A COMPREHENSIVE PROFILE OF ELITE TENNIS AND STRATEGIES TO ENHANCE MATCH PLAY PERFORMANCE

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ABSTRACT

This dissertation illustrates an interdisciplinary sport science approach to further understand the interaction between physiology and performance in tennis. An integral theme throughout experimental phases was the emphasis on obtaining information from actual competitive scenarios or settings that simulated a match environment. Investigation 1 produced physiological and performance profiles of 14 male, internationally ranked, tennis players competing in entry level professional tournaments. A descriptive notational analysis was simultaneously conducted. It was revealed that many professional tennis players commence matches in a poor state of hydration and experience significant thermoregulatory strain and dehydration during competition. Adverse physiological responses were found to relate to notational analyses and measures of match performance. The existence of such relationships demonstrated that physiological condition can influence match dynamics and its subsequent outcomes. Investigation 2 used this information to devise a prolonged simulated match capable of inducing physiological perturbations equivalent to that observed *in situ*. In a cohort of 12 high performance tennis players, the simulated match was used as a vehicle to implement strategies (caffeine, carbohydrates and cooling) to address specific facets of fatigue and enhance performance. Prolonged simulated tennis, of match-like intensity, induced significant decrements in tennis skills. Caffeine supplementation displayed fatigue reversal characteristics, preventing deterioration of, and increasing serve velocity. Carbohydrate and cooling strategies did not afford ergogenic properties to any of the measured performance variables (stroke velocity and accuracy, serve kinematics or perceptual skill). This study extended the work of similar investigations through the multifaceted methods in which performance was quantified. Overall the thesis provides

unique insight into the physiological demands of professional tournament tennis and the constraints these impose on performance. Furthermore, evidence was accrued to support some of the common preparatory and in-match behaviours used by players to enhance performance.

STATEMENT OF AUTHORSHIP

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgement in the main text and bibliography of the thesis.

Signed:_________________________ Dated:__________________________

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Candidate

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LIST OF ABBREVIATIONS

AIS:	Australian Institute of Sport
AOW:	Australian Open Wildcard
ATP:	Association of Tennis Professionals
BCAA:	Branched-Chain Amino Acids
BGL:	Blood Glucose
BLa:	Blood Lactate
BMT:	Ball Machine Test
BM:	Body Mass
BMD:	Body Mass Deficit
bpm:	Beats Per Minute
CAF:	Caffeine
CHO:	Carbohydrate
CK:	Creatine Kinase
CNS:	Central Nervous System
CV:	Coefficient of Variation
EID:	Exercise-Induced Dehydration
ES:	Effect Sizes
FFA:	Free Fatty Acids
f-TRP:	Free Tryptophan
HR:	Heart Rate
Hex:	Hexagon Test
IOC:	International Olympic Committee
ITF:	International Tennis Federation
Kph:	Kilometres Per Hour
Lat L:	Lateral Left
Lat R:	Lateral Right
LITT:	Loughborough Intermittent Tennis Test
LTPT:	Leuven Tennis Performance Test
LTST:	Leuven Tennis Skill Test
PCM:	Phase Change Material

PLA:	Placebo
PRL:	Prolactin
REML:	Restricted Maximum Likelihood
RH:	Relative Humidity
RPE:	Rating of Perceived Exertion
Sum 6:	Sum of Six Skinfolds
Sum 7:	Sum of Seven Skinfolds
TA:	Tennis Australia
T_C:	Core Body Temperature
TE%:	Relative Typical Error of Measurement
TFL:	Total Fluid Loss
TRP:	Tryptophan
TS:	Thermal Sensation
TST:	Tennis Sprint Test
T_{WB}:	Wet Bulb Temperature
U_{sg}:	Urine Specific Gravity
USTA:	United States Tennis Association
VJ:	Vertical Jump Test
VO_{2max}:	Maximum Oxygen Consumption
WADA:	World Anti-Doping Authority
5-HT:	5-Hydroxytrytamine (Serotonin)
% Dec:	Percent Decrement

PUBLICATIONS & PRESENTATIONS

This thesis has produced the following scientific articles and conference presentations.

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Hornery, D.J., Farrow, D., Mujika, I., & Young, W. (2007) An integrated physiological and performance profile of professional tennis. *British Journal of Sports Medicine.* (in press).

Hornery, D.J., Farrow, D., Mujika, I., & Young, W. Do caffeine, carbohydrate and cooling strategies mitigate the fatiguing effects of prolonged tennis play? *International Journal of Sports Physiology and Performance.* (in review).

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Development of a tennis-specific fatigue inducing protocol to assess potential ergogenic strategies. IV World Congress of Science & Racket Sports. Madrid, Spain. 21 - 23 September 2006.

Caffeine, carbohydrates and cooling: Are these strategies beneficial to tennis performance? 8th International Congress of the Society for Tennis, Medicine & Science. Peak performance for game, set & match. Melbourne, Australia. 14 - 15 January 2006.

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A COMPREHENSIVE PROFILE OF ELITE TENNIS AND STRATEGIES TO ENHANCE MATCH PLAY PERFORMANCE

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Abstract

This dissertation illustrates an interdisciplinary sport science approach to further understand the interaction between physiology and performance in tennis. An integral theme throughout experimental phases was the emphasis on obtaining information from actual competitive scenarios or settings that simulated a match environment. Investigation 1 produced physiological and performance profiles of 14 male, internationally ranked, tennis players competing in entry level professional tournaments. A descriptive notational analysis was simultaneously conducted. It was revealed that many professional tennis players commence matches in a poor state of hydration and experience significant thermoregulatory strain and dehydration during competition. Adverse physiological responses were found to relate to notational analyses and measures of match performance. The existence of such relationships demonstrated that physiological condition can influence match dynamics and its subsequent outcomes. Investigation 2 used this information to devise a prolonged simulated match capable of inducing physiological perturbations equivalent to that observed *in situ*. In a cohort of 12 high performance tennis players, the simulated match was used as a vehicle to implement strategies (caffeine, carbohydrates and cooling) to address specific facets of fatigue and enhance performance. Prolonged simulated tennis, of match-like intensity, induced significant decrements in tennis skills. Caffeine supplementation displayed fatigue reversal characteristics, preventing deterioration of, and increasing serve velocity. Carbohydrate and cooling strategies did not afford ergogenic properties to any of the measured performance variables (stroke velocity and accuracy, serve kinematics or perceptual skill). This study extended the work of similar investigations through the multifaceted methods in which performance was quantified. Overall the thesis provides unique insight into the physiological demands of professional tournament tennis and the constraints these impose on performance. Furthermore, evidence was accrued to support some of the common preparatory and in-match behaviours used by players to enhance performance.

CHAPTER 1

PREFACE

Thesis Format

This thesis has been presented in accordance with University of Ballarat guidelines. However, presentation of the two experimental chapters (Chapters 3 & 4) in publication format has lead to some repetition in content. Specifically, each experimental chapter's introduction and discussion sections have some overlap with the review of literature (Chapter 2) and the overall conclusions (Chapter 5).

Thesis Content

This thesis is an investigation of the physiology underlying professional tournament tennis, specifically identifying adverse physiological responses that manifest during match play and the implications of these on performance. Understanding the locus of fatigue and therefore the aetiology of performance impairments represents an integral step towards identification of methods to ultimately counteract fatigue-induced performance deterioration. It is very common for overt performance reductions to be anecdotally linked to fatigue, however there currently stands a lack of uniform empirical support for the assertion that fatigue impairs the proficiency of skills that underlie tennis performance.

