient temperature was found (26-33^{o}C) (173). Interestingly, reduced heat illness rates in women were evident compared to men (1.45 vs 2.45/1000h) (173); potentially due to the variation in their heat policy compared to the men's, as well as the shorter match durations, reduced number of sets and/or the more baseline oriented playing style of the female game(145). Further, the available 10-minute rest period between the 2nd and 3rd set in the women's competition in conditions above 28°C WBGT may mitigate the rise in core temperature and reduce the risk of heat illness (191). This gender-based policy difference may have some physiological basis as it has been suggested that women gain heat faster once the environmental temperature rises above that of the skin due to their larger skin surface area to body mass ratio (46). However, it must be noted that these claims remains contentious owing to a lack of definitive supporting evidence (46). Regardless, reported heat illness rates do not necessarily capture all player discomfort, which might otherwise be informed by the behavioural responses of players (i.e. cooling and water call outs). These changes in behavioural responses may also infer that increased core temperature >39.0°C can affect cognitive function (172). Hence, thermal comfort, decision making and tennis performance may become compromised.

From a performance perspective the impact of environmental conditions on the characteristics of professional women's tennis matchplay have not been examined. In men's tennis in the heat (33.6 ± 0.9°C WBGT), an increase in rest periods (+9.6 ± 3.6s) between points has been reported, while point length, number of points and games, aces and double faults were stable between hot and cool conditions (154). This increase in rest may explain the maintenance of core temperatures (<39.5°C) during matchplay even in extreme environmental conditions (154). Further, such a manipulation could also explain the absence of reduced physical performance outcomes, i.e. speed and power, following matchplay in the heat (76). However, as yet there is no comparable insight describing the effect of higher thermal stress on tennis matchplay characteristics in professional women's tennis.

Accordingly, this study aimed to retrospectively determine the effect of environmental conditions on heat-related trainer and doctor call outs, behavioural responses and match characteristics in women's Grand Slam tennis at the AO. It was hypothesised that with increasing WBGT there would be an increase in heat related medical consults, along with increases in water and cooling device call outs but with minimal changes to match characteristics.

4.3 Methods

Data were obtained from all 360 matches in the first four rounds of the 2014, 2015 and 2016 AO Women's Main Draw. The participants held a mean Women's Tennis Association rank of 67 ± 72, age 25 ± 4 and were from 45 different countries. Participant consent for the use of data for research purposes was gained upon tournament entry via tournament conditions of entry. Ethical approval was granted by the institutional Human Research Ethics Committee (UTS HREC REF NO. 2015000126).

Descriptive point level data and player rank information were collected from the AO tournament organisers (Table 4.1). Data from match umpires and match coding professionals were combined to provide real-time point level data. The coding professionals were extensively trained and used a platform that is widely used in professional tennis and has high inter- and intra-tester reliability (91). Weather data were retrospectively collated from half-hourly recordings from an Australian Bureau of Meteorology weather station located within 100m of the venue.

Table 4.1: Descriptors of match characteristics data collected.

Measure	Description
Medical and Behavioural Characteristics	
On court trainer calls	A call by the on court umpire for a trainer to the court for a specific player.
On court doctor calls	A call by the on court umpire for a doctor to the court for a specific player.
If on court doctor or trainer call was heat related incident	If the nature of the on court consult was recorded as heat related
Post match consults with Doctor for heat related incident	The number of post match doctor heat related incident consults made by athletes
Retirements	The number of athletes that retire from a match, and if the retirement was due to heat stress
On court calls for cooling devices	If the on court match umpires made a court call for any cooling devices including, ice, ice towels or ice vests.
On court calls for water	If the on court match umpires made a court call for any water or sports drinks
Match Characteristics	
Match Duration (min)	Length of the match in minutes
First serve (%)	The percentage of first serves made
Number of Aces	Total number of aces
Double Faults	Total number of double faults
Unforced Errors	Total number of unforced errors
Winners	Total number of winners
Winning on first serve (%)	Percentage of points won when first serve was made
Winner on Second Serve (%)	Percentage of points won when second serve was made
Break point conversion (%)	Percentage of break points won
Return points won	Percentage of return points won
Total points won	Total number of points won by the player in the match
Total match points	Total number of points in the match
Number of net approaches	Total number of net approaches
Net approaches won (%)	Percentage of net approach points won
Fastest serve (km/h)	Speed of the fastest serve in the match
Average first serve speed (km/h)	Average speed of all first serves by the athlete in the match
Average second serve speed (km/h)	Average speed of all second serves by the athlete in the match

As this station did not record globe temperature, an estimated WBGT is provided by Australian Bureau of Meteorology, based on the formula;

WBGT = 0.567 x Ta + 0.393 x e + 3.94,

Where: Ta= dry bulb temperature (^{o}C) and e = Water vapour pressure (hPa) [humidity] (1, 13).

Whilst recognised as a limitation, this formula has previously been used to estimate WBGT without black globe temperature (5, 88, 182). It is also acknowledged that WBGT is only one measure of thermal stress, and has limitations related to air movement, calibration and lack of adjustment for clothing type (41). Regardless, it is currently the primary measure of heat stress at the AO and throughout international tennis, and as such is the most relevant measure for this study over multiple years and courts (196).

Records of on-court calls for medical consults made by AO medical doctors and physiotherapists as well as calls for cooling devices/water were gathered from time stamped tournament communication call logs. Post-match heat related consults were collated from the tournament's medical database, where consults were considered to be heat related if identified by the treating medical practitioner as the result of hot environmental loads or heat illness. Matches with large amounts of missing data were excluded from analyses (i.e., WBGT, on-court calls, or large amounts of match data; n=12), as were matches suspended for rain or played under a closed roof (i.e., environmental conditions altered or unknown; n=2). All data were collated into Microsoft Excel and classified into a WBGT zone according to the ASCM classification

(7), zone 5: >32.3^{o}C, zone 4: 30.1-32.2^{o}C, zone 3: 27.9-30^{o}C, zone 2: 22.3-27.9^{o}C, zone 1: <22.2^{o}C (with ACSM's zones <10 and 10.1-22.2^{o}C being combined to form zone 1, and zones 22.3-25.6^{o}C and 25.7-27.8^{o}C being combined to form zone 2). Thus, a numerical increase in zone indicates a change from more temperate to extreme heat temperatures.

Analyses for the present study were completed in RStudio version 0.99.902 (RStudio: Integrated Development for R. RStudio, Inc., Boston, MA). The association of estimated WBGT zone and study outcomes were assessed through GLM's. Poission distributions were modelled with count outcomes, and continuous outcomes with a Gaussian distribution. Medical and behavioural outcomes were considered per match as well as per 1000 match hours. For medical and behavioural characteristics odds ratios were calculated, with zone 5 being used as the reference group. As zone 5 was the reference group the baseline odds were reported rather than the odds ratio. The odds for zone 5 were obtained by exponentiation of the intercept term of the logistic model while the odds ratios were obtained by exponentiation of the model coefficients corresponding to each comparison WBGT zone. The risk of inconsistency in trends owing to rare events was measured with the average relative standard error, with continuity corrections for cases where no events were observed.

Recognising that player quality may influence matchplay outcomes, analysis of match performance was undertaken with (adjusted model) and without (unadjusted model) adjustments for player quality. In the adjusted analyses, players were considered of similar quality when pre-match Elo ratings were within 50 points (112). Elo ratings are based on the strength of each player's career wins and have been proposed to provide a more accurate sense of player ability than traditional ranking systems (112). Unadjusted analyses simply compared the performance outcomes of all matches in each zone. To limit the impact of different distributions of player quality, which can confound the assessment of the associations, adjusted analysis matched each player and opponent in an extreme group (5-3) to a moderate zone (1-2). Confidence intervals are reported at the 95% level and statistical significance was defined as an effect of 5% significance or less.

4.4 Results

With each increase in estimated WBGT zone, there was an increase in total trainer calls (+19.5%/zone; p=0.019), total doctor calls (+54.1%; p<0.001), total calls for heat related incidents (+55.9%; p<0.001), post-match heat related consults (+68.3%; p=0.010), and calls for cooling devices (+31.4%; p<0.001). When medical and behavioural events were examined as a rate per 1000 h (Table 4.2), both heat related call outs and non-heat related call outs increased with each increase in estimated WBGT zone. Calls for cooling devices were highest in zone 4 (107.84/1000h) and calls for water increased in zone 4 (53.92/1000h) and 5 (55.47/1000h).

Table 4.2 Medical and behavioural characteristics: rate per 1000 hours (absolute occurrence) according to ACSM WBGT zones in women.

Variable	Zone 5 >32.3°C	Zone 4 30.1-32.2°C	Zone 3 27.9-30°C	Zone 2 22.3-27.9°C	Zone 1 <22.2°C
Total match play time in minutes (number of matches)	6490 (29)	5564 (30)	3870 (21)	38590 (207)	11514 (59)
Retirement	0(0)	10.78(1)	0(0)	6.22(4)	0(0)
Heat Stress Retirement	0(0)	0(0)	0(0)	0(0)	0(0)
Trainer Call	101.7(11)	43.1(4)	31.0(2)	59.1(38)	52.1(10)
Doctor Call	64.7(7)	32.4(3)	15.5(1)	9.3(6)	0(0)
In match Heat Stress Call	64.7(7)	32.4(3)	15.5(1)	7.8(5)	0(0)
Non Heat Stress Call	64.7(7)	21.6(2)	31.0(2)	48.2(31)	52.1(10)
Post Match Heat Stress Call	27.7(3)	0(0)	0(0)	1.6(1)	0(0)
Cooling Device Call	46.2(5)	107.8(10)	15.5(1)	32.7(21)	15.6(3)
Water Calls	55.5(6)	53.9(5)	15.5(1)	15.6(10)	10.4(2)

Table 4.3 shows the odds ratio of a medical and behavioural events when compared to zone 5. All zones showed lower odds than zone 5 for trainer call outs ($p<0.05$), while on-court calls for water and cooling devices did not show any significant differences ($p>0.05$). Zone 2 showed significantly lower odds of an on-court doctor call ($p<0.001$) than zone 5. Players calling for a doctor or trainer regarding heat related event ($p<0.001$) and post-match heat related events ($p=0.007$) in zone 2 had a lower odds of occurrence than that of zone 5.

Table 4.3 Odds for medical and behavioural characteristics according to ACSM WBGT zone in women.

	Zone 5 Reference Group[a]	**Odds ratio compared to zone 5**			
	Zone 5 >32.3°C	Zone 4 30.1-32.2°C	Zone 3 27.9-30°C	Zone 2 22.3-27.9°C	Zone 1 <22.2°C
Player calling for trainer during match	0.234±0.335 (0.000)	0.305±0.616 (0.050)	0.214±0.798 (0.050)	0.432±0.376 (0.025)	0.396±0.471 (0.049)
Player calling for Doctor during match	0.137±0.403 (0.000)	0.383±0.716 (0.181)	0.178±1.089 (0.113)	0.107±0.576 (<0.001)	0.000±989.987(0.986)
Call for trainer or doctor was Heat stress related	0.137±0.404 (0.000)	0.383±0.716 (0.181)	0.178±1.089 (0.113)	0.089±0.604 (<0.001)	0
Post match heat stress consultation	0.055±0.593 (0.000)	0	0	0.044±1.164 (0.007)	0
Non heat stress trainer or doctor call	0.137±0.403 (0.000)	0.251±0.824 (0.094)	0.364±0.829 (0.223)	0.590±0.444 (0.234)	0.675±0.521 (0.450)
Cooling device call	0.094±0.468 (0.000)	2.120±0.582 (0.197)	0.259±1.115 (0.225)	0.566±0.519 (0.273)	0.277±0.749 (0.086)
Water call	0.074±0.518 (0.000)	0.229±1.134 (0.193)	0.329±1.137 (0.329)	0.334±0.609 (0.072)	0.233±0.881 (0.098)

Odds ratio for medical and behavioural characteristics when compared to zone 1: odd ratio ± standard error (p value). a The effect shown for the reference category are the odds of the outcome for zone 5 matches

Table 4.4 shows the match characteristics per estimated WBGT zone along with change per estimated WBGT zone, without the player quality adjustment. With increased estimated WBGT zone, increases were observed in match duration by 2.5 ± 0.1 min ($p=0.022$), double faults by 9.3±0.01% ($p<0.001$), unforced errors by 1.5 ± 0.01% ($p=0.024$), and return points won by 1.9 ± 0.55%. First serve percentage (-0.64 ± 0.3%; $p=0.034$), winners (-3.2 ± 0.008%, $p<0.001$), net approaches (-6.2 ± 0.01%, $p<0.001$), fastest serve (-1.31 ± 0.6 km/h, $p=0.039$), first serve speed (-1.86 ± 0.51 km/h, $p<0.001$), and 2^{nd} serve speed (-1.65 ± 0.46 km/h, $p<0.001$) all decreased with each increase in the estimated WBGT zone.

Table 4.4: Match characteristics averages and rate of change per ACSM WBGT zone in Non-ELO adjusted matches in women.

	WBGT 5 >32.3°C	WBGT 4 30.1-32.2°C	WBGT 3 27.9-30°C	WBGT 2 22.3-27.9°C	WBGT 1 <22.2°C	Rate of change per change in WBGT zone
Match Duration (min) ø	101.78±37.02	100.38±37.27	94.98±31.66	94.93±31.96	94.06±30.89	+2.523±0.1.100 (0.022)
1st Serve Percentage (%) ø	60.92±9.87	60.70±10.06	61.14±8.30	61.67±8.79	61.85±8.37	-0.638±0.300 (0.034)
Aces (count) ¥	3.07±2.73	3.02±2.74	3.19±3.18	3.12±3.16	3.16±3.29	+0.015±0.019 (0.426)
Double Faults (count) ¥	4.3±2.98	4.32±3.03	3.75±2.72	3.61±2.65	3.44±2.56	+0.093±0.017 (<0.001)*
Winning on 1st Serve (%) ø	65.13±12.49	64.83±13	64.38±11.78	64.37±12.06	64.49±11.79	+0.410±0.412 (0.319)
Winning on 2nd Serve (%) ø	44.62±12.88	44.64±13.07	45.36±12.18	45.14±12.36	45.36±12.38	+0.092±0.428 (0.83)
Unforced Errors (count) ¥	25.92±15.58	25.91±15.38	25.14±14.52	24.95±14.58	25.18±14.40	+0.015±0.007 (0.024)
Breakpoint Conversion % (count) ø	50.49±22.07	51.43±21.98	50.32±21.87	50.43±21.61	49.9±21.52	+0.152±0.759 (0.841)
Return Points Won (%) ø	42.93±10.12	43.15±10.34	37.92±17.17	38.97±16.20	37.04±17.52	+1.946±0.547 (<0.001)*
Total Points Won (count) ø	71.43±24.99	70.83±25.17	69.65±22.85	69.21±22.94	69.23±22.75	+0.692±0.789 (0.381)
Total points (count) ø	142.86±47.19	141.67±47.48	139.30±42.36	138.42±42.55	138.46±42.09	+1.384±1.465 (0.345)
Winners (%) ¥	17.35±11.35	17.16±11.11	18.29±11.31	18.20±11.35	18.85±11.28	-0.032±0.008 (<0.001)*
Net Approaches (%) ¥	10.25±7.88	10.48±7.89	11.30±8.52	11.45±8.30	11.99±8.68	-0.062±0.012 (<0.001)*
Net Approaches Won (%) ø	63.72±21.34	65.19±19.77	67.32±18.28	67.07±18.47	67.94±17.72	-1.113±0.711 (0.118)
Fastest Serve (km/h) ø	169.72±21.06	169.41±20.50	173.28±13.52	172.46±15.17	173.54±13.59	-1.311±0.633 (0.039)
Average 1st Serve Speed (km/h) ø	151.51±18.82	151.6±18.61	157.31±9.94	156.39±12.33	158.03±9.88	-1.859±0.512 (<0.001)*
Average 2nd Serve Speed (km/h) ø	127.57±16.29	127.44±16.34	132.01±9.28	131.19±11.11	132.39±9.40	-1.645±0.464 (<0.001)*

Match characteristics: match characteristics average ±SD. Table gives match characteristics average across each temperature zone in from ELO adjusted matches characteristics and the association of change per change in WBGT zone as calculated through GLM analysis. –or+ indicates the direction of slope (- = decrease in hotter condition, + = increase in hotter conditions). ø denotes continuous data, data displayed as a change of the mean. ¥ denotes count data, data displayed as a rate ratio. *=(p<0.05).

Table 4.5 shows the match characteristics per WBGT zone and change per zone when adjusted for differences in player quality. Following adjustment, double faults showed a 13.8 ± 0.03% ($p<0.001$) increase per increase in WBGT zone, whilst winners (-7.3 ± 0.013%,) and net approaches (-8.4 ± 0.019%) decreased per WBGT zone ($p<0.001$).

Table 4.5: Match characteristics averages and rate of change per ACSM WBGT zone in ELO adjusted matches in women.