At present many players implement potentially ergogenic strategies into their ritualistic match preparation or as routine behaviour during breaks in play. Examples of such behaviours, adopted with the intended purpose of preventing fatigue and affording a competitive edge, include consuming strong coffee pre-match, drinking Coke®, Redbull®, Gatorade® or other "sports drinks" during a change of ends, or concurrently applying cooling jackets or ice packed towels to the legs, neck and torso. Unfortunately, little explorative research specific to tennis has been conducted to firstly identify the underlying mechanisms of fatigue, and secondly to substantiate implementation of potential strategies to minimise the impact of fatigue. Players currently employ these strategies based on anecdotal experiences, usage by other sports, or advice from coaches. In a sequential order, this thesis intended to address these fundamental knowledge gaps in tennis literature by first measuring the magnitude of fatigue's manifestations during real tournament match play, and second by quantifying the efficacy of experimental strategies to prevent physiological distress and associated performance impairment during a prolonged simulated match.

Physical fitness is an obvious trainable characteristic to resist fatigue and performance deterioration during match play. Cardiovascular and muscular endurance of the highest standard are an enormous advantage in this repetitive, explosive, intermittent sport particularly when matches extend beyond 2 - 3 hr, equivalent to the time taken to complete a marathon run. At the elite level it is assumed that athletes' skills and fitness are of a similar standard. Therefore, players constantly search for strategies that offer an immediate performance advantage, rather than committing to an intensive training block which may offer fewer benefits at the high end. The physiological responses to match play support the decision to explore the performance enhancing efficacy of potential ergogenic aids rather than rely solely on an 8 - 12 week training intervention.

Tennis is a unique sport of multiple components; it demands a complex integration of dynamic balance, power and explosiveness when reacting to an opponent's stroke and attempting to chase down a ball, yet simultaneously players must be composed and demonstrate fine motor control when executing a shot to a precise area of the court. The repetitive nature of the game and the often lengthy duration of single rallies, games and matches ensure that players must also possess a high level of muscular and aerobic endurance. Perceptual skills are reciprocally linked to the motor components of performance and are vital to proficient skill execution under the time-stressed demands of tennis. Challenging the integration of the various perceptual-motor components central to tennis success, are the variable court surfaces, intensities and environmental conditions under which the game is played. Specifically, men's Grand Slam tournament matches frequently exceed 3 hr duration, on occasion 5 hr (O'Donoghue & Liddle, 1998a), and are often contested under extreme ambient and court temperatures. The potential impact of these combined factors was obvious during the final of the 2000 Australian Open and the 2004 French Open Tennis Championships, when Pat Rafter of Australia and Guillermo Coria of Argentina respectively suffered episodes of cramping and overt performance deterioration. Introduction of the "Extreme Heat Rule" by organisers of the Australian Open and attempts to educate players on the risks of poor hydration and nutritional strategies have undoubtedly alleviated associated health risks. However, few empirical attempts have been made to offset the development of fatigue-induced performance impairments and of these attempts a number of methodological shortcomings limit the strength of the findings (E. R. Burke & Ekblom, 1982; Struder, Ferrauti, Gotzmann, Weber, & Hollmann, 1999; Vergauwen, Brouns, & Hespel, 1998).

The execution of skills that underlie elite performance in tennis, and other sports alike, is revered by many. However, just as these skills are revered for their finesse and virtuosity, they are undoubtedly susceptible to impairment. In most cases this observable capitulation, whether overt or subtle, is associated with fatigue or one of the many facets of fatigue that evolve almost inadvertently with performance. Largely a product of time, intensity and environmental conditions fatigue responses occur as athletes push themselves outside equilibrium toward physiological boundaries in the quest for success. The ataxia displayed by a marathon runner at the finish line of a race is an overt demonstration of physiological duress compromising performance. To a far lesser degree the reduced cognitive capacity of a tiring tennis player is apparent in their decision to terminate a rally prematurely by attempting a drop-shot from behind the baseline. In an uncompromised state the player would theoretically remain in the rally and construct a point-winning play. Given the multitude of mechanisms by which fatigue emerges during sport, to create an understanding of which form/s predominates in a particular sport, in this instance tennis, is of enormous benefit to coaches, trainers, players and sport scientists. Previous *in situ* attempts to define tennis have resided solely in retrospective notational and time-motion analyses (Kovacs, 2004; O'Donoghue & Liddle, 1998a, 1998b; O'Donoghue & Ingram, 2001; Richers, 1995) or using junior and non-professional level tournaments (Girard & Millet, 2004; McCarthy, Thorpe, & Williams, 1998; Misner, Boileau, Courvoisier, Slaughter, & Bloomfield, 1980; Reilly & Palmer, 1994), where the transferability of findings to elite tennis is an obvious limitation. Comparatively others have simulated match and tournament scenarios (Davey, Thorpe, & Williams, 2002, 2003; Dawson, Elliott, Pyke, & Rogers, 1985; Vergauwen, Spaepen, Lefevre, & Hespel, 1998) but methodological limit the strength of the findings. This thesis initially focuses specifically on professional tournament tennis and produces an integrated profile of physiology, match notation and performance. This comprehensive approach is fundamental to the subsequent stage of the experimental series that examines practical interventions that address specific facets of fatigue in an attempt to mitigate associated performance reductions.

This thesis therefore seeks to address several fundamental questions in relation to understanding tennis physiology and maximising performance.

- What are the typical anthropometric and physical characteristics of male professional tennis players?
- What physiological responses underlie performance during professional tournament tennis?
- Consequently, do these physiological perturbations effect match performance or skills central to performance (e.g., stroke velocity, stroke kinematics, error rates)?
- In a controlled and standardised environment do experimental strategies focused at negating specific manifestations of fatigue have the capacity to enhance performance?

In order to address the above questions a systematic approach was adopted and this is reflected in the sequential nature of each chapter, illustrated in Figure 1.1 (see page 10).

Chapter 2 provides a critical review of tennis literature. Notational analyses and the energetic demands of match play are initially described. Also discussed are the physical capacities and the functional and cognitive skills that underpin performance. The integration of these components is central to success in the sport. However, tennis is a unique sport characterised by many variables including different playing styles, court surfaces, environmental conditions and match durations and it is the physiological response to these variables that challenge performance proficiency. The psychological aspect of match play cannot be undermined, however it is beyond the scope of this thesis to address this aspect of performance. Hence, the initial concern of the review is facets of fatigue that potentially manifest during match play and the implications of these to performance.

Several investigators have attempted to quantify the effects of fatigue on performance, however a number of methodological shortfalls are familiar to these efforts. A lack of ecological validity when attempting to induce fatigue and the lack of sensitivity of selected measurement approaches are the typical limiting factors. These limitations highlight a fundamental gap in tennis literature, in that a greater understanding of tennis physiology *in situ* is required. Addressing these limitations will enhance attempts to replicate the demands of tennis in a controlled setting and will generate a greater understanding of the effects of relevant physiological responses on performance skills. To provide a framework for future exploratory procedures, an all-encompassing descriptive investigation was attempted in Investigation 1 (Chapter 3). The holistic approach adopted covered notational and performance parameters and their interaction with the evolving physiological profile.

Furthering the work of investigators who attempted to describe the effects of fatigue on tennis performance, several researchers have employed experimental strategies to counteract fatigue-induced effects and sustain or enhance performance (Ferrauti, Weber, & Struder, 1997; Magal et al., 2003; Op 't Eijnde, Vergauwen, & Hespel, 2001). These attempts centred around supplementation and hydration strategies and the review highlights some methodological shortcomings that fostered inconsistency in findings. A common theme central to these investigations was the measurement of physical capacities, such as agility, and simple outcome measures as markers of tennis performance. Generally, researchers neglected to assess process measures (biomechanical and perceptual skills) which are subsequently described in relevant sections as underlying skills integral to tennis success. Future research sections illustrate the contribution of these skills to overall performance, their discriminative powers, and the need to incorporate measurement of such skills into performance assessment batteries.

Chapter 3 tracks a subset of entry level professional tennis players and reports the tennis-specific physiological perturbations that manifest as they contest individual matches. Men's professional hard and clay court international tournaments were analysed during the 2003/2004 Australian Summer and Autumn Tennis Circuit. The purpose of this investigation was to produce a comprehensive profile of notational, physiological and performance characteristics measured simultaneously during match play. Prior to the experimental phase the morphological characteristics and physical capacities exhibited by the cohort of elite tennis players was defined. This process is detailed in Chapter 3 and creates an understanding of the physical attributes that underpin success at the entry level of elite tennis. Match statistics obtained during the tournament analyses were comparable to statistics of previously reported Grand Slam tournaments (Kovacs, 2004; O'Donoghue & Liddle, 1998a; O'Donoghue & Ingram, 2001). In addition, over time it was revealed that a number of specific physiological conditions have the capacity to impair performance, for example alteration to serve kinematics. These observations provided the impetus for the subsequent experimental phase (Chapter 4), being the implementation of practical strategies to counteract the development of fatigue and prevent associated performance decrements.

Targeting specific physiological disturbances, namely dehydration, hypoglycaemia, hyperthermia and central fatigue, Investigation 2 (Chapter 4) involved the development of a prolonged simulated tennis match and the implementation of strategies to attenuate the occurrence/severity of the typical conditions encountered during match play. The protocol devised was based on the notational analysis of tournament match play, obtained in Investigation 1 (Chapter 3), and published literature. Adopting a multifaceted approach to the measurement of performance was imperative and this was reflected in the skills analysed, which were deemed indicative of performance and included both outcome and process measures. The experimental strategies chosen to counteract ensuing fatigue and the associated deleterious performance implications were caffeine supplementation, carbohydrate supplementation and pre- and in-match body cooling. The interventions were additionally selected due to current usage by players and were applied in a placebo-control single-blinded manner. This chapter revealed the capacity of the interventions to supersede the effects of time and fatigue on competitive tennis skills. The findings are used to provide evidence-based recommendations that can be adopted by players, coaches and sport scientists in the training and competition environment. Finally, the constraints encountered when conducting field-based research and attempting to simulate the demands of the “real world” in a controlled setting are discussed. Ecological validity of simulated matches and testing devices in concert with maintenance of participant motivation/desired intensity were obvious limitations that compromised application of the findings. Methods for future investigators to eliminate such factors are suggested, as are areas that warrant further exploration.

In the concluding chapter (Chapter 5), the composite findings from Investigations 1 and 2 are considered and the generality of the findings from the research series discussed. Recommendations are made concerning further examination and implementation of the interventions during men’s professional tennis matches and the potential for similar exploration with other tennis populations, like women’s and wheelchair tennis. This chapter not only summarises the overall findings of the thesis, but also suggests directions for future research. Some practical conclusions are offered, regarding the physical capacities exhibited by professional male tennis players, the adverse physiological conditions that manifest during match play and their implications to various facets of performance. Ultimately, the capacity of these easily employable strategies to counteract fatigue and maximise performance are discussed.

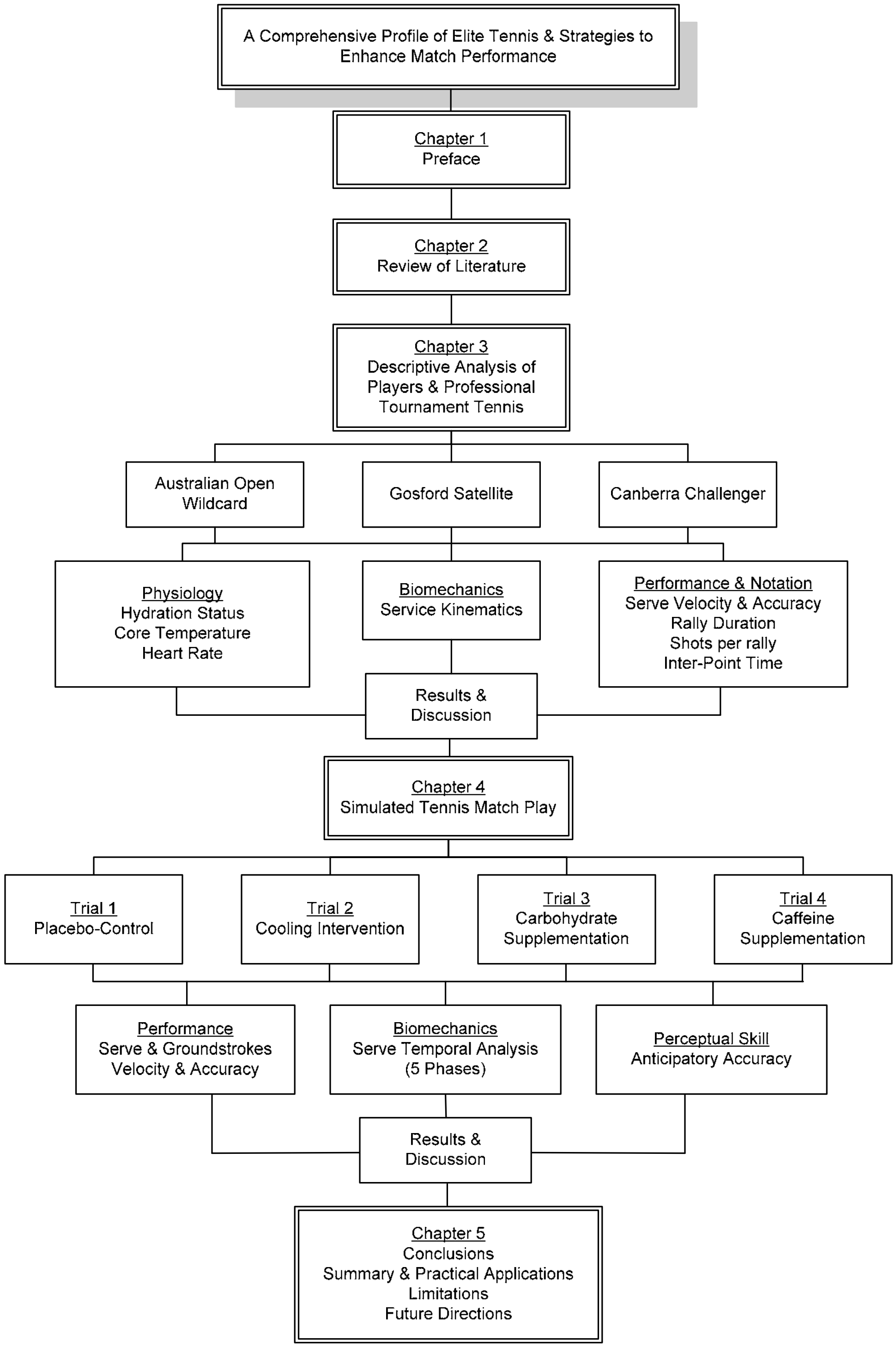

Figure 1.1. A schematic illustration of the entire experimental series.

CHAPTER 2

LITERATURE REVIEW

Fatigue in Tennis: Mechanisms of Fatigue and Effect on Performance

Abstract

This article reviews research sourced through sport science/medicine journal databases (PubMed and SPORTdiscus; search dates unspecified) that has attempted to quantify the effects of fatigue on skills integral to tennis match play. Additionally, specific physiological perturbations (i.e., hyperthermia, dehydration, hypoglycaemia, and central/neural aspects) associated with fatigue, and their effects on functional performance characteristics such as stroke velocity and accuracy are discussed. The current standpoint pertaining to this field is that previous research has struggled to find support for the anecdotal assertion of reduced performance resulting from matches of prolonged duration, or matches played during unfavourable, hot and humid environmental conditions. The constraints and difficulties of field research in this largely unexplored tradition-based sport is a major factor limiting previous investigations. Additionally, a number of methodological oversights have confounded empirical attempts to identify the causative mechanisms of the suggested performance perturbations.