	WBGT 5 (ELO) >32.3°C	WBGT 4 (ELO) 30.1-32.2°C	WBGT 3 (ELO) 27.9-30°C	WBGT 2 (ELO) 22.3-27.9°C	WBGT 1 (ELO) <22.2°C	Rate of change per change in WBGT zone
Match Duration (min) ø	103.45±37.37	101.93±37.72	101.53±36.51	103.50±35.88	105.04±35.98	+3.29±1.97 (0.097)
1st Serve Percentage (%) ø	60.97±10.10	60.72±10.32	60.73±8.23	62.28±8.44	62.58±8.68	-0.832±0.535 (0.122)
Aces (count)	2.99±2.69	2.93±2.68	3.19±2.83	3.56±3.29	3.61±3.33	+0.009±0.032 (0.775)
Double Faults (count)	4.45±±3.06	4.47±3.11	4.41±2.95	3.07±1.94	3.06±2.03	+0.138±0.029(<0.001)*
Winning on 1st Serve (%) ø	64.85±12.50	64.51±13.06	64.08±11.58	62.54±11.62	62.04±11.83	+1.274±0.709 (0.074)
Winning on 2nd Serve (%) ø	44.53±12.77	44.55±12.98	45.48±12.20	41.89±10.57	41.29±10.35	+0.364±0.706 (0.607)
Unforced Errors (count)	26.06±16.19	26.06±15.99	27.65±15.52	22.64±15.99	22.32±16.17	+0.001±0.011 (0.928)
Breakpoint Conversation (%) ø	50.39±21.59	51.43±21.47	52.34±21.41	53.26±17.50	54.38±16.98	-1.098±1.219 (0.369)
Return Points Won (%) ø	43.28±9.68	43.54±9.93	43.77±9.22	45.77±9.72	46.18±9.66	-0.892±0.569 (0.118)
Total Points Won (count) ø	72.31±24.98	71.67±25.20	72.70±24.23	75.06±26.65	76.17±27.16	+1.455±1.342 (0.279)
Total points (count) ø	144.62±47.27	143.34±47.64	145.40±45.36	150.12±50.58	152.33±51.67	+2.911±2.511 (0.248)
Winners (count)	16.97±11.22	16.74±10.95	18.56±10.99	17.77±11.94	17.15±11.96	-0.073±0.013 (<0.001)*
Net Approaches (count)	10.48±8.06	10.73±8.08	10.98±7.70	11.18±8.69	10.51±6.11	-0.084±0.019 (<0.001)*
Net Approaches Won (%) ø	63.99±20.64	65.69±18.68	66.92±17.33	64.52±14.07	65.29±14.26	-1.076±1.206 (0.373)
Fastest Serve (km/h) ø	168.32±22.34	168±21.66	170.92±19.04	166.62±10.77	166.69±10.87	+0.506±1.625 (0.756)
Average 1st Serve Speed (km/h)ø	150.18±19.97	150.32±19.71	155.21±9.66	151.40±10.67	151.89±10.91	-1.121±1.192 (0.348)
Average 2nd Serve Speed (km/h)ø	126.54±17.28	126.42±17.30	130.11±9.75	126.73±8.67	127.33±8.67	-1.715±1.049 (0.104)

Match characteristics: match characteristics average ±SD. Table gives match characteristics average across each temperature zone in from ELO adjusted matches characteristics and the association of change per change in WBGT zone as calculated through GLM analysis. –or+ indicates the direction of slope (- = decrease in hotter condition, + = increase in hotter conditions). ø denotes continuous data, data displayed as a change of the mean. ¥ denotes count data, data displayed as a rate ratio. *=(p<0.05).

4.5 Discussion

The current study showed higher estimated WBGT's were associated with increased heat (and non-heat) related on-court trainer and doctor callouts, peaking >32^{o}C WBGT (zone 5), despite no heat-related retirements. However, the increased prevalence of heat call outs from zone 4 implies that players started to become noticeably thermally challenged in zone 4 (>30^{o}C WBGT). The positive linear association between estimated WBGT and non-heat related trainer and doctor call outs may infer that players are either more susceptible to injury or use trainer call outs strategically as thermal strain climbs. Possible reasons for the absence of heat related retirements may relate to the format of Grand Slam women's tennis (where a maximum of 3 sets are played) and/or the playing styles of elite female players. For example, professional women's tennis features higher proportions of baseline rallies with a slower shot rate, a less dominant serve and fewer net approaches, relative to their male counterparts (145). The comparatively shorter format and different tactical structure of the female game may assist in the preservation of core temperature and explain the reduced rates of heat illness in women's tennis compared to their male counterparts (173).

Another aspect of the women's game that may aid in the preservation of core temperature and the reduction in match retirements may be the implementation of a subsection of the EHP, which provides a 10-minute break in play between the 2nd and 3rd set if WBGT > 28^{o}C and if a 3rd set is to be played (191). This subsection may have had a substantial impact on the prevention of heat related match retirements in the current data set. With previous evidence supporting the use of the heat rule in professional women's tennis by demonstrating the successful reduction in core temperatures (0.25 ± 0.20°C) during matchplay in the heat in live professional women's tennis, which potentially reduces the risk of heat illness (191). Calls for cooling devices and water also increased with estimated WBGT, particularly in estimated WBGT >30°C (i.e. zone 4 and 5). We reason that this presents a behavioural sign of players feeling thermally challenged, although due to zonal analysis used here a specific inflection point was not determined. This inference is supported by the commensurate rise in calls for medical assistance noted earlier. Previous investigations of simulated matchplay settings show male players to record core temperatures as high as ~39.4°C (154). Whilst direct measurement of core temperature is precluded in this Grand Slam context, it would appear that conditions >30°C WBGT might sufficiently increase the core and skin temperatures of female players resulting in additional calls for cooling devices and water. The increased call outs for heat-related issues and cooling devices >30°C WBGT, without heat-related retirements, might suggest appropriate implementation of the EHP for women's tennis at the AO.

Changes in estimated WBGT were associated with significant changes in particular match characteristics. In the unadjusted analyses, an increased estimated WBGT was associated with increased match duration. It has previously been demonstrated that match durations were increased during professional men's simulated matchplay in the heat (33.6°C WBGT) (154). In these simulated contexts, longer rest periods between points (+9.6 ± 3.6 s) were observed to contribute to this increase (154). However, due to the enforcement of a maximum of 20s rest between points on the Women's Tennis Association tour and at Grand Slams (99), other explanations should be considered (i.e. point duration, toilet breaks etc.). That said, the increased match duration was not present when adjusted for player quality. Given that an individual player can influence rest time independent of the opponent, this may represent an artefact of mismatched player quality in these zones.

The unadjusted analyses highlighted a negative association between estimated WBGT zone and serve speed. This reduced serve speed, in conjunction with no significant change to first serve percentage, points to players potentially reducing their serve speed to preserve the accuracy of their serve. Such a response to higher WBGT would suggest altered serve tactics, albeit one that is in keeping with the situational evidence that women tend to rely less on their serve to win points than men (145). The increase in double faults evident in both adjusted and unadjusted analysis highlights that the second serve appears to become particularly more vulnerable in the heat in women's tennis (92). The balance between speed and accuracy that is seemingly adjusted in hotter conditions is not uncommon in other skill and team-based sports where there is a decreased level of fine motor control with fatigue that is exacerbated in the heat (186). Hence, in Grand Slam women’s tennis, the heat may challenge the technique and/or tactics of players on their first and second serves.

The increase in unforced errors (unadjusted analysis) and reduction in winners (in both adjusted and unadjusted analysis) during matchplay in hotter WBGT conditions can be variously explained. First, heat induced fatigue may force players to attempt shots that are riskier, heightening the chances of committing unforced errors (93). Second, players might be less prepared to create appropriate opportunities to attack once heat induced fatigue increases (163), meaning that unforced errors rise and winners fall.

Third, it may be speculated that players attempt to preserve energy during matchplay in hot conditions, and position themselves further behind the baseline, which creates a less favourable court position (on the opponent's side of the net) to exploit. Simultaneously, and logically, it lengthens the distance to the net, which might explain the reduced number of net approaches observed in both the adjusted and unadjusted group.

Despite the novel findings reported here regarding medical, behavioural and matchplay responses for women's Grand Slam tennis in the heat, several limitations need to be acknowledged. Firstly, many heat indices are available, and although the WBGT has been subject to criticism due to its limitations, it is the most relevant measure in professional tennis (including the AO) and thus most practical measure for this study (196). Nevertheless, it is still important to highlight that WBGT limitations include concerns surrounding the standardisation of equipment and calibration, the use of a natural wet bulb as a thermodynamic parameter, lack of accounting for air movement and clothing within WBGT calculation (41), as well as the noted variation in thermal stress between conditions with equivalent WBGT's (103). It is also important to note that WBGT provides an indicator of thermal stress, but does not directly inform thermal strain. This study also relied on the use of estimated WBGT from a central position (not courtside) which could underestimate the true WBGT in the full sun and high humidity (13). However, the use of zone analysis and the large data set is proposed to reduce the impact of this measurement method. Further, given the elite nature of a Grand Slam event, measurement of physiological or perceptual responses were not possible, though such data would feasibly add to greater understanding of the thermal strain of such conditions. Similarly, information of prior heat exposure, predisposition to heat tolerance and if athletes underwent acclimatisation prior to the AO was not available, and hence not accounted for in the analyses. It is also important to note that some medical and behavioural data reported trend inconsistencies within the average relative standard error trend analysis.

4.6 Conclusion

This is the first study to examine the effect of environmental temperature on heat related incidents, behavioural responses and matchplay characteristics in women's professional Grand Slam Tennis. In line with previous findings, as estimated WBGT increases so did match duration, the number of calls for cooling devices and medical heat-related call outs, particularly in conditions >30^{o}C WBGT, however there were no heat related retirement within the current studies data set. Significant associations between estimated WBGT and changes in matchplay characteristics such as the number of winners, unforced errors, double faults and number of net approaches were also found, suggesting that estimated WBGT impacted on the manner in which female tennis players competed in the heat. Possible changes to serve tactics and the court positioning of players may explain some of these changes. Accordingly, heat related incidents and behavioural responses in women's Grand Slam tennis appear to significantly increase at 30^{o}C WBGT.

4.7 Practical Applications

- For professional tennis tournaments in conditions > 30^{o}C WBGT; tournament organisers should have extra cooling device and water available court side for athletes and be vigilant for signs of heat illness.
- Tournament organisers should also encourage the use of the heat rule in Women's matches; once the WBGT reaches 30^{o}C with the suspension of match play above 32^{o}C WBGT.
- In high environmental temperatures coaching staff should also be aware of the potential changes to women player's performance, particularly the decreased number of winners and net approaches, reduced serve speed and an increase in the number of double faults.

Chapter Five

Study 3

Men's *Grand Slam Tennis in the Heat;*
the Consistency of Within-match Performance at the Australian Open

5.1 Abstract

Objectives: To assess the effect of increased estimated wet bulb globe temperature (WBGT) on within-match changes in matchplay performance of professional men's tennis players at the Australian Open (AO).

Methods: Set-by-set matchplay data from the 2014-16 AO men's tournaments were collated into estimated WBGT zones (zone 5: >32.3°C, 4: 30.1-32.2°C, 3: 27.9-30°C, 2: 22.3-27.9°C, 1: <22.2°C). For each matchplay variable, the change from the first to last set (i.e. direction) and the standard deviation (SD; representing inconsistency) of each set were assessed based on WBGT zone via a GLM. The relationship between match WBGT zone and 1) directional change in match characteristic performance from first to last set and 2) the set-to-set consistency of matchplay characteristics were determined.

Results: Change between first and last set showed no significant relationship with match WBGT zone in any of the measured match characteristics ($p>0.05$). Total points won (1.52 ± 0.58%; $p=0.008$), number of net approaches (1.21 ± 0.58%; $p=0.049$) and set duration (0.910 ± 0.43%; $p=0.033$) showed significant decreases in consistency i.e. higher SD, with increased match WBGT zone. No other match characteristic showed significant change ($p>0.05$) in set-to-set variability based on match WBGT zone.

Conclusion: Within-match changes in matchplay performance characteristics were not affected by WBGT zone, and as such are unlikely related to excessive environment-induced fatigue. However, the reduced set-to-set consistency in set duration, total points won and net approaches were evident in increased WBGT zones. Accordingly, a deliberate alteration to matchplay intensity during select passages of play is likely during matchplay in the heat by either or both players.

5.2 Introduction

The Australian Open (AO) is one of the four major Grand Slam tennis tournaments played in the tennis world calendar, and as it is held during summer, players can compete in temperatures that exceed 40°C (150). Despite these environmental extremes, the effect of such conditions on elite Grand Slam tennis matchplay has only attracted recent research attention (54, 154). For example, summary level match data at the AO showed limited associations between estimated wet bulb globe temperature (WBGT) and matchplay characteristics; though an increase in the number of aces and a decrease in the use of net approaches in high WBGT zones were observed (177). While these findings are novel and instructive, the use of cross-sectional analysis in these studies prevents an understanding as to how individual player performance may change over the course of a match due to extreme WBGT.

During simulated matchplay in the heat (33.6 ± 0.9°C WBGT) among players ranked outside of Grand Slam contention there were no reported changes in match characteristics in high WBGT (33.6 ± 0.9°C); though an increase in between-point rest periods existed (154), which may have prevented the manifestation of changes in matchplay characteristics. This altered work-to-rest ratio was suggested to be driven as an attempt to increase rest periods and reduce match involvement due to the increasing demands of exercise in the heat (154). The reduction of matchplay involvement in the heat to preserve core temperature is not unique to tennis, having been observed in a multitude of other sports for example Football, Field Hockey and Australian Rules Football (10, 135, 186). Further, it has previously been reported that competitors during lower ranked professional matchplay in the heat will increase rest periods (94). However, at Grand Slam level events such as the AO there is likely to be a higher standard of match refereeing where rest periods are more rigorously monitored (99), preventing regular extension of between-point or set rest periods. Consequently, given the inability to alter rest periods, players may reduce match involvement by hitting risker serves to shorten points or may reduce efforts when returning the serve (177). These responses, when coupled with a reduced willingness to approach the net, suggest players point construction and court movement changes during matchplay in higher WBGT (177). However, the use of cross-sectional analysis between different players/matches in different WBGT zones does not permit an understanding of how matchplay performance varies in professional players over the course of a match in response to matchplay in the heat. Therefore, assessing changes in match characteristics from one set to the next, and the set-to-set consistency of match characteristics would provide a more complete understanding of the within match changes to performance during matchplay in the heat.

As such, investigating the directional changes in matchplay performance from the first to last set in hot conditions in comparison to cooler conditions might better demonstrate the impact of environmental conditions on competitors, and indicate the effects of the progression of within match fatigue on performance (162). Further, determination of the association between match WBGT and set-to-set consistency of matchplay characteristics may inform how hotter conditions may result in selective changes in performance during matches, particularly when matches may be of varying set number and duration. For example, reduced set-to-set consistency in match characteristics may suggest a more deliberate alteration in matchplay (194), in turn impacting on total match performance (52). Thus, the aim of this study was to investigate the relationship between match WBGT zone and 1) change in match characteristic performance from first to last set and 2) the set-to-set consistency of matchplay characteristics. It is hypothesised that increased WBGT will negatively affect the change in performance from first to last set of match characteristics related to the serve and net approaches, while reducing the set-to-set consistency of these match characteristics.

5.3 Methods

To assess the effect of WBGT on the within match (i.e. set-to-set) changes and consistency in performance during men's Grand Slam tennis, set-level data were obtained from all 360 matches that comprised the first four rounds of the AO between 2014-2016. These were the same matches used for the previous study in Chapter Three, however set-by-set data was collected separately for this study. This data set included 189 professional male tennis players with an Association of Tennis Professionals rank of 66 ± 69 and an age of 27.8 ± 3.8 years at the time of the match. Consent for the use of data for research purposes was gathered from all participants upon entry to the tournament. This study was approved by the University of Technology Sydney Human Research Ethics Committee (UTS REF: 2015000126).

Umpires and/or tennis match coding professionals, whom were extensively trained and familiar with the deployed annotation software, generated real time matchplay data as supplied by AO tournament organisers. While the reliability of their coding was not available, previous studies have reported high levels of inter- and intra-tester reliability for these types of performance statistics (91). Point level data of all match characteristics (outlined in Table 5.1) were collected and aggregated to the set level.

Table 5.1: Descriptors of match characteristics data collected.

Measure	Description
Match Characteristics	
Set Duration(min)	Length of the set in minutes
First serve (%)	The percentage of first serves made
Number of Aces	Total number of aces per set
Double Faults	Total number of double faults per set
Unforced Errors	Total number of unforced errors per set
Winners	Total number of winners per set
Winning on first serve (%)	Percentage of points won when first serve was made
Winner on Second Serve (%)	Percentage of points won when second serve was made
Break point conversion (%)	Percentage of break points won
Return points won	Percentage of return points won
Total points won	Total number of points won by the player per set
Number of net approaches	Total number of net approaches made per set
Net approaches won (%)	Percentage of net approach points won

These match characteristics were selected for assessment due to their regular use to describe match performance and association with match outcome at Grand slam events (65). This set level data was firstly used to assess the linear change in performance over the course of the match by calculating the difference between the last and first set values, which provided a measure of change in performance over the course of the match. The rationale for the use of first and last set data for calculating the within-match change in performance allowed for standardisation of matches consisting of a different number of sets. The use of set level data to calculate the set-to-set standard deviation (SD) of each characteristic was to provide a measure of consistency in performance. The rationale here was to obtain an understanding of the fluctuation and spread of performance from the set values away from the matches mean values; particularly where matchplay performance changes were not progressive in nature, or were hidden due to increased efforts at the end of matchplay by losing players (32, 118).

These aforementioned measures of change from first to last set and set-to-set consistency were aligned with estimated match WBGT zone. Weather data for each match was collected from an Australian Bureau of Meteorology weather station located within 100m of the tournament venue. Weather data was recorded in half hour increments, and was used to calculate match and set averaged estimated WBGT. As the Australian Bureau of Meteorology does not measure black globe temperature, estimated WBGT was calculated using the formula:

WBGT = 0.567 x Ta + 0.393 x e + 3.94,

where Ta = dry bulb temperature (^{o}C) and e= Water vapour pressure (hPa) [humidity].