In light of these constraints, the review initially addresses previous attempts made to demonstrate the effects of fatigue and exhaustion on elements of physical fitness and technical skills imperative to tennis performance. More recent theorising, concerning the potential for central fatigue to be an explanatory factor in performance decrements is also

discussed. Methodological inadequacies are highlighted throughout and directions for future research suggested.

The review then describes contrasting findings relative to the efficacy of interventions designed to mitigate performance decrements. To date the sport of tennis has largely relied on its traditions and thus has not yet realised the benefits that sport science affords, hence the majority of previous experimental trials have centred around supplementation and hydration strategies. The prevalence of dehydration during simulated and tournament tennis is described, however a lack of research exists offering practical strategies that may positively impact on performance. Exploration of the effects of hyperthermia on tennis performance is similarly scarce despite the demonstrated oppressive conditions under which matches are regularly played. Inferences are therefore drawn from other related sources rather than tennis-specific research. The summary and future recommendations focus on adopting measurement strategies that capture the multi-dimensional nature of tennis performance and hence suggest the measurement of perceptual and biomechanical performance components.

Introduction

The Nature of Tennis and General Match Conditions

Tennis is an intermittent sport often performed over a prolonged duration and under mild to extreme environmental conditions. Early notational analyses characterised the energetic demands of the sport as predominantly anaerobic during points (Elliott, Dawson, & Pyke, 1985; Richers, 1995), with a significant aerobic contribution to metabolism during recovery. Repetitive short duration (4 - 10 s) high intensity efforts interspersed with short (10 - 120 s) recovery periods underline match play, for a recent review see (Fernandez, Mendez-Villanueva, & Pluim, 2006). The development of notational analysis tools has significantly enhanced the detail of match dynamics able to be described. For example, O'Donoghue and Ingram (2001) reported average rally lengths of 6.3 $\pm$ 1.8 s and 7.7 $\pm$ 1.7 s for men's Grand Slam tournament matches played at the Australian and French Opens respectively (data collected from years 1997 to 1999). The average match duration during Grand Slam tournaments (5 set matches) approximates 2 hr, however on occasion some matches have been observed in excess of 5 hr.

Despite the actual playing time approximating only 17 – 28% of total match duration (Christmass, Richmond, Cable, & Hartmann, 1994; Docherty, 1982; Elliott et al., 1985; Fernandez, Mendez-Villanueva, Fernandez-Garcia, & Terrados, 2005; Girard, Lattier, Micallef, & Millet, 2006; Misner et al., 1980; Reilly & Palmer, 1994), it is the cumulative effects of the repetitive high-intensity efforts over the duration of a match and tournament that disrupt homeostatic equilibrium and impose constraints on performance. Lengthy match durations, extreme on-court temperatures and compromised nutritional and hydration status are a combination of likely contributors to the manifestation of fatigue and associated suboptimal performances. Successful performance however, can not be defined by one predominating physical attribute; tennis demands a complex interaction of speed, agility, power, muscular and aerobic endurance. Underlying these physical components are cognitive and psychological processes. Players must display supreme reactive, anticipatory and decision making capacities whilst possessing the mental rigor to cope with ensuing fatigue and the pressures of match-deciding points and significant extrinsic rewards (ranking, money endorsements).

Tennis and Fatigue

While a review of the literature reveals a number of investigations that have examined the effects of fatigue on tennis skill and performance (Davey et al., 2002, 2003; Dawson et al., 1985; Struder, Hollmann, Duperly, & Weber, 1995; Vergauwen, Brouns et al., 1998; Vergauwen, Spaepen et al., 1998) very few, if any, have adequately identified the specific facets of fatigue that affect tennis performance. An initial critique of the typical methodologies employed revealed limitations, both in terms of experimental protocols utilised and the sensitivity of chosen performance measures. Accordingly the skills indicative of performance that are most detrimentally impacted by fatigue have not been unequivocally articulated.

Fatigue, from a physiological perspective, can be defined as an acute impairment of exercise performance, which ultimately leads to the incapacity to produce maximal force output or control motor function (St Clair Gibson et al., 2003). Described holistically, it is a multifactorial response to prolonged or high intensity physical exertion. Experiencing fatigue during or following exercise is often a direct result of athletes reaching one or a combination of the following states: the accumulation of metabolic by-products, dehydration, hypoglycaemia, hyperthermia or perturbation of the central nervous system (Noakes, 2000).

The first section of this review focuses on previous research, or lack thereof, that has attempted to identify the effects of fatigue on tennis performance. Specifically, the review addresses the occurrence of physiological perturbations during training and simulated tournament tennis matches and their associated effects on a number of performance variables. A summary of the research findings is presented in Table 2.1. Subsequently, the review describes experimentally-based investigations that examined the performance effects of potential ergogenic aids and their ability to mitigate common physiological stressors. A summary of these research findings is presented in Table 2.2.

Table 2.1

Research on Fatigue Indices and Performance Impairment during Tennis

Investigator	Exercise protocol	Fatigue indices	Performance measures	Results
Dawson et al. (1985)	1 hr simulated match vs. 1 hr intermittent running in hot & humid conditions (*N* = 8)	HR T_C (39.0 °C) BM loss (2.4%)	Serve quality Groundstroke quality - BMT Volley quality - BMT	All skills ↓ (accuracy & power) significantly more after treadmill test
Vergauwen, Spaepen et al. (1998)	2 hr strenuous training session (with a player of matched ability) (*N* = 10)	70 m Shuttle run RPE	LTPT Serve quality Groundstroke quality - BMT	 ↓ Velocity & accuracy ↓ Velocity (accuracy unaffected)

(Table continues)

Investigator	Exercise protocol	Fatigue indices	Performance measures	Results
Davey et al. (2002)	LITT performed to volitional exhaustion (N = 18, 9 M & 9 F)	Volitional exhaustion	LITT	Accuracy ↓ by ~69% at volitional exhaustion
		BLa (peak 9.6)		
		HR (max. 190)	LTST	
		RPE (max. 20)	Groundstroke accuracy - BMT	No change
		BM loss (1.5%)	Serve accuracy (Consistency, accuracy, out)	↓ to right court by ~30% (Pre- vs. Post-LITT)
Davey et al. (2003)	92 min simulated match	Volitional exhaustion	Groundstroke accuracy - BMT	Accuracy ↓ by ~81% at volitional exhaustion
	LITT	HR		
	Tennis hitting sprint test	BM loss (1.7%)		
	(N = 10, 5 M & 5 F)			

Note. BLa = Blood lactate; BM = Body mass; BMT = Ball Machine Test; F = Females; HR = Heart rate; LITT = Loughborough Intermittent Tennis Test; LTPT = Leuven Tennis Performance Test; LTST = Loughborough Tennis Skill Test; M = Males; RPE = Rating of perceived exertion; T_C = Core body temperature.