This formula has been suggested by the American College of Sports Medicine (ACSM) for estimating WBGT when black globe temperature is not available (5, 7), and used accordingly in previous research literature (87, 88). The limitations of WBGT are well recognised (4, 41); including the potential underestimation of thermal stress in restricted evaporative environments, and lack of accounting for air movement and clothing (41). Further, the limitations of using estimated WBGT are also widely understood, particularly in relation to precision in low and high solar radiation conditions due to the use of a fix black globe temperature (13). However, the widespread use of WBGT in the global sporting landscape, including during the AO in these tournament years, makes the WBGT the most practically relevant measure for this study. Issues surrounding measurement error and bias are also limited by the standardisation of measurement and comparison of data across temperature zones within the study and are discussed later.

Matches were excluded from analysis if they were missing data (i.e., WBGT, or match characteristic data) (n = 22), suspended for rain, or played under a closed roof (n = 4). All match characteristic and WBGT data were entered into a customised spreadsheet (Microsoft Excel for Mac, version 15.13.4, Washington, USA) and grouped into a WBGT zone according to the ACSM classification for non-continuous, fit, low risk individuals(7), zone 5: >32.3^{o}C, zone 4: 30.1-32.2^{o}C, zone 3: 27.9-30^{o}C, zone 2: 22.3-

27.9°C , zone 1: <22.2°C (with ACSM's zones <10 and 10.1-22.2°C being combined to form zone 1, and zones 22.3-25.6°C and 25.7-27.8°C being combined to form zone 2).

Analyses were completed in RStudio version 0.99.902 (RStudio: Integrated Development for R. RStudio, Inc., Boston, MA). Respective GLM's were used to undertake two separate analyses. Firstly, the association between match WBGT zone and change in match characteristics over the course of the match were examined. Secondly, the relationship between match WBGT zone and the set-to-set consistency of matchplay characteristics was assessed. All analysis used the Gaussian distribution with confidence intervals reported at the 95% level and statistical significance defined as an effect of 5% significance or less, all results are reported as a percentage of change (± standard error). Funnel plots were used to graphically present data, with consistency (standard deviation) displayed on the Y axis, and first to last set change on the X axis, and 95% confidence interval lines were also displayed. Funnel plots are often used to describe systematic heterogeneity within data (178, 183, 184), with symmetrical inverted funnel shaped data showing homogenous data, while asymmetrical funnel plots indicate systematic heterogeneity. Thus, the funnel plots used here are a novel way to show the consistency of performance in relation to first to last set change in performance of each match characteristic across each estimated WBGT zone.

5.4 Results

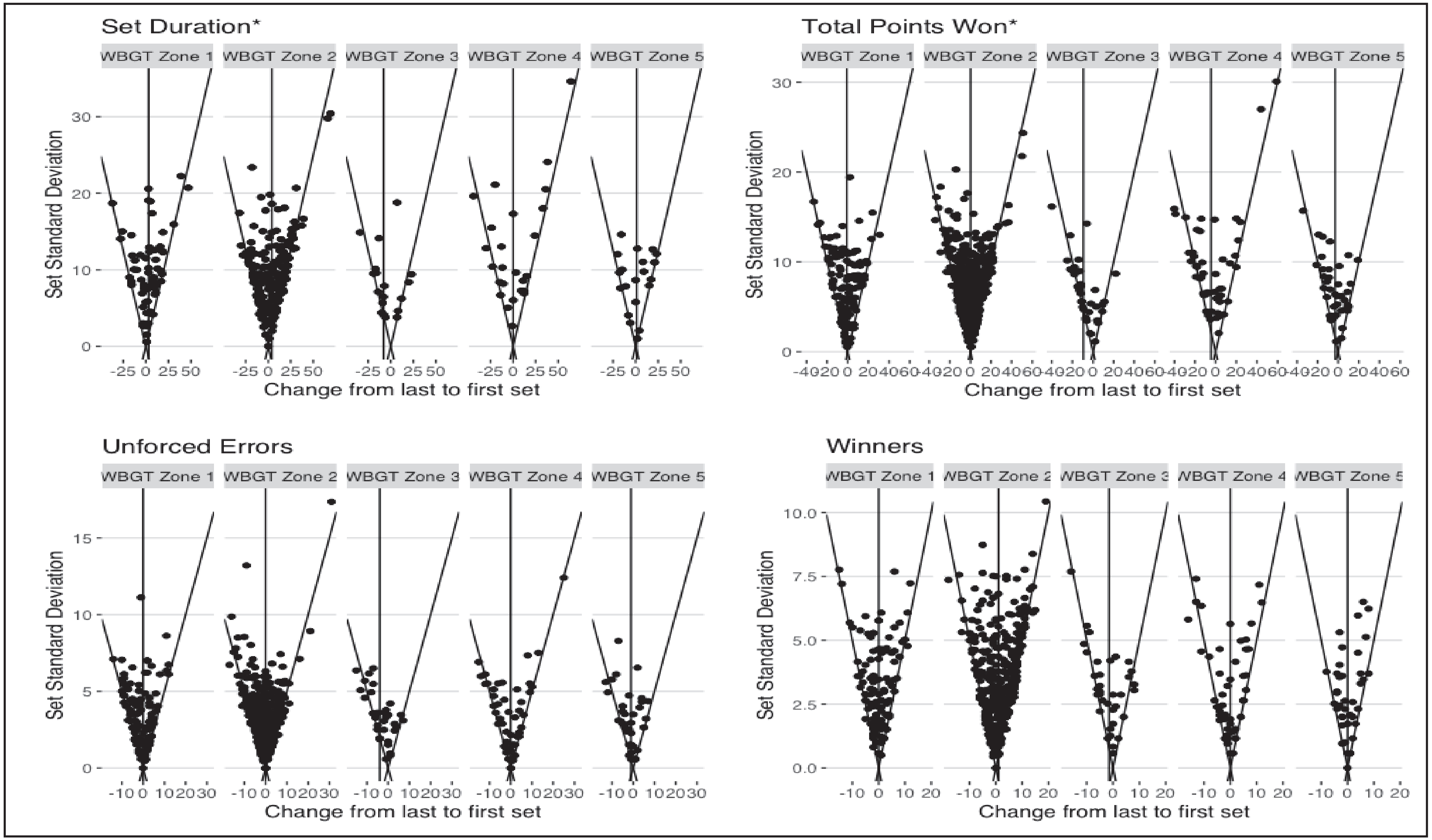
From the analysis of the data set there were 30 matches with a mean 3.7 ± 0.7 sets in the WBGT zone >32.3°C, 29 matches with 3.8 ± 0.8 sets in WBGT zone 30.1-32.2°C, and

18 matches with 3.7 ± 0.8 sets in WBGT zone 27.9-30.0°C. Further, in WBGT zone 22.3-27.9°C there were 203 matches with 3.7 ± 0.7 sets and 60 matches with 3.6 ± 0.8 sets in WBGT zone < 22.2°C.

When examining the relationship between estimated WBGT zone and change in match characteristics from first to last set, set duration (0.28 ± 0.80%; p=0.73), total points won (0.30 ± 0.62%; p=0.63), unforced errors (0.05 ± 0.27%; p=0.86) and winners (0.02 ± 0.26%; p=0.96) were not significantly different with increased match WBGT zone (Figure 5.1). Similarly, changes in the number of net approaches (0.13 ± 0.21%; p=0.55), net approaches won (%) (1.16 ± 2.00%; p=0.56), return points won (0.29 ± 0.64%; p=0.66) and break points won (1.11 ± 2.38%; p=0.64) from first to last set showed no significant change with increased in estimated WBGT zone (Figure 5.2). Changes from first to last set in serve related match characteristics; including first serve percentage (-1.14 ± 0.71%; p=0.11), aces (-0.09 ± 0.13%; p=0.505), winning first serve points % (0.46 ± 0.81%; p=0.57), winning second serve points % (-0.09 ± 1.14%; p=0.90), and double faults (0.07 ± 0.08%; p=0.33), also showed no change with increased estimated WBGT zone (Figure 5.3).

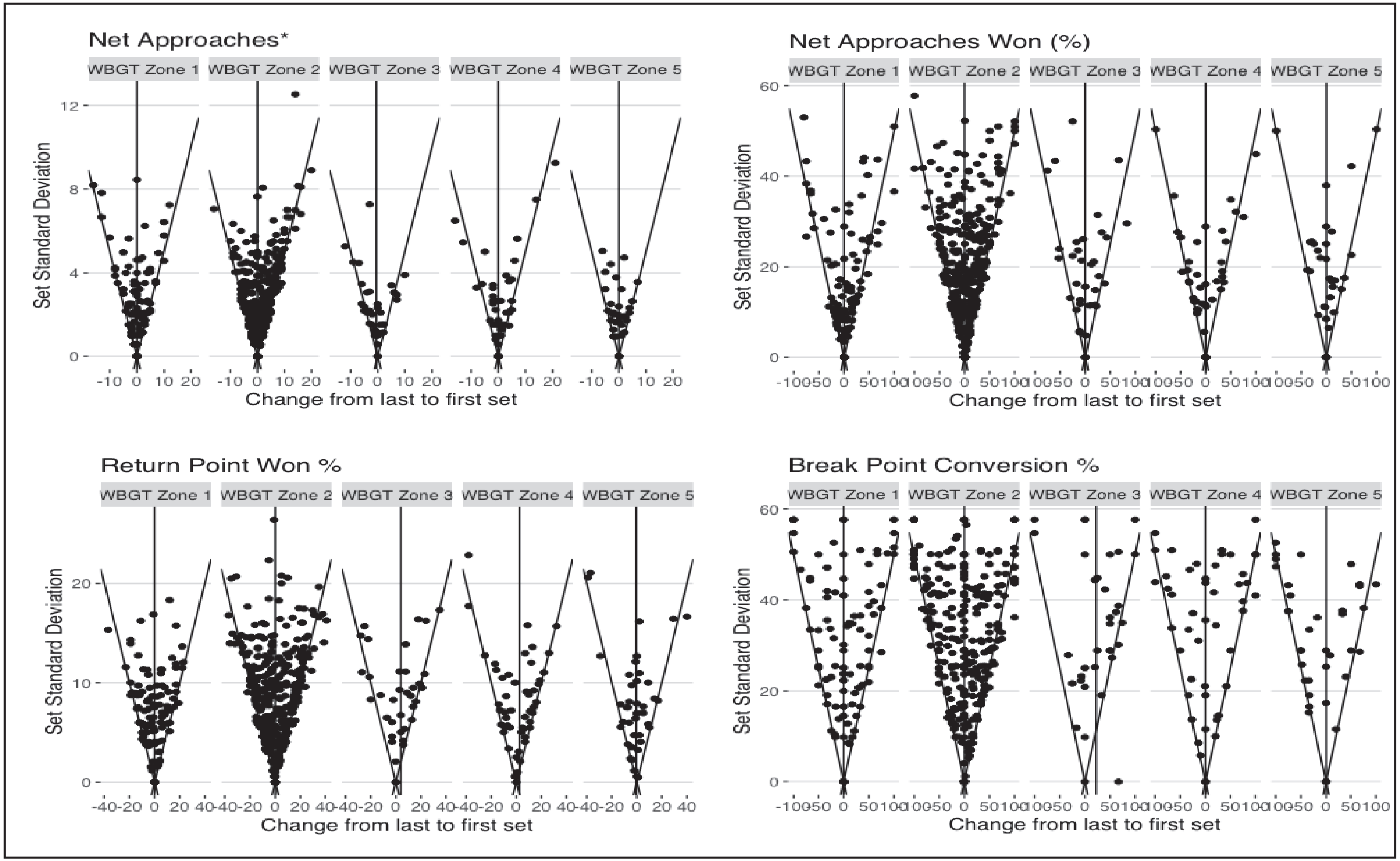
Examination of the relationship between match WBGT zone and set-to-set consistency of performance showed a significant decrease in consistency with an increased WBGT zone in set duration (0.91 ± 0.43%; p=0.03) and total points won (1.52 ± 0.58%; p=0.008) (Figure 1). The set-to-set consistency of unforced errors (0.42 ± 0.30%; p=0.16) and winners (0.37 ± 0.27%; p=0.16) showed no change with an increase in estimated WBGT zone (Figure 5.1). The set-to-set consistency of the number of net approaches showed a significant decrease with increased estimated WBGT zone (1.21 ± 0.58%; p=0.04); while set-to-set variability of number of net approaches won (0.28 ± 1.97%; p=0.87), return points won (%) (0.04 ± 0.73%; p=0.99) and break point conversion (%) (3.39 ± 2.56%; p=0.19) showed no change with WBGT zone (Figure 5.2). Finally, the set-to-set consistency of serve related match characteristics; first serve percentage (0.13 ± 1.27%; p=0.31), aces (0.15 ± 0.14%; p=0.29), winning first serve points % (1.07 ± 0.82%; p=0.19), winning second serve points % (1.19 ± 1.04%; p=0.56) and double faults (0.77 ± 0.03%; p=0.35), showed no change with increased match WBGT zone (Figure 5.3).

Figure 5.1: Within-match changes and set-to-set consistency of match characteristics of set duration, total points won, unforced errors and winners count as based on estimated WBGT zone in men.



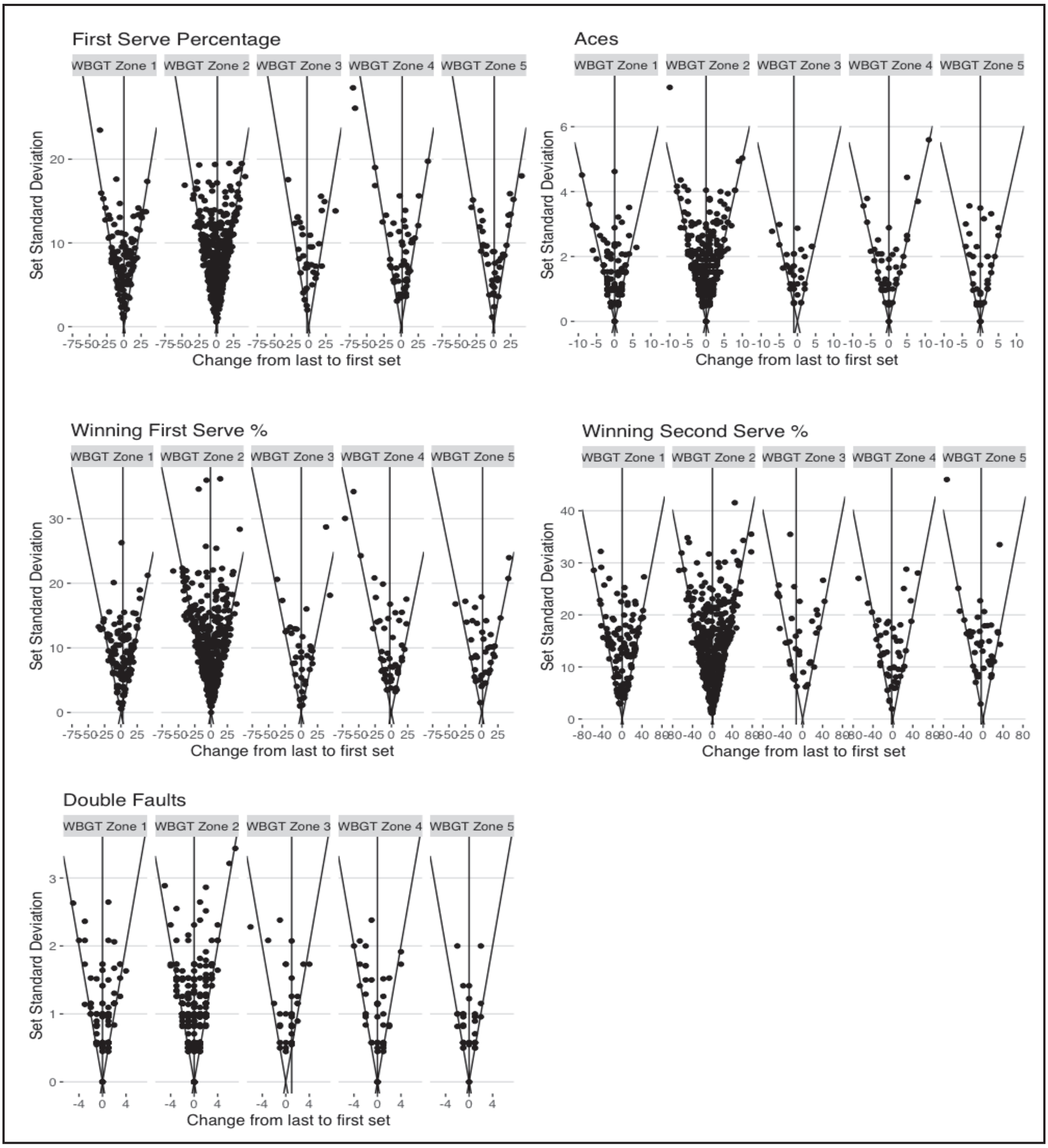
* Indicates significant association between standard deviation and WBGT ($p < 0.05$) and can be found next to the title of each variable.

Figure 5.2: Within-match changes and set-to-set consistency of match characteristics of net approaches, net approaches won (%), return points won (%) and break point conversion (%) as based on estimated WBGT zone in men.



*Indicates significant association between standard deviation and WBGT ($p < 0.05$) and can be found next to the title of each variable.

Figure 5.3: Within-match changes and set-to-set consistency of match characteristics of first serve percentage, aces, winning on first serve (%), winning on second serve (%) and double faults as based on estimated WBGT zone in men.



* indicates a significant association between standard deviation and WBGT ($p < 0.05$) and can be found net to the title of each variable.

5.5 Discussion

The findings from this study demonstrated that the changes from first to last set in reported match performance characteristics were not influenced by match estimated WBGT zone. However, an increased match WBGT zone was related to a decrease in the set-to-set consistency of total points won, net approaches and set duration. Accordingly, in higher WBGT conditions players will undergo nuanced matchplay performance changes resulting in less consistent performance surrounding net approaches, set duration and the number of points won per set.