Table 2.2

Research on Interventions to Mitigate Performance Decrements in Tennis

Investigator	Exercise protocol	Interventions	Performance measures	Results
Burke & Ekblom (1982)	2 hr simulated tournament tennis (*N* = 5)	CHO Polymer vs. Water, No-fluid, Control & Thermal Dehydration.	Groundstroke accuracy - BMT	Maintained with CHO only
			Sargent Vertical Jump Test	↑ 11.6% with CHO
Mitchell et al. (1992)	2 x 3 hr tennis matches (*N* = 12)	CHO vs. Water (PLA)	Serve velocity	No benefit from CHO
			183 m shuttle run test	No benefit from CHO
Ferrauti et al. (1997)	4 hr interrupted tennis	CHO vs. CAF (4mg.kg) vs. PLA (double-blind)	Groundstroke accuracy - BMT	CHO > CAF (M)
				CAF >CHO & PLA (F)
	3 x 75 min matches (*N* = 16, 8 M & 8 F)		Games won during match play	CAF >CHO & PLA (F)
			Tennis sprint test (6 x 15 m, 30 s recovery between each)	Improved with CHO (All)

(Table continues)

Investigator	Exercise protocol	Interventions	Performance measures	Results
Vergauwen, Brouns et al. (1998)	2 hr strenuous training session (*N* = 13)	CHO vs. CHO + CAF (5mg.kg) vs. PLA (double-blind)	Groundstroke quality - BMT Serve quality 70.5 m shuttle run test	CHO & CHO + CAF > PLA (All measures pre- vs. post-exercise) (No effect of CAF vs. CHO)
Struder et al. (1999)	4 hr interrupted tennis 3 x 75 min matches (*N* = 8)	CHO vs. CAF (4mg.kg) vs. PLA (double-blind)	Groundstroke accuracy - BMT Games won during match play	No benefit from CHO or CAF
Op 't Eijnde et al. (2001)	LTPT (*N* = 8)	Creatine (20g.day for 5 days) vs. PLA (double-blind)	Groundstroke quality - BMT Serve quality 70 m shuttle run test	No benefit from Creatine
Magal et al. (2003)	2 hr exercise-induced dehydration (*N* = 11)	Hyperhydration Glycerol vs. Water (double-blind)	Groundstroke & serve quality Repeat-effort agility test 5 & 10 m sprint test	No performance benefit of Glycerol over Water (all performance measures)

Note. BMT = Ball Machine Test; CAF = Caffeine; CHO = Carbohydrates; F = Females; LTPT = Leuven Tennis Performance Test; M = Males; PLA = Placebo.

Effects of Fatigue on Tennis Performance

The effects of physical and peripheral fatigue.

Initial field-based investigations, whilst setting the scene for future research, were generally unsuccessful in their attempts to replicate the physiological demands of tennis and neglected to explore the multifaceted skill basis integral to success in tennis. In 1998 and 2002, Vergauwen, Spaepen et al. (1998) and Davey et al. (2002) respectively, conducted very similar investigations, attempting to identify the effects of fatigue on tennis performance. Both experiments developed tennis-specific fatigue-inducing protocols and utilised a ball machine to administer pre- and post-fatigue on-court skill assessments. Experimental findings must be carefully interpreted as both investigations yielded similar results yet Davey et al. (2002), in particular, reported profound decrements in serve and groundstroke quality.

Vergauwen, Spaepen et al. (1998) induced fatigue during a 2-hr on-court strenuous training session by pairing participants with an opponent of matched ability. The researchers did not report work to rest ratios or physiological responses to the 2-hr session, thus no indication of training intensity or specificity to real match conditions was provided. Comparatively, Davey et al. (2002) not only induced volitional exhaustion during the intermittent tennis test, but measured performance simultaneously and recorded physiological perturbations far beyond that experienced under match conditions. Despite the comparative degrees of physiological strain induced, both investigations returned only subtle pre- versus post-intervention performance discrepancies.

Vergauwen, Spaepen et al. (1998) observed a modest decrease in serve and groundstroke velocity and impaired accuracy (motor control) of only the second serve. Davey et al.

(2002) conversely observed dramatic performance reductions as participants neared or had in-fact reached volitional exhaustion. Of particular interest is the observation that performance quickly returned to pre-fatigue levels in the post-intervention skill test. One exception to these findings was serve accuracy to the advantage court which decreased by 30%. Inherently, performance reductions would be expected at the point of volitional exhaustion, however it is highly unlikely that players under match conditions would experience this degree of physiological strain (reported peak blood lactate concentration was 9.6 $\pm$ 0.9 mmol·L^{-1}). Although the knowledge of how tennis skills respond under extreme duress is beneficial, the majority of previous research does not support this level of fatigue during match play scenarios; Bergeron et al. (1991) reported in-match blood lactate values of 2.3 $\pm$ 1.2 mmol·L^{-1}; Reilly and Palmer (1994) reported 2.0 $\pm$ 0.4 mmol·L^{-1}; and Ferrauti, Bergeron, Pluim, and Weber (2001) reported 1.53 $\pm$ 0.65 mmol·L^{-1}. Only Christmass et al. (1998) reported similar values beyond the anaerobic threshold, 5.86 $\pm$ 1.33 mmol·L^{-1}; see Fernandez et al. (2006) for further information on blood lactate levels during match play.

Collectively, both investigators observed very few fatigue-induced performance deficits, specifically when performance was measured under physiological strain equivalent to match conditions. While the shift from the laboratory setting to a more ecologically valid on-court environment was a positive step by both investigators, it also presented some limitations. First, the lack of sensitivity of selected performance measures stands as an underlying methodological constraint and is proposed as an explanation for the minimal performance deficiency detected. Second, the chosen protocols to induce fatigue (i.e., match play with no control over intensity or conversely an incremental intensity skills test performed until volitional exhaustion) and the decision to measure only motor skill proficiency, and not perceptual or kinematic parameters, limited the generalisation of the findings. Not undermining the importance of serve and groundstrokes to tennis success, match performance is multifaceted. Quantification of the processes that underscore these (outcome) performance measures would therefore be a positive addition to future testing batteries.

An earlier investigation implicated both dehydration and thermal strain as mechanisms for *in situ* performance deterioration (Dawson et al., 1985). Dawson et al. (1985) compared performances on a tennis skills test after (a) participants played a 1-hr simulated match in cool conditions and (b) the same participants completed a 1-hr intermittent treadmill run in a hot climate chamber. The thermally challenging laboratory exercise induced more significant physiological perturbations than the on-court protocol and the prevailing response was greater decrements in a tennis-specific test of stroke accuracy and power. A recent review of hydration and temperature related issues in tennis (Kovacs, 2006a) revealed that the physiological responses encountered by participants during the climate chamber run (mean core body temperature reached 39.0 °C, and mean total fluid loss was 2.4% body mass) are not dissimilar to those experienced during training or simulated matches in challenging environmental conditions. The inducement of match-equivalent physiological disruptions using tennis-specific interventions, and measurement of various facets of performance is an example of how this thesis sought to build on early initiatives, and is illustrated in the subsequent experimental chapters.

Girard et al. (2006) recently suggested reductions in functional strength characteristics as the possible cause of match performance decrements. During 3 hr of interrupted tennis match play, progressive reductions in maximal voluntary strength and leg stiffness as well as increases in perceived exertion and muscle soreness were reported. Assessment of tennis performance skills and physiological measures were not conducted. This would have been a sound compliment to the measurement of physical characteristics but limits the application of the findings. The transfer of these findings to stroke production and court movement is at best speculative.