The change in matchplay characteristics from the first to last set was not affected by estimated WBGT zone of the match. This somewhat concurs with previous evidence from the AO in the same cohort as Chapter Three, whereby no association was evident between estimated WBGT zone and changes in match-averaged matchplay characteristics, other than aces and net approaches. The current findings infer that match performance changes during competition are not progressive throughout the match (i.e. start to end), and are not directly a result of heat-induced fatigue (84, 162, 163). Evidence from simulated matchplay in the heat also suggests that the physical fatigue of tennis players is no higher after matchplay in extreme heat (33.6 ± 0.9°C WBGT) (76). In explanation of the current finding, the AO is one of the pinnacle events in the tennis calendar as such competitors are likely highly fatigue resistant due to their regular competitive matchplay at high level events (163). Alternatively, players may also increase their efforts during the final set of matchplay in an effort to finish the match or stay in the competition. This increased effort towards the end of matchplay has previously been described as an 'end spurt' in individual sports (3, 194).

This potential increased effort in the final set of matchplay may have prevented a progressive decrease in performance from the first to last set, and thus this study further examined changes in matchplay consistency based on WBGT.

Minor but significant decrease in the set-to-set consistency of net approaches, set duration and total points won were apparent during matchplay in hotter estimated WBGT zones. This decrease in consistency of net approaches sits alongside previous cross-sectional evidence from the same cohort, where a significant decrease in match total net approaches was observed during matchplay in the heat (177). Taken together, these findings indicate a more selective and strategic use of net approaches in the heat. The reduced set-to-set consistency of net approaches implies that athletes selectively use aggressive matchplay tactics, notably net approaches, based on the prevailing environmental conditions. The use of aggressive matchplay tactics is likely to require increased movement to allow net approaches to occur (65). This increased selectiveness, as represented by the reduced set-to-set consistency, in the use of aggressive matchplay likely resulted in a decreased volume and intensity of court movement, and may be a method to limit increases in thermal strain during matchplay in the heat (154). Thus, the reduced consistency of net approaches in higher estimated WBGT conditions, despite the lack of a change from start to end, supports previous evidence (94, 154, 177) suggesting altered matchplay engagement due to the conditions.

The decreased set-to-set consistency of set duration during matchplay in the heat is in contrast to previous evidence from whole-match analysis in the same cohort, which showed no significant associated change in match duration during matchplay in the heat (Chapter Three). However, previous simulated matchplay evidence shows significant increases in match duration due to increased rest periods between points (154). The reduced consistency of set duration during matchplay in the heat in the current study is likely related to the reduced consistency evident in the number of points won per set during matchplay in the heat. Alternatively, the reduced consistency of set duration may also relate to the increased use of on-court doctor and trainer consults previously reported within this cohort at the AO during matchplay in hotter conditions (177). With set duration in those sets that requested trainer or doctor consults likely being longer due to medical time outs and medical assessments, leading to a reduced consistency of set duration.

The reduced consistency of points won per set during matchplay in hotter conditions also contrasts with previous results in whole match data showing no change in total points won in extreme heat (128, 129, 154, 177). This decreased consistency of total points won may suggest that competitors will tactically forgo competing as hard in certain point situations, as they conserve energy for other more important passages of play that are likely to have a larger impact on match outcome (166, 193). While the reduction in competitive intensity in specific match contexts in the heat is highly speculative this strategy may be analogous with football players reducing the distance covered to then maintain high-intensity efforts during matchplay in the heat for important passages of play (123, 135). Thus professional tennis players may conserve effort during a particular set, or once they feel they are no longer able to win it, in preparation for the next set and thus represent a form of pacing within tennis (118, 166, 193) that is exacerbated by hotter WBGT environments. As such, matchplay quality may show higher variability during matches in extreme heat as players decrease their intensity during point play for energy conservation.

Despite the ecological validity of this Grand Slam tennis population, it is important to address the inherent limitations within this study. In particular, the use of the WBGT index with previous reports highlighting limitations related to the ability of the WBGT to account for air movement and clothing, and the fixed weighting of humidity (4, 36, 41). The limitations involving the use of estimated WBGT also need to be highlighted, with the use of fixed globe temperature reducing the accuracy of the WBGT measure (41). The use of a fixed black globe has also been shown to underestimate the actual on court WBGT, and it is likely the case that players are competing in conditions hotter than actually reported (41, 159). Regardless of these limitations, the use of estimated WBGT within this study was appropriate as all estimated WBGT measures were standardized across the data set, with all comparisons being made across the data set reducing the impact of the above stated limitations. Further, estimated WBGT was the most appropriate index for the current study, as WBGT is currently the most practically relevant and available temperature index due to its wide spread use of within sporting policy, particularly at the AO with its use in the implementation of the EHP.

5.6 Conclusion

In conclusion the absence of change in match characteristics from first to last set with increased match estimated WBGT suggests that any changes to match characteristic performance are not progressive in nature; and as such not likely to be due to increasing fatigue caused by increased WBGT conditions. However, the decreased set-to-set consistency of set duration, total points won and net approaches made during matchplay in the heat, suggests that competitors reduce the consistency in the use of aggressive matchplay tactics. Further competitors may reduce competitive effort in various match contexts. These forms of selective reductions in match involvement would indicate a form of pacing as found in other sports during matchplay in the heat.

5.7 Practical Applications

- Coaches staff should be aware that during best of 5 set matchplay in hot conditions male competitors will increase the use of pacing strategies, particularly surrounding the use of aggressive matchplay involving net approaches.
- Tournament organisers should monitor competitors within match changes to performance during professional matchplay in the heat, with male competitors likely to have less consistency in set duration and number of points won per set.

Chapter Six

Study 4

Women's *Grand Slam Tennis in the Heat;*
the Consistency of Within-match Performance at the Australian Open

6.1 Abstract

Objectives: To measure the effect of estimated WBGT on the within-match change in professional women's tennis matchplay performance at the Australian Open (AO).

Methods: Set-by-set matchplay data from the 2014-16 AO tournaments were collated into estimated WBGT zones (zone 5:>32.3^{o}C, 4: 30.1-32.2^{o}C, 3: 27.9-30^{o}C, 2: 22.3-27.9^{o}C, 1: <22.2^{o}C). For each matchplay variable, the change from the first to last set and the standard deviation (SD) between sets were calculated. Respective GLM's then assessed 1) directional changes in the first to last set performance and 2) set-to-set consistency as based on WBGT zone for matchplay variables.

Results: Increased estimated WBGT resulted in increased set duration (3.31 ± 1.02%; p=0.001), and unforced errors (0.16 ± 0.37%; p=0.002) and decreased points won on first serve (-2.17 ± 1.07%; p=0.04) from the first to last set of matchplay. Set-to-set consistency of set duration (2.16 ± 1.89%; p=0.05) and percentage of break points converted (3.65 ± 1.89%; p=0.05) significantly decrease with increased WBGT zone. The set-to-set consistency of all other measured match characteristics showed no significant (p>0.05) change with increased WBGT zone.

Conclusion: Higher estimated WBGT conditions led to longer sets, more unforced errors and reduced percentages of points won on first serve as Women's Grand Slam matchplay unfolds. These changes during matchplay in the heat likely contributed to the observed decreases in the consistency of set duration and percentage of break points converted. Such changes may represent an increased influence of heat-induced fatigue over the course of the match.

6.2 Introduction

The professional tennis circuit is played on a year-round calendar and the summer-based nature of the sport exposes professional competitors to hot environmental conditions. These environments are regularly encountered at the Australian Open (AO), where conditions can often exceed 40^{o}C Dry Bulb during matchplay. Despite a significant amount of media speculation (2, 185), there is limited peer-reviewed literature examining the impact of extreme heat on tennis performance in elite competitors (94, 154). This is particularly evident in the women's game, with fewer studies examining the effect of environmental heat on professional tennis performance (176). Additionally, the women's tournament competes under a different format to the men (99), with different physiological (63) and tactical demands (65). These physiological and tactical differences between competition's limit the ability to extrapolate data on the effect of extreme heat on tennis performance between genders.

Despite limited evidence in professional women's tennis, whole match analysis from the AO reports increased estimated WBGT results in an increase in the number of whole match double faults, and a reduction in net approaches (176). This increase in double faults was suggested to highlight competitors unsuccessfully attempting to hit risker serves in order to reduce point length, or as a result of increased fatigue during matchplay in the heat reducing shot accuracy (94, 117). Additionally, the reduced use of net approaches was also suggested to be due to competitors attempting to decrease match intensity by reducing the use of aggressive matchplay (176). As evidence, previous studies in simulated matchplay in males showed players will extend rest periods as a method of behavioural thermoregulation (154). While rest periods have been reported to increase during professional tournament matchplay in hot conditions (32.0 ± 4.5°C dry bulb) (94), rest periods at the AO are routinely monitored to prevent the regular extension of rest periods (99). This monitoring of rest periods may have lead competitors to find alternative methods of reducing match intensity, i.e. reduction in net approaches (176). While these previous studies informed on whole match changes during matchplay in the heat, the use of cross-sectional analysis does not inform the within-match effect of hotter environmental conditions on matchplay performance in women. Therefore, assessing the changes in first to last set match characteristics, and the set-to-set consistency of match characteristics will provide a more complete understanding of the within match adjustments to performance during matchplay in the heat.

In light of these gaps in the literature the aims of this study were to investigate the relationship between match WBGT zone and changes in 1) the performance characteristics of professional female players from first to last set and 2) the set-to-set consistency of these same characteristics in women’s Grand Slam tennis. We hypothesized that within match performance of net approaches and double faults will reduce with increased match estimated WBGT; while the set-to-set consistency of those performance characteristics would decrease.

6.3 Methods

The current study assessed the effect of estimated WBGT on within-match changes to match characteristics during women's Grand Slam tennis. To assess the within-match changes to performance, the set level match characteristics data of the 360 matches that made up the first four rounds of the 2014-2016 AO women's main draw were obtained. The participants held a mean Women's Tennis Association rank of 67 ± 72, with an age of 25 ± 4 and were from 45 different countries. This was the same cohort used within the study of Chapter Four; however, set by set data was collected separately for this study. Matches were excluded from analysis if they were missing data (i.e., WBGT, or match characteristic data) (n = 12), suspended for rain, or played under a closed roof (n = 2). Given that Grand Slams are the pinnacle of tennis competition and these players have regular exposure to similar environments prior to the AO, it was assumed a high level of fitness existed among the participants. Consent for the use of data for research purposes was gathered from all participants upon entry to the tournament. This study was approved by the University of Technology Sydney Human Research Ethics Committee (UTS REF: 2015000126).

Extensively trained umpires and tennis match coding professionals generated real time matchplay data which was then gathered and supplied by AO tournament organisers. Although the reliability of this data has not been assessed, previous reports have found high levels of inter- and intra-tester reliability for similar performance statistics (91). Point level data of all match characteristics (outlined in Table 6.1) were collected and aggregated to the set level, the selected match characteristics were assessed due to their regular use in describing match performance and association to match outcome in Grand Slam tennis (65).

Firstly, the linear change in performance over the course of the match was assessed by calculating the difference between the last and first set values of matchplay. This first to last set measure was used to describe the directional change in performance over the course of the match, and allowed for standardisation of measurement across matches consisting of either 2 or 3 sets. This measurement of first to last set change provided an indication of progressing fatigue within the match. Secondly, set-to-set standard deviation (SD) of each match characteristic was calculated from the collected set data, providing a measure of consistency in performance. This measure of set-to-set consistency was used to measure fluctuations and the spread of performance away from the mean match values. Measuring the consistency of performance also allowed for the detection of potential non-linear changes in performance, possibly hidden by increased effort within the final set of the matchplay by the losing competitor (32, 118).

Table 6.1: Descriptors of match characteristics data collected.

Measure	Description
Match Characteristics	
Set Duration(min)	Length of the set in minutes
First serve (%)	The percentage of first serves made
Number of Aces	Total number of aces per set
Double Faults	Total number of double faults per set
Unforced Errors	Total number of unforced errors per set
Winners	Total number of winners per set
Winning on first serve (%)	Percentage of points won when first serve was made
Winner on Second Serve (%)	Percentage of points won when second serve was made
Break point conversion (%)	Percentage of break points won
Return points won	Percentage of return points won
Total points won	Total number of points won by the player per set
Number of net approaches	Total number of net approaches made per set
Net approaches won (%)	Percentage of net approach points won

The measures of within-match changes in performance were aligned with weather data. Weather data was recorded in half hourly increments and was gathered from an Australian Bureau of Meteorology weather station located within 100m of the tournament venue. This data was then used to calculate match averaged estimated WBGT. All match characteristic data and WBGT recordings were entered into a customised spreadsheet (Microsoft Excel for Mac, version 15.13.4, Washington, USA) and grouped into a WBGT zone according to the ACSM classification for non-continuous, fit, low risk individuals (1), zone 5: >32.3°C, zone 4: 30.1-32.2°C, zone 3: 27.9-30°C, zone 2: 22.3-27.9°C , zone 1: <22.2°C (with ACSM's zones <10 and 10.1-22.2°C being combined to form zone 1, and zones 22.3-25.6°C and 25.7-27.8°C being combined to form zone 2). Although, due to the Australian Bureau of Meteorology not explicitly measuring black globe temperature estimated WBGT was calculated using the formula:

$$WBGT = 0.567 \times Ta + 0.393 \times e + 3.94,$$

where Ta = dry bulb temperature (°C) and e = Water vapour pressure (hPa) [humidity].

While the limitations surrounding the use of WBGT have been well documented (41), most notably surrounding the use of a fixed weighting of the naturally wet bulb temperature, which reduces the ability of WBGT to accurately account for thermal stress in hot restricted evaporative conditions (41). However, Melbourne summers are typically hot and dry reducing the impact of this limitation within the current data set. Further, the likely under reporting of thermal stress in hot conditions due to the use of a fixed black globe temperature in the estimation of WBGT (13, 41) is well understood.

However, the widespread use of WBGT within sport, particularly tennis (196), and the use of a retrospective data set, which includes the most elite group of tennis players, made estimated WBGT the only relevant and available measure for the current study. Furthermore, limitations surrounding the use of estimated WBGT in the current study are somewhat limited by the use of zonal analysis.

Analyses for the present study were completed in RStudio version 0.99.902 (RStudio: Integrated Development for R. RStudio, Inc., Boston, MA), where respective GLM's were used to undertake two separate analyses. Firstly, the relationship between match WBGT zone and change in match characteristics over the course of the match were examined. Secondly, the relationship between match WBGT zone and the set-to-set consistency of matchplay characteristics was assessed. All analysis used the Gaussian distribution with confidence intervals reported at the 95% level and statistical significance defined as an effect of 5% significance or less. Funnel plots were used to graphically present data, with consistency (standard deviation) displayed on the Y axis, and first to last set change on the X axis and 95%, confidence interval lines were also displayed. Funnel plots are often used to describe systematic heterogeneity within data (178, 183, 184), with symmetrical inverted funnel shaped data showing homogenous data, while asymmetrical funnel plots indicate systematic heterogeneity. The use of funnel plots within this study provide a unique display of the consistency of performance in relation to first to last set change in performance of each match characteristic across each estimated WBGT zone.

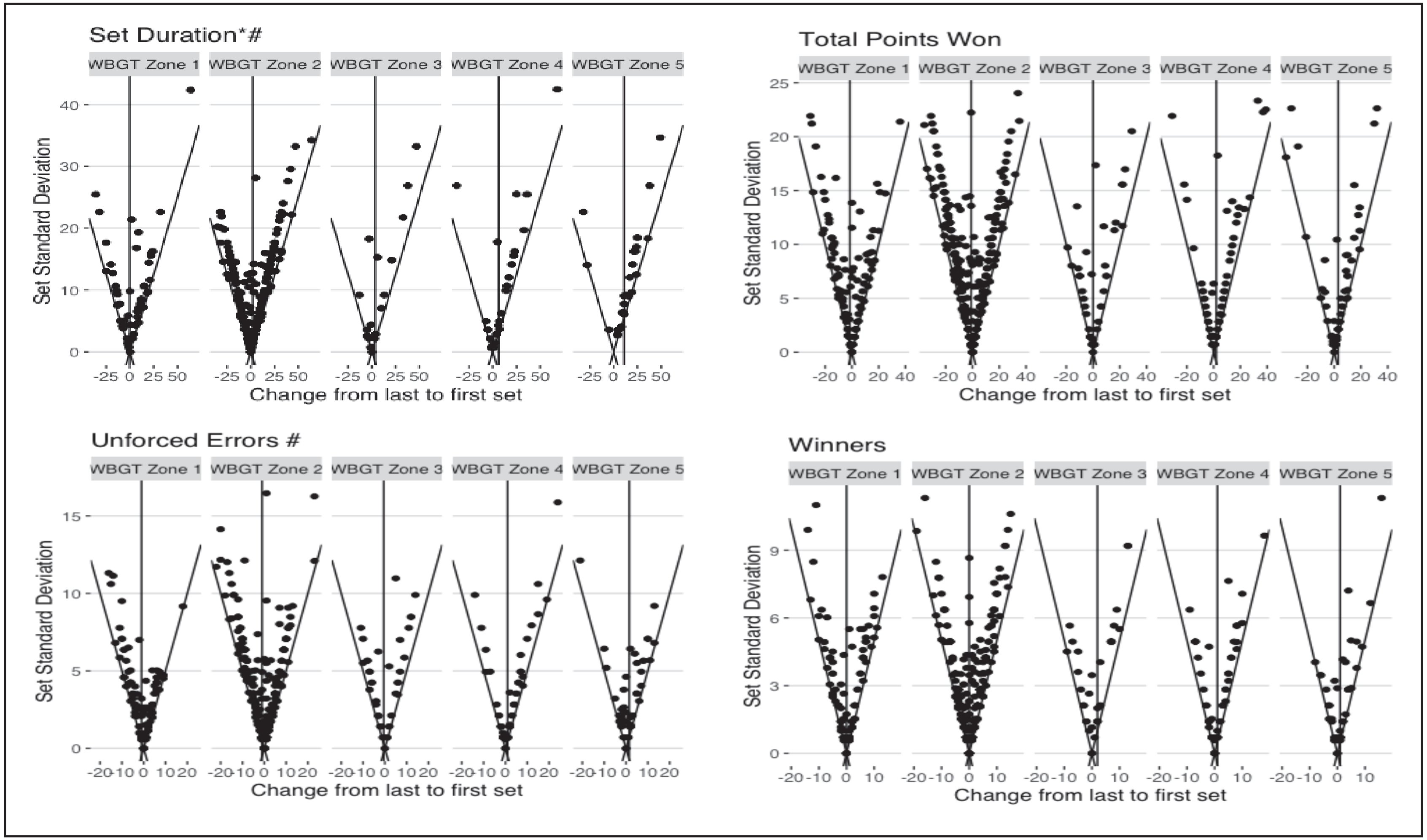
6.4 Results

From the current data set there were 29 matches with a mean 2.4 ± 0.5 sets in the WBGT zone >32.3^{o}C, 30 matches with 2.2 ± 0.4 sets in WBGT zone 30.1-32.2^{o}C, and 21 matches with 2.3 ± 0.4 sets in WBGT zone 27.9-30.0^{o}C. Further, in WBGT zone 22.3-27.9^{o}C there were 207 matches with 2.3 ± 0.4 sets and 59 matches with 2.4 ± 0.5 sets in WBGT zone < 22.2^{o}C.