Making inferences from the above empirical findings, it appears that functional tennis skills are impaired only under extreme forms of physiological stress (i.e., exhaustive cardiovascular strain, hyperthermia, and dehydration). The findings also suggest that under physiological strain stroke accuracy is largely maintained whereas stroke velocity is more likely to deteriorate. This observation can be indirectly likened to Fitts' speed-accuracy trade-off theory (Fitts, 1954). Specifically, as task complexity increases (with fatigue) stroke velocity is sacrificed in order to maintain stroke accuracy. Ferrauti et al. (2001) proposed a likely reason for this effect, suggesting that as players become fatigued a decrement in maximal running speed is observed, resulting in suboptimal stroke preparation (e.g., footwork and balance) and a decrement in stroke velocity transpires. It is also suggested that with ensuing physiological fatigue the mentally strong player may alter their stroke intention to avoid errors, rather than attempting to hit winners. In opposition to this view, terminating a point early reduces the work interval, effectively increasing the proportional recovery time which is a powerful incentive to the tiring player who succumbs to the mental challenge. The multiple possible explanations for performance decrements during match play demonstrate the complexity of performance quantification in tennis. Despite the limitations of simulated tennis scenarios, they offer a means to control player intentions and potentially observe performance impairments that occur beyond the conscious level. This will be explored in later chapters of this thesis.

An alternative explanation to the speed-accuracy trade-off is proposed by Welsh et al. (Welsh, Davis, Burke, & Williams, 2002). On the basis of central nervous system (CNS) control of motor units the authors proposed that fatigue is associated with a decrement in central control. In turn, individuals must decrease the rate at which a task is completed in order to maintain a high degree of accuracy. Contrary to this explanation, proportional increases in serve accuracy and consistency have been reported as players serve closer to maximal velocity (Cauraugh, Gabert, & White, 1990). Participants served at incremental intensities of maximal serve velocity but did not perform under a state of physiological fatigue. Thus the reduction in timing errors as movement velocity increased could simply be interpreted as a case of task or training specificity. Irrespective of the causative mechanism, match equivalent fatigue (not volitional exhaustion) appears to inhibit stroke velocity, more so than accuracy and precision (Vergauwen, Spaepen et al., 1998). Given that shot quality during match play increases proportionally when hit with greater power and closer displacement to sidelines (Vergauwen, Spaepen et al., 1998) this finding stands as a significant performance limitation.

The effects of central fatigue.

Central fatigue is a phenomenon whereby alterations within the CNS decrease the ability to voluntarily send a signal to the neuromuscular junction, essentially inhibiting development and transfer of the stimulus for muscular contraction (Davis & Bailey, 1997). At present, researchers have struggled to consolidate their views on the occurrence of a specific mechanism associated with reduced physical state, despite drawing some interesting correlations with mental and physical performance (Bailey, Davis, & Ahlborn, 1993; Blomstrand, Hassmen, & Newsholme, 1991; Davis et al., 1992; Davis, 1995;

Lepers, Hausswirth, Maffiuletti, Brisswalter, & Van Hoecke, 2000; Nybo & Nielsen, 2001). Reductions in voluntary force development, endurance time and cognition are examples of the proposed implications of central fatigue. Inferences from these findings arouse interest relative to the existence of central fatigue, and its effect on performance, during prolonged dynamic exercise under thermally challenging conditions.

Nutritional supplements have been suggested to play a role in attenuating the rise in concentration of circulating blood-borne precursors of central fatigue (L. M. Burke, 2001; Davis, Alderson, & Welsh, 2000). In separate investigations Davis, et al. (2000) and L.M. Burke (2001) delineated how the chain of events occurring centrally during prolonged physical activity increases the plasma concentration of free tryptophan (f-TRP) and reduces the concentration of branched-chain amino acids (BCAA). These concomitant responses ultimately induce heightened levels of brain serotonin or 5-hydroxytryptamine (5-HT). The observed rise in concentration of this neurotransmitter during prolonged exercise evoked interest in its role as a potential mediator of central fatigue through association with arousal, lethargy, sleepiness, and mood (Davis et al., 2000). Reversal or mitigation of these brain neurochemistry responses has been hypothesised, examined and questioned relative to a variety of supplements including carbohydrates (CHO), BCAA or both (Blomstrand, Andersson, Hassmen, Ekblom, & Newsholme, 1995; Blomstrand, Hassmen, Ekblom, & Newsholme, 1997; L. M. Burke, 2001; Calders, Matthys, Derave, & Pannier, 1999; Davis, 1995; Davis, Welsh, De Volve, & Alderson, 1999; Struder et al., 1998; Struder et al., 1999), omega-3 fatty acids (Huffman, Altena, Mawhinney, & Thomas, 2004), and even infusion of Red ginseng (Min et al., 2003). It is beyond the scope of this review to extensively discuss all these potential fatigue-reversal mechanisms, as such the reader is directed to the individual articles.

Prolonged submaximal and exhaustive exercise is recognised to deplete muscle glycogen stores, this in turn stimulates a rise in circulating free fatty acids (FFA) which have a higher affinity for albumin than the loosely bound tryptophan, and ultimately induces a rise in the ratio of f-TRP-to-BCAA (Davis et al., 2000). Carbohydrate supplementation prior to, or during, exercise of this nature essentially attenuates the rise in FFA by ensuring adequate blood glucose and muscle and liver glycogen availability. Similarly, ingestion of BCAA has also been proposed to potentially suppress the rise of f-TRP-to-BCAA by increasing the circulating BCAA, however evidence-based findings relative to an ergogenic effect on performance are by no means sound (Banister & Cameron, 1990; Blomstrand, Hassmen, Ekblom, & Newsholme, 1991; Blomstrand, Hassmen, & Newsholme, 1991; Blomstrand et al., 1995; Blomstrand et al., 1997; Cheuvront et al., 2004; Davis et al., 1992; Davis et al., 1999).

The potential for central fatigue to be an explanatory mechanism behind the overt performance decrements commonly/anecdotally reported over the course of a prolonged tennis match is highlighted in an investigation by Struder et al. (1995). Following 4 hr of continuous tournament-style singles tennis between eight German, nationally ranked male tennis players, the investigators observed reduced plasma BCAA concentration, elevated non-esterified fatty acids which led to propagation of free tryptophan and ultimately an increase in the ratio of f-TRP to BCAA. Evidently, if this ratio is in-fact a precursor to the manifestation of central fatigue and reduced functional and cognitive performance, these findings indicate that measures need to be applied in order to counteract the genesis of such unfavourable responses to prolonged match play.

Nutritional supplements are an example of such measures and Struder et al. (1999) later examined their efficacy using the same experimental methodology. Participants supplemented with carbohydrates and caffeine (CAF) prior to and during match play. Performance was quantified through groundstroke accuracy and the number of games won and lost per match. Carbohydrate ingestion was the only strategy to effectively suppress augmentation of central fatigue precursors (plasma ratio of f-TRP to BCAA, and Prolactin), however performance remained unaffected by either strategy when compared to the placebo trial. Despite failing to report enhanced performance with attenuated central fatigue markers (Struder et al., 1999), the prolonged cognitive demands of competitive tennis and variant physiological stressors implicate central fatigue as a potential performance constraint. This thesis revisits and extends the initiatives of Struder et al. (1999), by employing robust testing measures and a multifaceted approach to performance.

The previously discussed findings by no means substantiate the anecdotal claims of reduced performance capacity during matches of prolonged duration or those contested under hot, humid conditions. But, they do highlight the capacity for fatigue in its various forms to be prevalent in tennis, however the performance implications remain largely unidentified. Therefore, the need for further research is warranted to firstly establish if fatigue does in-fact impair tennis performance. In attempting to identify the fatigue effects, it is recommended that investigators broaden the scope of their research to include the multifaceted skill set fundamental to tennis performance. That is, by examining perceptual skills such as anticipation and biomechanical aspects of strokes rather than simply assessing outcome measures such as stroke velocity and accuracy. In light of this statement, an underlying theme of this thesis, evident in the experimental chapters, was the holistic approach to performance, including measurement of both performance processes and outcomes.