When comparing the first to last set of matchplay there was a significant increase in set duration (3.31 ± 1.02 %; p=0.001) and unforced errors (0.16 ± 0.37%; p=0.002) from the first to last set of matchplay with each increase in WBGT zone (Figure 6.1). However, the change from the first to last set for total points won (1.17 ± 0.76%; p=0.12) and winners (0.32 ± 0.30%; p=0.28) showed no significant change with increased WBGT zone (Figure 6.1). Additionally, the number of net approaches (0.37 ± 0.21 %; p=0.08), net approaches won (%) (0.45 ± 2.18%; p=0.84), return points won (%) (1.18 ± 0.85%; p=0.17) and break point conversion (%) (0.63 ± 2.75%; p=0.81) showed no significant change from first to last set of matchplay with increased match WBGT zone (Figure 6.2). When examining serve related match characteristics, winning on first serve (%) decreased from first to last set of matchplay (-2.17 ± 1.07% p=0.04) as match WBGT zone increased (Figure 6.3). Lastly, changes in first serve percentage (0.02 ± 0.80%; p=0.98), aces (-0.07 ± 0.11%; p=0.55), double faults (0.09 ± 0.11%; p=0.42) and winning on second serve (-1.0 ± 1.47%; p= 0.50) showed no significant change with increased WBGT zone (Figure 6.3).

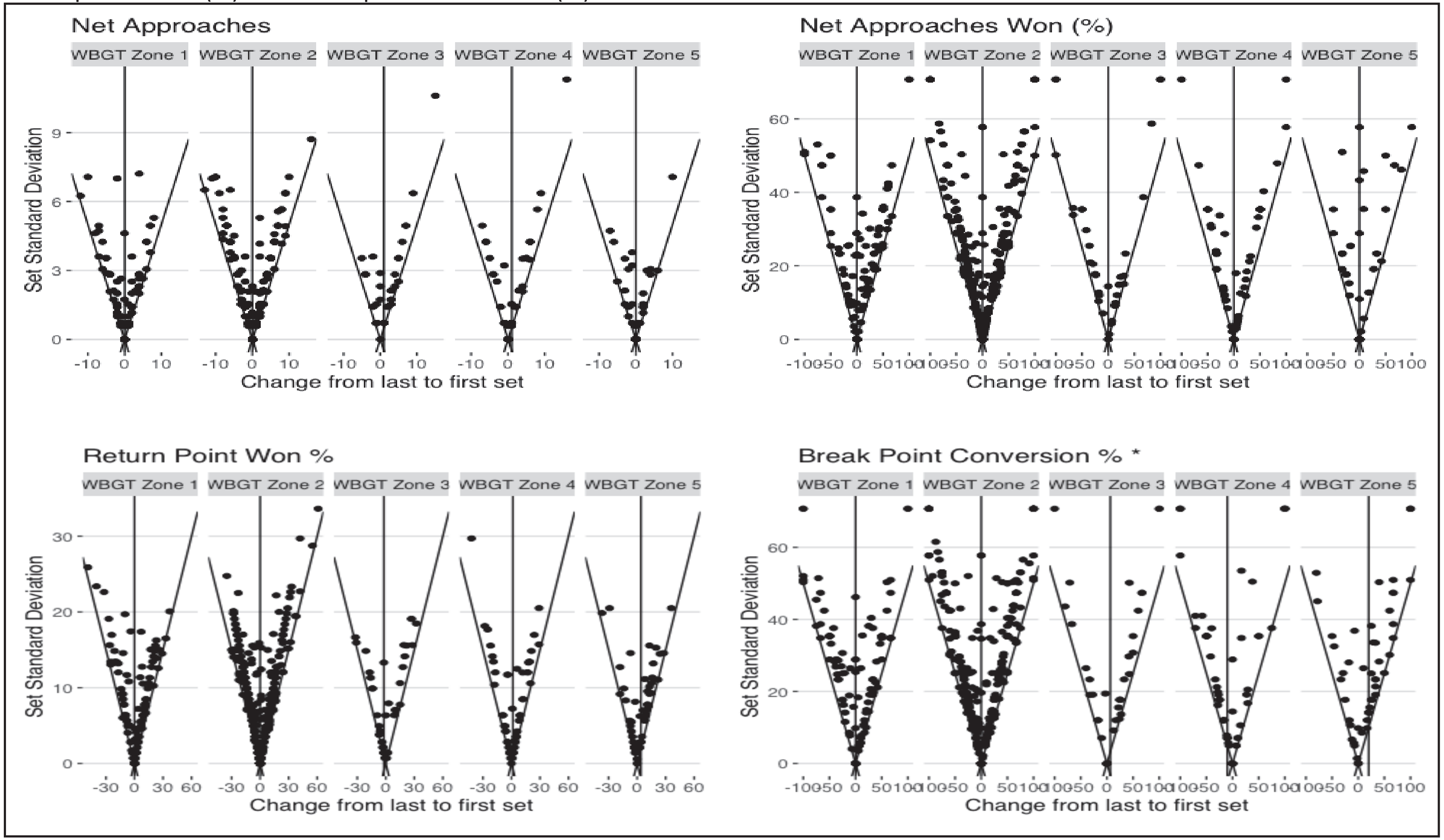
In regards to the consistency of match characteristics with increased match WBGT zone, a significant reduction in the consistency of set duration (2.16 ± 1.89 %; p=0.05) was evident with increased match WBGT zone. However, total points won (0.89 ± 0.51%; p=0.08), unforced errors (0.31 ± 0.27%; p= 0.25), and winners (0.20 ± 0.21%; p=0.35) showed no significant change in consistency with increased estimated match WBGT zone (Figure 6.1). Break point conversion (%) (3.65 ± 1.89%; p=0.05) showed a significant reduction in consistency with increased match WBGT zone, while net approaches (0.11 ± 0.17%; p=0.50), percentage of net approaches won (0.78 ± 1.7%; p=0.65), and return points won (0.46 ± 0.59%; p=0.44) showed no significant change with increased match WBGT zone (Figure 6.2). The examination of serve related match characteristics showed that there was no significant change to the set-to-set consistency of double faults (0.13 ± 0.08%; p=0.09), first serve percentage (0.05 ± 0.51%; p=0.93), aces (0.06 ± 0.09%; p=0.25), winning on first serve (%) (0.81 ± 0.69%; p=0.24) and, winning on second serve (%) (0.91 ± 0.94%; p=0.34) with increased match WBGT zone (Figure 6.3).

Figure 6.1: Within-match changes and set-to-set consistency of match characteristics of set duration, total points won, unforced errors and winners count as based on estimated WBGT zone in women.



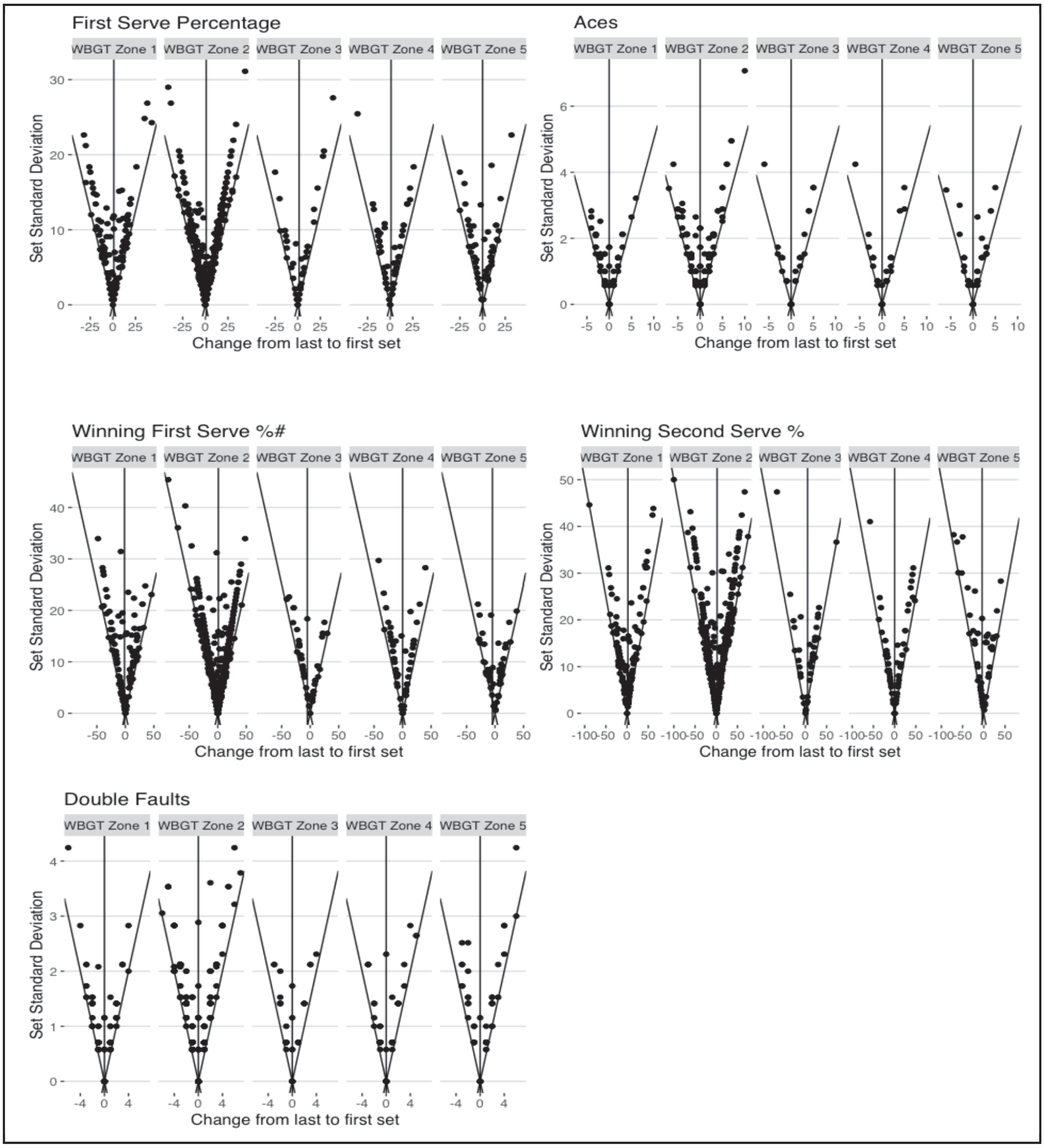
# Indicates significant association between change and WBGT (p < 0.05), * indicates significant association between SD and WBGT (p<0.05) and can be found next to the title of each variable.

Figure 6.2: Within-match changes and set-to-set consistency of match characteristics of net approaches, net approaches won (%), return points won (%) and break point conversion (%) as based on estimated WBGT zone in women.



# Indicates significant association between change and WBGT (p < 0.05), * indicates significant association between SD and WBGT (p<0.05) and can be found next to the title of each variable.

Figure 6.3: Within-match changes and set-to-set consistency of match characteristics of first serve percentage, aces, winning on first serve (%), winning on second serve (%) and double faults as based on estimated WBGT zone in women.



# Indicates significant association between change and WBGT ($p < 0.05$), * indicates significant association between SD and WBGT ($p<0.05$)

6.5 Discussion

The current study demonstrated that with increased estimated WBGT there was an associated increase in set duration and unforced errors from the first to last set during professional women's tennis matchplay. Further, a progressive reduction in the percentage of points won on first serve was evident during matches played in hotter WBGT conditions. The increasing occurrence of unforced errors and reducing percentage of points won on first serve may suggest that increased estimated match WBGT results in a progressive decline in shot accuracy, particularly when considered in combination with previous whole match adjustments to performance in the heat in the same cohort as Chapter Four.

Previous whole match data at the AO has shown no significant relationship between estimated match WBGT and match duration in the same cohort of players (176). However, the current study shows that with increased match WBGT zone, there is an increase in set duration alongside reduced set-to-set consistency of set duration. Previous evidence from simulated matchplay in the heat has demonstrated a significant increase in match duration in sub-elite male players (154), likely achieved by players extending rest periods between points as a means to improve recovery (154). Such a tactic is difficult in a Grand Slam setting given the closer monitoring of rest periods, limiting the ability of players to regularly take extended breaks between points (99). The increased duration of the final set of matchplay in the current study was likely due to the increased use of on court calls for trainers and doctors during matchplay in the heat previously reported (176). To confirm this hypothesis, unpublished data from this cohort shows a majority (89%) of on-court heat related consultations occurred after the first 60 min of matchplay in the heat, suggesting consults occurred late within the match.

The decrease in the percentage of points won on first serve from the first to last set during matchplay in higher WBGT zones reported here supports previous evidence from the same cohort, which showed an increase in double faults during matchplay in the heat (176). These two findings also likely lead to a reduction in the set-to-set consistency of break point conversion (%). The combination of the increased number of double faults, reducing percentage of points won on first serve and reduced set-to-set consistency of break point conversion, suggests that female competitors do not maintain as significant a level of dominance during service games in the heat. This reduced dominance of service games during matchplay in the heat is likely due to the higher intensity of service games in comparison to returning games (110, 128). In turn, the increased intensity likely leads to an exacerbation of heat-induced fatigue and reduction in dominance during service games as the match progresses in hotter WBGT zones.

The current study demonstrated a small increase in unforced errors from the first to last set of matchplay. In isolation, this increase in unforced errors appears negligible; but when considered alongside the decrease in percentage of points won on first serve, and previously reported increases in whole match double faults (176), it may represent a decrease in the shot accuracy in hotter WBGT conditions. Specifically, the progressive onset of more unforced errors and relatively fewer points won on first serve could be emblematic of rising heat-induced fatigue (143) resulting in poorer precision (94, 117, 140). This supposition receives some support in other sports literature with a decrease in fine motor skill and increased fatigue during hockey matchplay in hot conditions (186). Alternatively, it could be reasonably argued that the combination of these factors (more unforced errors and more double faults) is representative of higher risk taking behaviour by players in attempts to shorten points to reduce match intensity (154).

While this study is unique with the use of an elite Grand Slam tennis population in live competition, there are inherent limitations within this study. Notably, the use of the WBGT index has previously been highlighted for having limitations in appropriately accounts for the impact of high humidity on human thermoregulation in hot conditions, due to the use of a fixed naturally wet bulb weighting (41). However, the heat experienced in Melbourne during the summer is usually dry in nature which likely reduced this limitation. Further, the use of a fixed black globe temperature equating to a moderately sunny day with light wind has previously been reported to underestimate WBGT in hot environments (13), particularly for a tennis court from an off court location (159). Regardless of these limitations, the use of zonal analysis along with standardisation of data across the data set reduced these limitations. Additionally, the wide spread use of WBGT within sport (7, 135) and tennis (196) made the use of WBGT the most logical choice for determining environmental conditions. Similarly, the use of a retrospective data set meant that estimated WBGT was the only relevant and available measure in the current study. Furthermore, it should be noted that there was no specific measurement of fatigue in the current study, although the progressive decline in match characteristic performance from the first to last set was used as proxy for the effect of fatigue (16, 52, 122).

6.6 Conclusion

The results from the current study suggest that during professional women's tennis matchplay in the heat there is a significant increase in set duration over the course of the match, along with an increase in unforced errors and a decrease in the percentage of points won on first serve. The progressive nature of these changes suggests that these alterations in performance are the result of a heightened level of fatigue due to increased estimated WBGT. These changes in performance, particularly surrounding the serve, also likely lead to a reduction in the set-to-set consistency of converting break point opportunities.

6.7 Practical Applications

- In hot conditions coaches should be aware of female competitor's performance surrounding unforced errors and winning point on first serve will reduce over the course of the match.
- The increased number of unforced errors and reduced percentage of points won on first serve in the women's competition may indicate a decrease in shot accuracy.
- Tournament organisers should monitor within match changes to competitor's performance, with the potential for matchplay in hot conditions to impact the competitive integrity of the tournament's competition.