Interventions to Mitigate Performance Decrements

If fatigue is found to induce decrements in tennis performance, to propose an exact aetiology requires some former methodologies to be modified and ultimately the development of an intervention/s to counteract the underlying mechanisms. The findings of previous research using popular sports supplements in attempt to underpin the causes of fatigue, and in so doing, reduce associated performance decrements are discussed in subsequent sections and summarised in Table 2.2 (see page 18).

Effects of hypoglycaemia.

Hypoglycaemia is a physiological state characterised by an excessive depletion of circulating blood glucose the body's and liver and muscle glycogen stores, therefore decreasing the substrate availability for energy production, and resynthesis of the high-energy substrate adenosine triphosphate (Noakes, 2000). Such depletion is widely recognised to govern a decrement in performance of intermittent or continuous exercise over a moderate to prolonged duration (Hawley, Schabort, Noakes, & Dennis, 1997; Noakes, 2000). Specific to the nature of tournament tennis, players are often required to train and compete for prolonged periods twice in one day and on successive days. This causes fluctuations in energy levels throughout training and competition (Ferrauti, Pluim, Busch, & Weber, 2003) and emphasises the need for players to follow stringent nutritional practices. Low blood glucose concentration is a mechanism for performance deterioration as it reduces muscle metabolism and neural integration which controls muscle function. Fortuitously, several investigators have reported maintained or enhanced physical capacities and sport-specific motor skills, and the postponement of fatigue with various methods of carbohydrate supplementation (E. R. Burke & Ekblom, 1982; Coggan & Coyle, 1987; Coyle, Coggan, Hemmert, & Ivy, 1986; Graydon, Taylor, & Smith, 1998; Ostojic & Mazic, 2002; Vergauwen, Brouns et al., 1998; Welsh et al., 2002).

Specific to tennis, Vergauwen, Brouns et al. (1998) reported maintenance of stroke velocity and accuracy following 2 hr simulated match play when participants ingested carbohydrates (CHO). In particular, CHO supplementation attenuated the rise in error rate and the percentage of non-reached balls that was demonstrated by participants undertaking the placebo trial. Maintenance of running speed/agility was also afforded to the CHO trial, whereas this capacity decreased in the placebo trial. Additionally, Vergauwen, Brouns et al. (1998) utilised CHO + Caffeine ingestion as a separate intervention to counteract fatigue, however this addition failed to surpass the effects of CHO ingestion. Quantification of neither the intensity of the prolonged training session nor of the residual fatigue effects limits the observations slightly, and the maintenance of functional capacities (i.e., stroke quality and running speed) does not constitute performance as a whole. It would however be remiss to ignore the potential performance benefits afforded to CHO supplementation over hydration with water alone.

A similar sport-specific study by Graydon et al. (1998) assessed the effects of CHO supplementation on shot accuracy and perceived exertion during a conditioned squash match. In keeping with previous results (Vergauwen, Brouns et al., 1998), Graydon et al. (1998) observed a profound decrement in shot accuracy during the placebo trial and only a mild reduction in performance (comparing pre- and post-training shot accuracy tests) during the supplementation trial. A tendency for lower perception of effort was also reported during the CHO trial. These findings are further supported by E.R. Burke and Ekbolm (1982), who reported increased skill proficiency, explosive power, and body weight when participants consumed a CHO polymer drink during 2 hr of simulated tournament tennis, over participants who consumed water only. Adequate blood glucose levels and hydration status are the suggested mechanisms underlying the maintenance of tennis performance skills. Investigators inferred that the greater blood glucose concentration contributed to sustained muscle metabolism and neural integration. In addition to reaffirming the ergogenic potential of CHO supplementation, the investigators linked heightened neural function to sustained blood glucose.

These findings implicate hypoglycaemia as a mechanism for performance deterioration but do not discount the effects of other facets of fatigue. Note, in extended tennis-specific scenarios the prevalence of hypoglycaemia is yet to be firmly established (Bergeron et al., 1991; Mitchell, Cole, Grandjean, & Sobczak, 1992). Collectively the findings do however appear to confirm the potential for CHO to reverse the effects of fatigue on outcome-based performance skills. The combination of limited available tennis literature, limited skills measured by those who have researched tennis and the difficulty of quantifying performance during a tennis match (i.e., beyond that of the actual outcome), encourages inferences from other sports of similar nature. Ostojic and Mazic (2002) over the course of a 90-min soccer match, observed enhanced soccer-specific skill performance and recovery when participants consumed a CHO-electrolyte solution compared to those participants who ingested equal volumes of a placebo solution. Enhanced performance in a sport that is also dominated by fitness, technical proficiency and gross motor control encourages further exploration in tennis. The latter experimental phase of this thesis followed a similar design in an attempt to avoid the occurrence, and performance implications, of hypoglycaemia.

Despite the above consensus on the potential performance enhancing effects of CHO ingestion, some refuting evidence is revealed in a field-based tennis investigation (Ferrauti et al., 1997). Ferrauti et al. (1997) compared a CHO and a caffeine treatment against a placebo treatment during 4 hr of "round robin" style match play on clay courts. In contrast to previous findings, the investigators failed to reveal any specific tennis performance benefits from CHO supplementation in terms of games won and hitting accuracy, but did observe an improvement in tennis-specific running speed. Note, participants commenced each trial following ingestion of a CHO-loaded meal, thus potentially in a hyperglycaemic state, dulling their sensitivity to additional supplementation over the course of the playing duration (L. M. Burke et al., 2000). Some interesting gender-specific findings were also revealed; in women's tennis, caffeine supplementation produced a greater number of games won, whereas male players scored significantly more valid strokes when performing the CHO trial when compared to the caffeine trial.

A similar investigation was earlier conducted by Mitchell et al. (1992), however the selected *in situ* method of performance assessment limited the capacity to identify effects of the experimental strategy. The researchers (Mitchell et al., 1992) compared tennis performance and fluid balance during 3 hr of match play in participants ingesting either a water placebo or a CHO beverage. Mitchell, et al. (1992) observed significantly greater blood glucose concentration and subjective rating of stomach fullness in the CHO trial, despite no added benefit to markers of tennis performance, measured as serve percentage and unforced error rate during each match. Variables intrinsic to match play compromised the reliability of the performance measures. The investigators also made no attempt to measure accuracy of serves, only velocity, permitting participants to modify their intentions prior to serving. In addition, the match play style protocol would impose varying levels of fatigue on participants relative to the playing style of opponents and their respective abilities. These inconsistencies within the methodology may explain why in this instance CHO supplementation did not prevent the decline in tennis performance that was observed in the placebo trial.

As evidenced in previous research, despite the existence of some contention, it appears advantageous to supplement with CHO prior to, and during, a prolonged tennis match and over successive days of a tournament. Generalised prescriptive guidelines are presented in a recent article by Kovacs (Kovacs, 2006b). However, the grounds supporting CHO usage are not robust. Increasing the sensitivity of performance measures and standardising experimental protocols may resolve this problem. The current standpoint on CHO supplementation affords benefits to functional skills only, namely power or velocity and running speed. As blood glucose is the driving energy substrate for central nervous system metabolism, the effects of CHO supplementation on perceptual processes such as anticipatory skill, was also of particular interest in the current thesis. The suggested methodological modifications would increase the probability of identifying subtle changes in performance and improve overall experimental reliability. These issues are addressed in experimental chapters of this thesis.

Effects of dehydration.