Chapter Seven

Discussion

7.1 Introduction

Playing conditions at the AO regularly lead to debate in both mainstream media (54, 115, 166, 185) and the scientific literature (44, 54, 64, 150, 157) on the implications of extreme heat on match performance and heat illness. Much of this debate relates to the impact of extreme heat on matchplay performance; however, outside of increased rest periods between points (154), there is relatively little data to support these suggested reductions in performance (2, 115, 157, 185). Further, there is limited literature describing the occurrence of heat illness in professional tennis (2, 115, 157, 185). Indeed, the only available data describing heat illness occurrence at a Grand Slam event has been the US Open, where no association between environmental conditions and heat illness was revealed (173). In light of this, it is challenging for tournament organisers and medical staff at Grand Slam tennis events to appropriately modify tournament matchplay to ensure the wellbeing of competitors, and protect the competitive integrity of the tournaments competition.

In response to this significant gap in the literature, the current thesis undertook a novel assessment of the effect of extreme heat on the occurrence of heat related medical events and adjustments to performance during tournament matchplay at the AO. By doing so, the current findings provide an evidenced-based platform from which decision-making by tournament organisers and medical staff on matchplay in the heat can occur. As such, this thesis examined the impact of increased estimated WBGT during matchplay at the AO on the occurrence of heat related events including on-court doctor and trainer call outs, heat related retirements and post-match heat related consultations. Additionally, the previously unexplored impact of increased estimated WBGT on professional tennis matchplay performance was examined.

Accordingly, the primary aims of this thesis were;

- To investigate the association between WBGT and the occurrence of heat related events, medical consultations and requests for cooling devices and water at the AO in the men's and women's main draw competition (study's 1 and 2).
- To assess the impact of increased estimated WBGT on whole match changes to match characteristics during main draw tournament matchplay at the AO (study's 1 and 2).
- To investigate the implications of increased estimated WBGT on changes in match characteristics from the first to last set of matchplay, and the set-to-set consistency of match characteristics of professional men's and women's players, during main draw tournament matchplay at the AO (study 3 and 4).

7.2 Frequency of Extreme Heat at the AO

There is often significant discussion surrounding the frequency of extreme heat at the AO in mainstream media (2, 48, 115). However, between 2009 and 2019 at the AO only 8% of days of competition resulted in a recorded air temperature of 40^{o}C (179). Further, within the data set compiled for the current thesis, the mean estimated WBGT within the men's competition was 25.8 ± 3.7^{o}C with a range of 17.5-32.8^{o}C. Of note, the mean dry bulb temperature in the men's competition was 27.2 ± 6.6^{o}C with a range of 17.2 - 41.7^{o}C, and a mean relative humidity of 50.1 ± 19.6% (15.8 - 92.6 %).

Similar conditions also existed in the women's competition, with a mean estimated WBGT of 25.7 ± 3.8°C (range of 17.7 - 32.8°C); alongside a mean dry bulb temperature of 27.5 ± 6.7°C (range of 16.7 – 42.0°C) and RH of 46 ± 20% (range 16.0 - 94.4%).

In light of these recorded environmental temperatures, the frequency of extreme heat at the AO may be over-reported by mainstream media. However, the regular occurrence of periods of extreme heat at the AO does provide a regular challenge for competitors, medical staff and tournament organisers. Such occurrence requires significant consideration and adequate assessment to ensure modifications to matchplay to safeguard competitor welfare and the tournaments competitive integrity are justified.

7.3 Medical Consultations in the Heat

Exercise in the heat has previously been suggested to increase the risks of developing exertional heat illness, such as heat stroke (17, 49, 50). As noted, the AO can expose competitors to significant heat stress, though the occurrence of heat illness during professional tennis matchplay has not been well documented (22, 155, 173). Whilst numerous studies report significant increases in core temperature during tennis matchplay in the heat (23, 24, 76, 94, 129, 153, 154, 191), few studies have reported the incidence or pervasiveness of heat illness in professional tennis (157, 173). To the knowledge of the authors, Studies 1 and 2 (Chapter Three and Four) in this thesis are the first studies to specifically examine the relationship between estimated WBGT and heat related events during Grand Slam men's and women's singles tennis. As discussed below, this body of work revealed a significant positive linear relationship between increased estimated WBGT zone and the use of on-court calls (for trainers and doctors) for both heat and non-heat related consultations in the men's and women's competition.

7.3.1 Heat related events in the men's competition at the AO

The men's draw at the AO had a higher rate of heat-related events (11.11/1000ME), and heat illness related retirements (4.17/1000ME) than previously reported at the US Open (2.84/1000ME) (173). This is, at least partly, due to the inclusion of doubles matchplay in the US Open study, with the physical demands of doubles matchplay significantly reduced in comparison to singles tennis (63, 130). Beyond this methodological difference, it was suggested that heat illness at the US Open was not associated with dry or wet bulb temperature, but rather high levels of air pollution caused by the close proximity of the US Open to New York city (67, 173). Regardless, to provide context to the AO heat incident data, the rate of musculoskeletal injury consults during singles matches at the AO (66.5/1000ME) (73) was significantly greater than the occurrence of heat related events. This data contextualise the occurrence of heat related events at the AO, and highlights heat-related events account for a small proportion of medical consultations at the AO.

As with the US Open (173), heat illness retirements in the men's draw at the AO were not associated with estimated WBGT (Chapter Three). Although, a larger sample size, and more matches played in conditions >32^{o}C WBGT may have yielded a different result. However, a significant association was observed between both on-court trainer calls for heat related incidents and post-match heat related doctor consultations with estimated WBGT in the men's competition (Chapter Three). Furthermore, heat related events, such as on-court calls for trainer and doctor consultations, post-match heat related doctor consultations and calls for cooling devices increased most dramatically in conditions > 32^{o}C estimated WBGT. These findings suggest that athletes may have become uncomfortable with the thermal conditions and may have displayed symptoms of heat-related stress (Table 7.1) (50). Indeed, the observed increase in heat related events at an estimated WBGT of >32^{o}C is consistent with the position of the ACSM, who have suggested that non-continuous exercise in conditions >32.3^{o}C WBGT be suspended (7). However, this thesis was unable to gauge the severity of the player's condition through these heat related consultations, and so it could be speculated that players utilised these breaks in play for tactical advantage.

When heat related events due to secondary causes such as gastrointestinal illness were ignored, dizziness (4.17/1000ME) was the most commonly reported symptom of heat stress in the men's competition followed by cramping (2.17/1000ME) (Table 7.1). Comparison of the frequency of the symptoms of dizziness and cramping during heat-related consultations is difficult, as only case studies are previously reported in tennis (22, 155). However, the occurrence of cramping is often attributed to hydration status; although, this relationship has been questioned in recent literature (35, 101), with alternate mechanisms such as hypocapnia offered (192). Further, dizziness has also been associated with heat syncope, the result of blood pooling in the lower extremities and increased blood flow to the skin for cooling (50). This pooling of blood reduces the flow of blood to the brain (138), ultimately leading to postural hypotension as players alter standing and seated posture at the changes of ends (138). Regardless of the underlying cause of dizziness and cramping during matchplay in the heat, medical staff at professional tennis events should prepare to manage a growing number of on-court consultations for dizziness and cramping at conditions >32^{o}C WBGT.

At the time of data collection and analysis (2015-2016), the EHP at the AO stated that, at the tournament referee's discretion, matchplay could be suspended once WBGT reached 32.5^{o}C and air temperature reached 40^{o}C (2). In Table 7.1, it is evident that in the majority of matches where heat-related events occurred in the men's competition, peak estimated WBGT and ambient air temperature were above the EHP in use at the time. Given that off-court WBGT recording can underestimate on-court WBGT recordings (159), AO competitors were likely competing in conditions significantly hotter than the EHP in 2015-16.

Table 7.1: Description of heat incidents occurrence in men at the Australian Open 2014-2016.

Court	Mean BoM estimated WBGT (°C)	Peak BoM estimated WBGT (°C)	Mean ambient temp (°C)	Peak ambient air temp (°C)	Mean Relative Humidity (%)	Time in match consult occurred	Retirement	In match Doctor / trainer calls	Post match consult	Description
Show court	27.2	28.0	33.5	34.5	22	2h0min	Y	Y	N	Hot, dizzy, and was concerned about collapse
Show court	32.1	33.1	39.1	41.5	22.0	PM	N	N	Y	Requested electrolyte replacements post match.
Show court	32.1	33.1	39.2	41.5	21.7	0h31min	N	Y	N	Headache, dizzy, heavy legs
Show court	32.5	33	40.1	41.1	20.1	PM	N	N	Y	In match dizziness and cramping
Show court	32.7	33	40.9	41.8	18.5	2h03min	Y	Y	Y	Collapsed on court, recovered quickly with leg elevation
Show court	32.7	33	40.9	41.8	18.5	2h04min	Y	Y	Y	Heat affected secondary to gastrointestinal illness
Arena Court	30.2	32.7	39.4	40.2	22.0	PM	N	N	Y	cramping
Arena Court	32.4	33.1	39.1	41.5	22.0	2h29min	N	Y	N	
Mean ±SD	**31.2±2.1**	**31.7±2.3**	**38.5±2.6**	**39.3±4.4**	**21.0±2.3**					

RH = relative humidity, WBGT = wet bulb globe temperature, N = no, Y = yes.

7.3.2 Heat related events in the women's competition at the AO.

In the women's draw at the AO, the occurrence of heat and non-heat related on-court calls for trainer and doctor consultations were significantly associated with match estimated WBGT (Chapter Four). These results contrast with the findings from the US Open study, where no association between environmental conditions and heat illness occurrence were found (173). Further, the incidence of heat-related events at the AO in the women's competition (13.89/1000ME; Table 7.2) was significantly higher than at the US Open (1.42/1000ME) (173). As abovementioned, the inclusion of doubles matchplay in the US Open dataset as well as New York's different thermal demands likely contributed to this disparity (173). However, it should also be considered that number of heat related calls for heat related events at the AO in the women's competition (13.89/1000ME) was relatively small in comparison to the number of musculoskeletal consultations (71.5/1000ME) reported at the same competition (73). As with the men, the occurrence of heat-related medical consultations accounts for a small fraction of the total medical consultations.

The absence of heat illness retirements in the women's singles competition at the AO is in contrast to the men's competition. Such a finding is likely related to shorter match durations (17, 50, 138), which decreases the absolute thermal load on competitors (7, 50). Further, the increase in post-match medical consultations in the men's competition in comparison to the women's competition is likely related to the increased rate of heat illness retirements requiring further post-match treatment. Additionally, the use of the extreme heat rule in the women's competition may have reduced the likelihood of heat illness retirements at the AO. This heat rule affords competitors a 10-min break between the second and third set once WBGT exceeds 28°C. This heat rule has previously been demonstrated to significantly reduce core temperature (-0.25 ± 0.20°C) during matchplay in the heat (191). Further, during the 10-minute break, competitors at the AO can access air-conditioned rooms. Thus, the use of the heat rule in AO women's singles competition, in combination with the shorter match durations, may have reduced the risk of heat illness retirement occurrence compared to the men's game.

When heat-related events were described as a rate per 1000 hours of matchplay, conditions greater than 32.3°C estimated WBGT were characterised by the most significant increase in (a) on-court trainer and doctor consultation calls for both heat and non-heat related events and (b) post-match heat related doctor consultations (Chapter Four). As described in the men's competition (Chapter Three), this suggests that female competitor's thermal tolerance became reduced during matchplay in these conditions. Further, the increase in heat-related events during matchplay in conditions above 32.3°C estimated WBGT supports the use of the current position stance from the ACSM surrounding exercise in hot conditions (7).

Similar to the men's competition, when describing the symptoms of heat illness consults in the women's draw, dizziness (5.56/1000ME), was the most commonly reported complaint during heat related events (Table 7.2). As described earlier, dizziness may represent the occurrence of heat syncope due to the redistribution of blood away from the brain in the heat (50, 138). Further, the frequent sitting and standing during tennis, in combination with the extended heat exposure while standing may increase the risk of heat related postural hypotension (heat syncope) during tennis matchplay in the heat (50, 138). Regardless of the speculation as to the underlying cause of dizziness during women's matchplay in the heat, the findings from the current thesis demonstrates that conditions above 32.3^{o}C WBGT are associated with a significant increase in heat related events. As such medical staff and tournament organisers should ensure appropriate policies and recourses are in place if such conditions occur.

In both the men's and women's competition, heat related medical consultations spiked in matches with estimated WBGTs exceeding 32.3^{o}C, suggesting an upper bound of tolerance for heat. The AO's EHP between 2015-2018 suggested the suspension of matchplay in conditions above 32.5^{o}C WBGT and 40^{o}C dry bulb temperature (2). While previous evidence has suggested similar heat policy's by the ACSM are to lenient for intermittent sports such as professional beach volleyball (15). However, from Table 7.1 and 7.2, it can be observed that a majority of heat related illness events at the AO occur well after the normal duration of intermittent sports such as beach volleyball (15, 147). This suggests that due to the extended duration of tennis matchplay, an estimated WBGT of 32.3^{o}C is an appropriate guide for the suspension of matchplay in tennis.

Table 7.2: Description of heat incidents occurrence in women at the Australian Open 2014-2016.

Court	Mean BoM estimated WBGT (°C)	Peak BoM estimated WBGT (°C)	Mean ambient temp (°C)	Peak ambient air temp °C	Mean Relative Humidity (%)	Time in match consult occurred	Retirement	In match Doctor / trainer calls	Post match consult	Description
Show court	31.0	32.2	38.4	40.5	22.6	1h 26m	N	Y	N	Dizziness
Show court	31.0	32.6	39.3	42.1	20.3	1h 12	N	Y	N	Dizziness/heat stress
Show court	31.1	32.2	37.5	40.5	24	1h10m	N	Y	N	Nausea, feels like vomiting, no cramping
Show court	32.5	33	40.1	40.8	20.2	1h18min	N	Y	N	
Show court	32.6	33	40.3	41.1	19.8	2h48m	N	Y	N	Mild dizziness
Show court	32.7	33	40.9	41.6	18.5	1h0min	N	Y	N	
Show court	32.7	33	40.8	41.8	18.7	2h41min	N	Y	N	
Arena court	32.27	32.5	42.0	42.2	14	1h 03min	N	Y	N	Dizzy, difficulties breathing, sweating,
Arena court	32.7	33	40.6	41.1	19.2	0h 43min	N	Y	N	
Arena court	32.2	33.6	40.0	42.4	19.2	PM	N	Y	Y	Requesting iv drip post match. no clinical justification for drip
Mean ±SD	31.9±1.2	32.5± 1.4	39.4 ± 2.4	40.8 ± 2.4	20.6 ± 4.0					

RH = relative humidity, WBGT = wet bulb globe temperature, N = no, Y = yes.

7.4 Effect of Match Estimated WBGT on Professional Tennis Performance

Despite the topical nature of the extreme heat on tennis performance at the AO, (64, 150), there is limited literature to inform current coaching practice and tournament operations. Further, most research examining the effects of extreme heat on tennis performance were conducted in simulated matchplay by amateurs and low-ranking professionals (54, 128, 154), or conducted at lower-tier professional events (94). Due to the use of such research methodologies and contexts, understanding of the implications of extreme heat on tennis performance at Grand Slam events is arguably less developed.

7.4.1 Estimated WBGT and match duration characteristics in men

With increased estimated WBGT there were significant decreases in the set-to-set consistency of set duration in the men's competition (Table 7.3). The use of medical consultations would likely have resulted in an increase in the set duration of those sets, increasing the variability of set duration during matchplay in higher WBGT zones, and thus reducing the set-to-set consistency of duration.

Table 7.3: Summary table of performance changes men's match characteristics as the result of increased estimated WBGT and the Australian Open.

	Whole Match	First to last Set Change	Set-to-set consistency
Match Duration (min)	-	-	-
Set Duration	-	-	↓
1st Serve Percentage (%)	-	-	-
Aces (count)	↑	-	-
Double Faults (count)	-	-	-
Winning on 1st Serve (%)	-	-	-
Winning on 2nd Serve (%)	-	-	-
Unforced Errors (count)	-	-	-
Breakpoint Conversation (%)	-	-	-
Return Points Won (%)	-	-	-
Total Points Won (count)	-	-	↓
Total points (count)	-	-	-
Winners (count)	-	-	-
Net Approaches (count)	↓	-	↓
Net Approaches Won (%)	-	-	-
Fastest Serve (km/h)	-	-	-
Average 1st Serve Speed (km/h)	-	-	-
Average 2nd Serve Speed (km/h)	-	-	-

↑ = increase in occurrence; ↓= decrease in occurrence

While consistency of set duration decreased, there was no change in match duration at higher WBGT's. This is in contrast to previous evidence where simulated matchplay in extreme heat resulted in significantly longer match durations than in cooler temperatures (154). Previous research reports this increased match duration in the heat results from increased between point rest periods (94, 154). This contrast to the present findings is likely due to the higher calibre of professional players and match officiating in the current study. With the professional officiating of the ITF rules at the AO (99) competitors were unlikely to be able to regularly extended rest periods, likely having less impact on match duration during matchplay in the heat. However, within the current study effective playing time data was unavailable, so it is not possible to determine how effective playing time may have been impacted by increased estimated WBGT.

7.4.2 Effect of estimated WBGT on serving performance in men

The current thesis demonstrates that matchplay in the heat increased the whole match count of aces, although without any other significant changes to serve performance (Chapter Three and Five) (Table 7.3). This increase in ace count in hotter conditions suggests that competitors were successfully hitting riskier serves; potentially as an attempt to shorten point length and reduce effective playing times (69). These results are in contrast with previous simulated matchplay in the heat, which revealed no change in ace or double fault count in the heat (154), and suggested reductions in effective playing time were achieved through longer rest periods between points (154). Given the simulated nature of this earlier work, factors such as reduced level of officiating and professionalism (i.e., players were required to retrieve their own balls and no prize money) may have contributed to their longer rest (94). An alternate view is that competitors applied less pressure on serve return, resulting in more aces accrued. Whilst speculative, if such potential reduction in effort occurred, it likely occurred on points where the returner believed that the point is unlikely to impact match outcome (193).

The concept of players reducing their competitive effort in particular match contexts, such as when contesting unimportant points, has been referred to as “pacing” within the literature in tennis (118, 193) and other intermittent sports (12, 118, 194). Furthermore, Grand Slam competitors have also been reported in mainstream media admitting to reducing efforts on returning points in cooler conditions when they believe points are unimportant to then conserve energy for serving (166). This conserving of energy on unimportant points in cooler conditions suggests during hotter conditions pacing strategies may be exacerbated during matchplay in the heat. Such engagement would align with previous evidence from soccer matchplay in the heat, where passing success increased during matchplay in the heat due to reduced defensive pressure from the defending team (123). As further evidence to this point, the increased set-to-set variation of total points won during matchplay in the heat (Chapter Five) might be interpreted as competitors reducing their competitive intensity during points that they deem unimportant, particularly if they were losing that set.

While players’ whole-match ace counts increased at higher WBGT’s, other serve performance characteristics remained consistent within the match (Chapter Five). This suggests that the whole-match increased ace count was not the direct result of an in-match adjustment to serving or returning tactics resulting from heat-induced fatigue (123, 154, 191). In support, it has been previously reported that simulated matchplay in extreme heat (33.6 ± 0.9°C WBGT, 36.8 ± 1.5°C air temperature) did not result in additional heat-induced fatigue in lower ranked professional male tennis players (76). This absence of evidence of increased fatigue during matchplay in extreme heat further suggests that the changes to serve performance in the men's draw competition during extreme heat is unlikely to be the direct result of heat-induced fatigue. Instead they are more likely the result of pacing strategies to preserve energy for important passages of play or to reduce match intensity.

7.4.3 Men's use of net approaches during matchplay in the heat

During matchplay in the heat in the men's competition at the AO the whole-match number of net approaches reduced, and the within-match use of net approaches became less consistent (Chapter Five) (Table 7.3). The reduction in net approaches suggests competitors were less aggressive with their match tactics in higher WBGT's (63). This contrasts with the riskier approach on first serve described above, but was likely an attempt to conserve energy due to the higher physiological demands of aggressive matchplay involving net approaches (163); further indicating a pacing phenomena, noted in other team sports in the heat (12, 123, 135). Though speculative, it is likely that net approaches were still utilised during important passages of play, such as holding serve (118, 166), where players are also more likely to be able to approach the net (163).

It is also important to acknowledge that outside of net approaches, aces, set duration and total points won, no other match characteristic changed with higher match WBGT. Further, aces and net approaches are relatively rare match events in the modern game; however, were most significantly affected by increased estimated WBGT. In turn, this may suggest the impact of increased estimated WBGT on men's Grand Slam tennis appears modest. Correspondingly, the need for pacing strategies to reduce the impact of extreme heat on tennis performance may have been moderated in comparison to other endurance-based exercise performance (12, 84, 123). That said a range of other factors that were not measured here need to be acknowledged, as between-point rest periods allows for continuous hydration (111), the high fitness levels of professional tennis players (64, 110) and year round player acclimation to the heat likely allowed competitors to continue to compete without significant reductions to match quality (15).

7.4.4 Influence of estimated WBGT on match duration characteristics in women

The current thesis found that during women's AO matchplay in the heat there was a significant increase in set duration (from the first to last set) and reduced set-to-set consistency of set duration (Chapter Six); despite no differences between matches in different WBGT zones for match duration (Chapter Four) (Table 7.4). These findings are the first to report matchplay changes in the heat in professional women's tennis players, and thus comparable literature is absent. Previous evidence from male tennis matchplay in the heat found a significant increase in simulated match duration in the heat by lower ranked professionals (154). As noted earlier, this increase in match duration during simulated matchplay in the heat was due to increased rest periods between points (94, 154) to reduce match intensity and the effective playing time percentage of the match (154). Although, the regular extension of rest periods during matchplay at the AO is unlikely due to the monitoring of rest periods by match umpires; albeit this was not assessed in the current thesis. Further, the increase in set duration from first to last set of matchplay and reduced set-to-set constancy of set duration found in women AO matchplay was possibly the result of increased on-court medical consultations during match play in the heat (Chapter Four). As evidence, Table 7.2 shows that a majority of heat related events occurred after the first 60 min of matchplay. Such occurrence indicates that a majority of medical consultations likely occurred in the final set of matchplay, resulting in the increased set duration from first to last set.

Table 7.4: Summary table of performance changes women's match characteristics as the result of increased estimated WBGT and the Australian Open.

	Whole Match	First to last Set Change	Set-to-set consistency
Match Duration (min)	-	-	-
Set Duration	-	↑	↓
1st Serve Percentage (%)	-	-	-
Aces (count)	-	-	-
Double Faults (count)	↑	-	-
Winning on 1st Serve (%)	-	↓	-
Winning on 2nd Serve (%)	-	-	-
Unforced Errors (count)	-	↑	-
Breakpoint Conversation (%)	-	-	↓
Return Points Won (%)	-	-	-
Total Points Won (count)	-	-	-
Total points (count)	-	-	-
Winners (count)	↓	-	-
Net Approaches (count)	↓	-	-
Net Approaches Won (%)	-	-	-
Fastest Serve (km/h)	-	-	-
Average 1st Serve Speed (km/h)	-	-	-
Average 2nd Serve Speed (km/h)	-	-	-

↑ = increase in occurrence; ↓= decrease in occurrence

7.4.5 Women's serve and stroke performance in the heat.

Increased estimated WBGT during AO women's singles matchplay was associated with an increase in whole-match double faults, indicating a reduction in serve performance. On the surface, this contrasts with the increased aces observed in the men's game (as discussed in section 7.3.2), however double faults also materialise as a result of a riskier serving strategies (69, 91). In this way, players of both genders are likely hitting risker serves in the heat to reduce point length, though aspects of serve mechanics that affect serve proficiency may have different outcomes (i.e. aces vs double faults) (69). This attempt to reduce effective playing time percentage during matchplay in the heat would somewhat align with previous evidence from simulated tennis matchplay (128, 129, 154). However, the mechanisms of increasing rest differ here to the extensions of rest period outlined earlier.

During women's matchplay in the heat, there was a reduction in whole-match winners, while unforced errors increased from the first to last set of matchplay. When considered alongside the increase in double faults reported above, there appears some suggestion of deteriorating stroke accuracy among female players competing in the heat at the AO. Similar reductions in shot accuracy after completing simulated tennis workloads in the heat have been observed previously in non-professional tennis players (54). The increase in unforced errors from first to last set in the heat may also infer increasing heat-induced fatigue (123), which aligns with suggested links between fatigue and reduced shot accuracy (54, 55, 117). Interestingly, technical changes to the serve have also been observed in professional male tennis players competing in hot conditions (32.0 ± 4.5^{o}C dry bulb; 38 ± 14% RH) (94). While the outcome of these technical changes to the serve were unclear (94), studies from other sports have also demonstrated that moderate heat (30 ± 0.5°C; 37.9 ± 4.6% RH) affects the performance of fine motor skills (186). As yet speculative, it may be that these technical changes or adjustments in fine motor skill increase the number of unforced errors committed during tennis matchplay in the heat (152).

Increased estimated WBGT during women's matchplay at the AO resulted in a reduction in percentage of points won on first serve from the first to last set of matchplay (Chapter 6). When considered in combination with increased whole-match double faults in the heat, it suggests a reduction in the dominance of the serving players. Previous evidence shows a significant relationship between the percentage of points won on first serve and Grand Slam match outcome, thus adjustment to the dominance of serving performance may have significant implications on match performance (65). Moreover, the increase in double faults and reducing points won on first serve also likely accounted for the reduced set-to-set constancy in break points won. As an increase in the occurrence of double fault and reduction in the percentage of points won on first serve may have presented more break point opportunities for the returner during matchplay in the heat. As the occurrence of break points within matchplay are rare and any adjustment to the occurrence of break point opportunities would likely impact percentage of break points converted (164). Additionally, the abovementioned adjustments to serve performance in the heat in the women's game are also in contrast to results reported in the men's competition (Chapter Four and Six) (94, 154), and may indicate a greater level of heat-induced fatigue in the women's competition in comparison to the men's competition, despite the shorter match durations.

7.4.6 Impact of WBGT on the use of net approaches in women

As similarly reported in the men's competition, female professionals approached the net less frequently during matchplay in hotter WBGT zones at the AO (Chapter Four and Six). This reduction in the use of net approaches are likely due to the high physiological demands of tactics surrounding the use of net approach (145, 163), and as such competitors attempted to reduce the use of net approaches to conserve energy (123). The reduction in the use of aggressive matchplay tactics during women's matchplay in the heat is further supported by the reduction in whole-match winners with increased estimated WBGT in the women's draw (Chapter Four). However, in contrast to the men's competition (Chapter Five) there was no adjustment to the set-to-set consistency of net approaches (Chapter Six), suggesting that these reductions in net approaches in the women's competition were consistent throughout the match and were not likely adjusted due to differing match contexts as outlined in the men's competition (Chapter Five). From the above-mentioned results, it appears extreme heat during matchplay in the women's competition at the AO resulted in a significant reduction in serving performance and limited use of aggressive matchplay, likely the consequence of increased heat-induced fatigue.

7.4.7 Comparison of the impact of estimated WBGT on men's and women's tennis performance

Both the men's and women's AO matchplay responses to increased heat displayed significant reductions in the use of net approaches and adjustments to serve performance. However, changes to serve performance in the heat in the men's competition was evidenced by increased number of aces; while the women increased double faults and reduced the percentage of points won on first serve during the match. This contrast in serve performance in the heat may be due to a number of factors including differences in serving tactics and pacing strategies (92, 118), along with higher relative aerobic intensity of women's matchplay (63), likely reducing stroke accuracy (45, 55, 84, 117). In contrast, in the men's competition competitors were either more successful at hitting risker servers, or there was a reduced level of pressure place upon the return of serve. Such differences in findings inform coaches and players as to potential adaptations to playing style that may exist in hotter environmental conditions.

While the men's and women's competition showed a number of similarities in their performance responses to matchplay in extreme heat, the within match changes to performance differed significantly. Most notably the men's competition showed no changes to match characteristics from the first to last set of matchplay during increased estimated WBGT. However, during women's matchplay in hot conditions there was an increase in set duration and unforced errors, and a reduction in the percentage of points won on first serve from the first to last set of matchplay. These contrasting findings during matchplay in hot conditions likely suggest significant differences in energy conservation strategies during matchplay. With the men's competition appearing to conserve energy during passages of play as displayed by the reduced set-to-set consistency of total points won and net approaches made within matchplay in hot conditions, and may suggest an exacerbation of pacing strategies employed during best of 5 set matchplay (118). Whilst due to the shorter match format of matchplay in the women's competition there may have been fewer opportunities to conserve energy, resulting in decreased performance of unforced errors and points won on first serve from the first to last set of matchplay.

7.5 Limitations

While the current thesis examines the impact of extreme heat on tennis performance, and heat illness occurrence in a previously unutilised cohort of professional competitors, there are a number of identifiable limitations. Within the current studies estimated WBGT from an off-court location was utilised to assess environmental conditions. Estimated WBGT was the most practically relevant temperature index for the current study due to the wide spread use of WBGT within the sporting landscape (4, 7, 12, 15, 72, 135), particularly tennis (196). However, estimated WBGT has previously been highlighted to underestimate WBGT in hot and sunny conditions such as those often experienced at the AO (13, 41). This underestimation of WBGT by estimated WBGT is due to the use of a fixed black globe temperature estimating a moderately sunny day with light wind (13, 41). Furthermore, off-court WBGT recordings from a government run weather service have previously been found to underestimate the true on-court WBGT of a tennis court (159). The significant under reporting of WBGT from an off-court location is likely due to the significant amounts of reflected solar radiation and ground thermal radiation from the tennis court (111, 159). However, due to the retrospective data set used within the current thesis off-court estimated WBGT previously archived by the Australian Bureau of Metrology was the most practically available option for determining environmental conditions. Further, this potential for overestimation will mean that competitors are able to compete in conditions hotter than those reported in the current study before changes in performance and heat related events occur. Furthermore, the use of a match averaged estimated WBGT did not account for potential fluctuations in WBGT throughout the match, which may have likely occurred during 5 set matchplay.

The WBGT index has previously been criticised for limitations in accounting for restricted evaporative environments due to the fixed weighting of the naturally wet bulb (4, 36, 41). Further the WBGT has also been criticised for not directly measuring air movement within its measurement, and relying on the change in black globe and naturally wet bulb to account for wind speed. By not directly measuring wind speed it has been suggested that WBGT cannot appropriately account for the impact of air movement on thermoregulation (4, 36, 41, 72, 98). However, due to the use of the WBGT at the time of data collection for implementing EHP's at the AO, and the current wide spread use of WBGT within tennis (87, 196), estimated WBGT was the most practically relevant and meaningful index for the current thesis. Further, the WBGT is currently utilised in a majority of sporting (7, 15, 87, 135), military (31, 41) and industrial policy's (98, 181), given this wide spread use of the WBGT particularly within the chosen field of study, justification of any other heat index would be difficult.

The abovementioned limitations of the use of the estimated WBGT index were reduced in the current thesis by the standardisation of estimated WBGT measurement and data collection within the data set. By standardising measurement and collection all potential errors in measurement were consistent, which reduced the implications of measurement error. Further, data was assessed through the use of zonal analysis reducing the potential impacts of inaccuracies in data collection. Matches were binned into WBGT zones according to the ACSM's EHP for analysis, through doing so reducing the implications of measurement error. However, the use of zonal analysis prevented the ability to detect any significant inflection points within the data, preventing the possibility to determine if at a specific temperature performance and heat related event occurrence change significantly. Regardless, due to limitations surrounding the use of off-court estimated WBGT this method of analysis was the most practical.

Limitations in the collection of on-court medical data in the current thesis also need to be highlighted, with on-court trainer consultation notes often brief, reducing the ability to determine and report the severity of the on-court consultations. Further, when considering previous evidence suggesting that competitors will increase rest periods during matchplay in the heat (154) and that rest periods at the AO are often restricted, it is possible competitors increased on-court trainer and doctor consultations in an attempt to increase rest periods. However, due to the brief on-court trainer consultation notes it is not possible to determine the severity of on-court consultation limiting the ability to determine the validity of this hypothesis. However, the understanding of how increased estimated WBGT affects the occurrence of heat related event at the AO will assist tournament organisers and medical staff to prepare to potential matchplay in the heat. Further, it also needs to be highlighted that due to the retrospective data collection and the elite nature of the AO it was not possible to gather subjective or physiological data from competitors including RPE, hydration status or perceived rating of environmental conditions.

Chapter Eight

Conclusion

8.1 Thesis Aims

This thesis provided a detailed description of the occurrence of heat related events, and adjustments to tennis matchplay performance at the AO in response to extreme heat. Specifically, studies 1 and 2 examined the impact of increased estimated WBGT on the occurrence of heat related events in the men's and women's main draw competition at the AO. Studies 1 and 2 were required to fill a significant gap in the literature describing the occurrence of heat illness within tennis, with the only previous available evidence from the US Open which is typically under different thermal environments (173). Accordingly, studies 1 and 2 isolated the singles main draw competition for examination to determine the occurrence of heat related events in relation to match estimated WBGT.

The impact of extreme heat on tennis performance in professional tennis has previously been suggested to have limited effect on professional tennis performance (94, 154). However, these previous studies only examined a small number of match characteristics and were not representative of Grand Slam competition (94, 154). Hence, the level of officiating between these previous studies and the AO is likely to be vastly different due to the level of tournament examined, significantly impacting the implications on match performance. Further, previous studies utilizing only male subjects who were not in contention for Grand Slam competition (54, 94, 154). To fill this gap in the literature studies 1 and 2 examined the impact of increased estimated WBGT on whole match changes to performance in the men's and women's main draw tournament matchplay at the AO. In doing so, providing a real-world assessment of the implications of extreme heat on tennis performance. Further, no previous studies have examined how extreme heat may alter elite tennis performance throughout the course of matchplay. In response to this gap in the literature, Studies 3 and 4 provide a examination of the impact of increased estimated WBGT on the first to last set changes in performance, and within match consistency of performance during men's and women's main draw tournament matchplay at the AO. By examining both the whole- and within-match changes to performance in response to extreme heat a comprehensive assessment of the performance implications of matchplay in extreme heat was undertaken.

8.2 Key Findings

The key findings delivered from this thesis are:

- Increased estimated WBGT lead to a significant increase in on-court and post-match medical consultations for heat-related events in both the men's and women's competition.
- A majority of heat illness retirements in the men's competition (n=3) occurred in conditions >32°C estimated WBGT; though there were no heat illness retirements in the women competition in the current data set.
- During matchplay in the heat whole-match aces increased in the men, while there was a reduction in net approaches. All other whole–match characteristics showed no change with increased estimated WBGT.
- During men's matchplay in the heat there were no significant directional changes to the first to last set performance of any of the measured match characteristics; however, there was a subtle reduction in the set-to-set consistency of net approaches, total points won and set duration.

- Women’s matchplay in the heat resulted in an increase in whole match double faults, and a reduction in net approaches and winners. All other whole-match, match characteristics showed no significant change with increased estimated WBGT in the women’s competition at the AO.
- During women’s matchplay in the heat there was a significant increase in set duration and unforced errors from the first to last set of matchplay. There was also a reduction in the percentage of points won on first serve from the first to last set of matchplay.
- During women’s matchplay in the heat there was a subtle reduction in the set-to-set consistency of set duration and percentage of break points converted.

8.3 Practical applications

Some of the practical applications that may be delivered from this thesis are:

- Tennis matchplay in conditions >28^{o}C estimated WBGT are associated with increased heat-induced behavioural characteristics markers including calls for cooling devices and calls for trainers in both the men’s and women’s competition. As such in conditions >28^{o}C estimated WBGT, tournament organisers should prepare for an increase in on-court requests.
- Medical staff at tennis tournaments that are at risk of high temperatures should be aware of the risks of heat illness development during tennis matchplay in hot conditions, with conditions >32^{o}C estimated WBGT showing an increase in heat related medical consultations in both the men’s and women’s competition. Further, matchplay in conditions >32^{o}C estimated

WBGT showed the highest rate of heat illness retirement in the men's competition.

- During match preparation for matchplay in high environmental temperatures coaches should take into consideration the decreased number of net approaches and modifications to serving performance; including increased aces in men and increased double faults in women.
- During matchplay in hotter conditions coaching staff and tournament organisers should prepare for a decrease in the set-to-set consistency of set duration, net approaches and total points won in the men's game which may require alter physical demands and the timing of matches.
- During match preparation in hotter conditions coaching staff should consider the within match reductions in winning points on serve, and the within match increases in unforced errors during matches played in the heat in the women's competition.

8.4 Future Research

Recommendations for future research related to the findings from the current thesis should look to examine

- The potential use of medical consults to adjust match intensity and increase rest periods during matchplay in the heat
- There is currently a gap in the literature examining the core temperature responses to live professional matchplay with restricted rest periods in the heat, particularly at Grand Slam level. Due to the increased physical demands and likely restricted rest periods during live Grand Slam competition, future

research should examine the potential increases to core temperature in these conditions.

- With the current thesis and previous research showing the potential effectiveness of the 10-min break during matchplay in the women's competition at preventing heat illness occurrence; future research should examine the potential introduction of a 10-min break during matchplay in the heat for the men's competition.
- With other major tournaments around the world regularly being impacted by hot conditions it would be beneficial to understand the impact of extreme heat on tennis performance and heat illness occurrence on the other playing surfaces (clay and grass).
- With the advent of technologies such as Hawkeye, there is a wealth of data to be utilised for research on potential changes to court positioning and movement during matchplay in the heat.

Chapter Nine

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Appendices

Appendix A – Ethics – UTS Ethics Approval

Dear Applicant

The UTS Human Research Ethics Committee reviewed your application titled, "The effect of environmental temperature on health outcomes, matchplay characteristics and court movement in professional tennis players.", and agreed that the application meets the requirements of the NHMRC National Statement on Ethical Conduct in Human Research (2007). I am pleased to inform you that ethics approval is now granted.

Your approval number is UTS HREC REF NO. 2015000126
Your approval is valid five years from the date of this email.

Please note that the ethical conduct of research is an on-going process. The National Statement on Ethical Conduct in Research Involving Humans requires us to obtain a report about the progress of the research, and in particular about any changes to the research which may have ethical implications. This report form must be completed at least annually from the date of approval, and at the end of the project (if it takes more than a year). The Ethics Secretariat will contact you when it is time to complete your first report.

I also refer you to the AVCC guidelines relating to the storage of data, which require that data be kept for a minimum of 5 years after publication of research. However, in NSW, longer retention requirements are required for research on human subjects with potential long-term effects, research with long-term environmental effects, or research considered of national or international significance, importance, or controversy. If the data from this research project falls into one of these categories, contact University Records for advice on long-term retention.

You should consider this your official letter of approval. If you require a hardcopy please contact Research.Ethics@uts.edu.au.

To access this application, please follow the URLs below:
* if accessing within the UTS network: http://rmprod.itd.uts.edu.au/RMENet/HOM001N.aspx
* if accessing outside of UTS network: https://remote.uts.edu.au , and click on "RMENet - ResearchMaster Enterprise" after logging in.

We value your feedback on the online ethics process. If you would like to provide feedback please go to:http://surveys.uts.edu.au/surveys/onlineethics/index.cfm

If you have any queries about your ethics approval, or require any amendments to your research in the future, please do not hesitate to contact Research.Ethics@uts.edu.au.
Yours sincerely,

Professor Marion Haas
Chairperson
UTS Human Research Ethics Committee
C/- Research & Innovation Office
University of Technology, Sydney
T: (02) 9514 9645
F: (02) 9514 1244
E: Research.Ethics@uts.edu.au
P: PO Box 123, BROADWAY NSW 2007

Appendix A– Ethics – Letter of Support from Tennis Australia

tennis
Australia's Favourite

Tennis Australia
Batman Avenue
Victoria Australia
Private Bag 6060
Richmond Victoria 3121
T +61 3 9914 4000
F +61 3 9650 2743
www.tennis.com.au

15/04/15

Re: Tennis Australia Heat and Match Play Research Study

Dear Matt Smith

This letter acknowledges our in-principle agreement pertaining to the research project that will investigate the effect of environmental conditions on health and performance outcomes in professional tennis players at the Australian Open. As part of this undertaking, access will be granted to previously collected tournament data that is specific to the research project. These data will include relevant court and medical call out logs, match statistics, video footage and Hawkeye information.

Regards,

Production Note:
Signature removed prior to publication.

Dr Machar Reid
Innovation Catalyst
Tennis Australia

Appendix B – Example of Collected Performance Data – Whole Match Characteristic Data

Detailed Statistics Report

(20) Dominika Cibulkova [SVK] d. (11) Simona Halep [ROU]
6-3, 6-0

WS503: Women's Singles - 5th Round	1	2	3	4	5
(20) **Dominika Cibulkova [SVK]**	6	6			
Tiebreaks:					
(11) Simona Halep [ROU]	3	0			
Elapsed Time by Set:	34"	26"			
Match Completed on Rod Laver Arena at 12:12 on 22 January 2014 in 1 hour, 0 minutes					

(20) Dominika Cibulkova [SVK]	Statistics Summary	(11) Simona Halep [ROU]
0 : 0 : 3	Aces : Service Winners : Double Faults	2 : 0 : 1
5 of 40 (13%)	Unreturned Serves	6 of 42 (14%)
33 of 43 (77%)	1st Serves In Play	29 of 43 (67%)
25 of 33 (76%)	1st Serve Points Won	13 of 29 (45%)
5 of 10 (50%)	2nd Serve Points Won	6 of 14 (43%)
7 : 1	Service Games (Won : Lost)	2 : 5
157 KMH : 139 KMH	Fastest Serve Speed (1st : 2nd)	163 KMH : 145 KMH
143 KMH : 126 KMH	Average Serve Speed (1st : 2nd)	140 KMH : 122 KMH
36 of 42 (86%)	Returns In Play	35 of 40 (88%)
1 : 1 : 3	Returns (Winners : Forced : Unforced)	2 : 2 : 3
5 of 9 (56%)	Break Points Won	1 of 3 (33%)
10 : 7 : **17**	Winners (FH : BH : **Total**)	2 : 5 : **9**
5 : 2 : **7**	Forced Errors (FH : BH : **Total**)	7 : 5 : **12**
8 : 5 : **16**	Unforced Errors (FH : BH : **Total**)	18 : 6 : **25**
0 of 0	Serve & Volley Points Won	0 of 0
3 of 4 (75%)	Net Points Won	1 of 4 (25%)
44 of 64 (69%)	Baseline Points Won	20 of 64 (31%)
54	Total Points Won	32

Page 1 of 5

Printed at 12:16 on 22 January 2014

Appendix B – Example of Collected Performance Data – Set-by-Set Match Characteristic Data

Detailed Statistics Report

(20) Dominika Cibulkova [SVK] d. (11) Simona Halep [ROU]
6-3, 6-0

(20) Dominika Cibulkova [SVK]						Set by Set Statistics	(11) Simona Halep [ROU]					
1	2	3	4	5	Match		1	2	3	4	5	Match
0	0				0	Aces	0	2				2
0	0				0	Service Winners	0	0				0
3	0				3	Double Faults	1	0				1
2/25 8%	3/15 20%				5/40 13%	Unreturned Serves	3/22 14%	3/20 15%				6/42 14%
22/28 79%	11/15 73%				33/43 77%	1st Serves In Play	14/23 61%	15/20 75%				29/43 67%
15/22 68%	10/11 91%				25/33 76%	1st Serve Points Won	8/14 57%	5/15 33%				13/29 45%
3/6 50%	2/4 50%				5/10 50%	2nd Serve Points Won	4/9 44%	2/5 40%				6/14 43%
4	3				7	Service Games Won	2	0				2
1	0				1	Service Games Lost	2	3				5
156	157				157	Fastest 1st Serve (KMH)	163	159				163
139	124				139	Fastest 2nd Serve (KMH)	145	132				145
146	138				143	Average 1st Serve (KMH)	143	137				140
134	120				126	Average 2nd Serve (KMH)	122	123				122
19/22 86%	17/20 85%				36/42 86%	Returns In Play	23/25 92%	12/15 80%				35/40 88%
0	1				1	Returns Winners	0	2				2
1	0				1	Return Forced Errors	1	1				2
2	1				3	Return Unforced Errors	1	2				3
2/2 100%	3/7 43%				5/9 56%	Break Points Won	1/3 33%	0/0				1/3 33%
6	4				10	Forehand Winners	1	1				2
3	4				7	Backhand Winners	3	2				5
9	8				17	Total Winners	4	5				9
3	2				5	Forehand Forced Errors	4	3				7
1	1				2	Backhand Forced Errors	4	1				5
4	3				7	Total Forced Errors	8	4				12
7	1				8	Forehand Unforced Errors	7	11				18
4	1				5	Backhand Unforced Errors	4	2				6
14	2				16	Total Unforced Errors	12	13				25
0/0	0/0				0/0	Serve & Volley Points Won	0/0	0/0				0/0
2/3 67%	1/1 100%				3/4 75%	Net Points Won	0/2 0%	1/2 50%				1/4 25%
24/39 62%	20/25 80%				44/64 69%	Baseline Points Won	16/40 40%	4/24 17%				20/64 31%
29	25				54	Total Points Won	22	10				32

Page 2 of 5 Printed at 12:16 on 22 January 2014

Appendix C – Example of collected Australian Bureau of Meteorology Weather data

Australian Government
Bureau of Meteorology
Commercial Weather Services

service for
Tennis Australia

WEATHER | FORECASTS | WARNINGS | OBSERVATIONS | RADAR
SATELLITE | CONTACT

Weather Conditions for Olympic Park for Wednesday 22 January 2014

Time (EDT)	Temperature °C	Dewpoint °C	Relative Humidity %	Wet Bulb Temperature °C	WBGT (sun) °C	Wind Direction	Wind Speed knots	Pressure hPa
12:00 AM	17.7	10.1	61	----	18.8	SSE	6.0	1017.5
12:30 AM	17.8	11.1	65	----	19.2	SSW	7.0	1017.5
1:00 AM	17.9	10.8	63	----	19.2	SE	3.0	1017.5
1:30 AM	17.6	11.2	66	----	19.1	S	6.0	1017.5
2:00 AM	17.5	10.6	64	----	18.9	SE	8.0	1017.7
2:30 AM	17.4	10.8	66	----	18.9	SSE	5.0	1017.7
3:00 AM	17.0	11.6	70	----	18.9	SE	7.0	1017.8
3:30 AM	16.7	12.0	74	----	18.9	SE	4.0	1017.8
4:00 AM	16.1	13.2	83	----	19.0	SSE	3.0	1017.8
4:30 AM	16.5	12.6	77	----	19.0	SSE	7.0	1018.0
5:00 AM	16.8	11.7	72	----	18.9	SSE	6.0	1018.2
5:30 AM	16.7	11.6	72	----	18.8	SSE	8.0	1018.5
6:00 AM	16.8	10.9	68	----	18.6	S	7.0	1018.9
6:30 AM	16.9	10.3	65	----	18.4	SSE	8.0	1019.2
7:00 AM	16.7	11.0	69	----	18.6	SSE	7.0	1019.6
7:30 AM	16.5	11.0	70	----	18.4	SSE	8.0	1019.9
8:00 AM	17.0	10.1	64	----	18.4	SSE	12.0	1020.5
8:30 AM	17.2	9.4	60	----	18.3	SSE	9.0	1020.8
9:00 AM	17.6	8.7	56	----	18.3	SE	10.0	1021.3
9:30 AM	18.2	8.5	53	----	18.6	SSE	9.0	1021.4
10:00 AM	18.3	8.3	52	----	18.6	SSE	8.0	1021.5
10:30 AM	19.5	7.6	46	----	19.1	ESE	8.0	1021.3
11:00 AM	19.8	6.9	43	----	19.1	SSE	9.0	1021.5
11:30 AM	20.3	7.0	42	----	19.4	SE	11.0	1021.4
12:00 PM	20.3	7.3	43	----	19.5	S	10.0	1021.2
12:30 PM	20.3	8.9	48	----	19.9	SSW	11.0	1021.2
1:00 PM	20.6	8.9	47	----	20.1	S	10.0	1021.3
1:30 PM	21.1	10.6	51	----	20.9	SSW	9.0	1021.1
2:00 PM	20.2	9.2	49	----	19.9	SSW	16.0	1021.1
2:30 PM	20.8	8.8	46	----	20.2	SW	8.0	1020.8
3:00 PM	20.8	8.8	46	----	20.2	SSW	10.0	1020.7
3:30 PM	20.4	9.6	50	----	20.2	SSW	15.0	1020.6
4:00 PM	21.1	10.0	49	----	20.7	SSW	9.0	1020.5
4:30 PM	20.0	9.0	49	----	19.8	S	16.0	1020.3
5:00 PM	20.6	9.8	50	----	20.4	SSW	10.0	1020.3
5:30 PM	20.9	11.0	53	----	20.9	SSE	7.0	1020.1
6:00 PM	20.4	10.2	52	----	20.4	S	11.0	1020.1
6:30 PM	20.2	10.6	54	----	20.4	S	10.0	1020.3
7:00 PM	19.9	10.6	55	----	20.2	S	12.0	1020.4
7:30 PM	19.3	10.6	57	----	19.9	S	9.0	1020.7
8:00 PM	18.7	10.8	60	----	19.6	S	8.0	1021.0
8:30 PM	18.1	9.2	56	----	18.8	SE	7.0	1021.4
9:00 PM	17.3	9.7	61	----	18.5	S	7.0	1021.6
9:30 PM	16.8	9.2	61	----	18.0	SSE	6.0	1022.0
10:00 PM	16.4	8.9	61	----	17.7	SE	6.0	1022.3
10:30 PM	16.2	8.9	62	----	17.6	SSE	3.0	1022.4
11:00 PM	16.1	9.3	64	----	17.7	SSE	6.0	1022.2
11:30 PM	15.7	9.4	66	----	17.5	SSE	4.0	1022.0

Appendix D – Examples of GLM analysis code in R

```
```{r medical,  echo = FALSE}
unlog_summary_table <- function(fit){
  table <- summary(fit)$coef
  table[, "Estimate"] <- exp(table[, "Estimate"]) # Exponentiate!
table
}

Tcall= glm(Trainer.called ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
dcall= glm(Doctor.called ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
TcallHS= glm(Trainer.HS ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
PMHS= glm(Post.match.HS ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
TotHS= glm(Total.heat.stress~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
cooling= glm(Cooling.D ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())
water= glm(Water ~ M.WBGT.ZONE, data=Men.study.1.1, family=poisson())


# Here is how you can show the table of the output
kable(unlog_summary_table(Tcall), format = "markdown", dig = 3)
kable(unlog_summary_table(dcall), format = "markdown", dig = 3)
kable(unlog_summary_table(TcallHS), format = "markdown", dig = 3)
kable(unlog_summary_table(PMHS), format = "markdown", dig = 3)
kable(unlog_summary_table(TotHS), format = "markdown", dig = 3)
kable(unlog_summary_table(cooling), format = "markdown", dig = 3)
kable(unlog_summary_table(water), format = "markdown", dig = 3)
```

```
```{r}
unlog_summary_table <- function(fit){
  table <- summary(fit)$coef
  table[, "Estimate"] <- exp(table[, "Estimate"]) # Exponentiate!
table
}


Fstserveper = glm( AVG.1st.serve.Per ~ WBGT.change.1.no.change..2    , data= Mens, family=gaussian())

kable(summary(Fstserveper)$coef, format = "markdown", dig = 3)

autoplot(Fstserveper, which = 1:6, ncol = 3, label.size = 3)


Aces = glm( AVG.Aces ~ WBGT.change.1.no.change..2    , data= Mens, family=gaussian())

kable(summary(Aces)$coef, format = "markdown", dig = 3)

autoplot(Aces, which = 1:6, ncol = 3, label.size = 3)

```

```
```{r}
unlog_summary_table <- function(fit){
  table <- summary(fit)$coef
  table[, "Estimate"] <- exp(table[, "Estimate"]) # Exponentiate!
table
}


Fstserveper = glm( SD.1st.serve.Per ~ WBGT.change.1.no.change..2    , data= Mens, family=gaussian())

kable(summary(Fstserveper)$coef, format = "markdown", dig = 3)

autoplot(Fstserveper, which = 1:6, ncol = 3, label.size = 3)


Aces = glm( SD.Aces ~ WBGT.change.1.no.change..2    , data= Mens, family=gaussian())

kable(summary(Aces)$coef, format = "markdown", dig = 3)

autoplot(Aces, which = 1:6, ncol = 3, label.size = 3)

```
```