Hypohydration and dehydration are physiological processes characterised by an excessive loss of body fluid (Sawka, 1992; Wilmore & Costill, 1999). The ramifications of body fluid loss are dramatic as deficits as little as 2% are widely recognised to govern decrements in athletic performance. The resultant reduction in plasma volume increases susceptibility to heat stress or hyperthermia and other related adverse conditions such as muscular cramps and exercise-induced exhaustion (Binkley, Beckett, Casa, Kleiner, & Plummer, 2002; L. M. Burke & Hawley, 1997; Devlin, Frasier, Barrar, & Hawley, 2001; Gopinathan, Pichan, & Sharma, 1988; Sawka, 1992; Sawka & Coyle, 1999; Wilkins, 2003). The magnitude of sweat loss increases substantially in thermally challenging environmental conditions (i.e., wet bulb globe temperature [WBGT] > 23 °C; (Binkley et al., 2002), which are often experienced in tennis. Several investigators have previously reported the rate of fluid loss or the total fluid loss as a percentage of body mass during competition or simulated match play, equating to 1.0 to 2.5 $l.h^{-1}$, 2.3%, and 2.7% respectively (Bergeron, 2003; McCarthy et al., 1998; Therminarias, Dansou, Chirpaz, Eterradossi, & Favre - Juvin, 1994). Specifically, McCarthy et al. (1998) investigating players in a junior tournament, observed a mean fluid loss of 2.3 $\pm$ 0.2% dry body mass over the course of a tennis match, where duration ranged from 50 min to 140 min. Despite the obvious flaws when drawing comparisons between heterogenous groups (Martin, Hahn, Ryan, & Smith, 1996), from the above findings, one would infer that elite senior players would be susceptible to a similar range of, or even greater fluid losses.

Despite stating the prevalence of hypohydration in tennis, the majority of research has failed to explore the performance implications. However, as previously mentioned E.R. Burke and Ekblom (1982) examined the effects of dehydration coupled with hypoglycaemia on tennis technical skill proficiency. Performances in the fluid restricted and thermal dehydration trials were, not surprisingly, more erratic when compared against the CHO polymer supplementation trial. Additionally, when participants were allocated only water, performance was again considerably worse than the CHO trial for both technical skill and vertical jump tests. The findings suggest that maintenance of euhydration through provision of water alone is not accompanied by sustained skill proficiency. However, participants may have conducted the post-exercise skill assessment of the water only trial under a greater state of dehydration in comparison to the CHO trial (1.1% decrement in body mass vs. 0.4% decrement in body mass, respectively). Consequently, interpretation of the effects of dehydration on the components of tennis performance examined is hampered by the ambiguous results. Moreover, the methods of performance assessment lacked specificity and transferability to actual tennis match play. The vertical jump test is an effective measure of lower body power however the correlation between maintenance of such a gross physical capacity and performance in this technically oriented sport is not clear. Groundstroke accuracy, on the other hand, is a learned skill contributing to tennis success, however performance variability, lack of test sensitivity, and the small sample size potentially confounded the ability to identify any significant effects for either of the experimental strategies.

A similar, more recent investigation (Magal et al., 2003) failed to observe any significant performance enhancements after exposing players to hyperhydration, exercise-induced dehydration, and rehydration. Investigators induced each of the above hydration states prior to having participants complete a custom designed tennis skill test and common field tests of speed and agility. Magal et al. (2003) concluded the “modest” level of exercise-induced hypohydration (~2.7% body mass) significantly affected sprint performance, but failed to impair serve or groundstroke accuracy and power. Failing the exercise-induced dehydration to negate performance, the researchers proposed that test sensitivity may have confounded the ability to observe performance decrements commonly associated with the induced level of hypohydration. Once again, investigators are left with only the ability to make inferences from performance reductions in gross motor skills to the execution of discrete skills. Extending the work of Magal et al. (2003) is recommended as the study design was very practical and represented the nature of fluid balance over the course of a match and a competition day.

In accordance with the tennis and fatigue findings of Vergauwen, Spaepen et al. (1998) where first serve precision was the main performance characteristic negatively affected by fatigue, Devlin et al. (2001) observed reduced bowling accuracy in hypohydrated cricketers (2.8% body mass deficit). This observation suggests that in a state of fatigue attributed to hypohydration, performance of ballistic closed motor skills may deteriorate with respect to motor control. Interestingly, the decrement in accuracy and precision of performance does not appear to be accompanied by diminished force development. Nevertheless, the findings illustrate the importance of maintaining adequate hydration status when attempting to sustain a finite level of athletic performance. These findings have tremendous crossover to the implications of hypohydration on serve proficiency and warrants further exploratory work. Prescribing individual hydration strategies would be a simple mechanism to counteract the obvious effects of dehydration on such a crucial element of tennis success.

Given the apparent performance and health implications of poor hydration practices, sport scientists should seek to provide players with individualised hydration regimens. This is imperative during hot humid conditions, such as those often occurring during tournament tennis, particularly as thirst is a poor indicator of hydration status (Bergeron, Armstrong, & Maresh, 1995; L. M. Burke & Hawley, 1997; Sawka, 1992) and ad libitum fluid consumption often leads to involuntary dehydration (Bergeron, Armstrong et al., 1995; Kay & Marino, 2000). Consequently, other inherent adverse physiological conditions (increased thermal strain and increased glycogen utilisation) occur concurrently with a progressive loss of body fluid. Therefore adherence to a strict hydration regimen should decrease susceptibility to heat stress and reduce the likelihood of compromised performance. As previously suggested, the playing demands of tournament tennis are high often leaving players with insufficient recovery time to achieve optimum nutrition and hydration status. Under these circumstances, failure to replace sweat and electrolyte losses during and between matches could potentially lead to a situation of chronic or accumulative hypohydration (Binkley et al., 2002; L. M. Burke & Hawley, 1997; Kovacs, 2006a). The ramifications of this condition are of paramount importance as players progress through rounds of a tournament and consistent optimal performance is critical. Future research should address the lack of robust information pertaining to the effects of dehydration on tennis-specific functional and more specifically cognitive capacities. In regards to exploration of this field, measures of tennis-specific perceptual skills (i.e., return of serve anticipation) are increasing in ecological validity and are recommended over previously used literacy and numeracy-based cognitive tasks.

Effects of hyperthermia.

Hyperthermia and heat stress are adverse physiological conditions caused by an excessive rise in core body temperature (Binkley et al., 2002) which results from increased heat storage (Bolster et al., 1999). Exercise-induced heat stress and hyperthermia are potential health and performance damaging characteristics of prolonged exercise in moderate to hot conditions, a situation often confronting tennis players. The extreme on-court playing temperatures are often compounded by prolonged match durations, heightening players' predisposition to hyperthermia, as fluid and electrolyte losses become excessive and core body temperature rises. In such circumstances, efforts to maintain adequate hydration status and substrate availability may become tenuous, as hyperthermia has been demonstrated to be the primary contributor to the onset of fatigue (Morris, Nevill, Thompson, Collie, & Williams, 2003) and can occur in only moderate conditions. Furthermore, if athletes' intentions are to offset the concomitant effects of total body water deficit and increasing core body temperature through fluid consumption strategies alone, they may be predisposed to additional complications, for example gastrointestinal distress (Mitchell et al., 1992). In extreme circumstances water intoxication and associated hyponatremia may develop (Nelson, Robinson, Kapoor, & Rinaldo, 1988; Toy, 1992). The volume of fluid consumption required to maintain euhydration, noting that sweat rates have been reported to reach 2.5 $L \cdot h^{-1}$ (Bergeron, Armstrong et al., 1995; Bergeron, Maresh et al., 1995) may contribute to gastrointestinal discomfort during play, keeping in mind that maximal gastric emptying rate rarely exceeds 1.2 $L \cdot h^{-1}$ (Coyle & Montain, 1992) and the limited opportunity for appropriate stoppages in tennis, that is, one toilet break during a best of three set match (ITF, 2004).

Extensive research exists detailing the detrimental performance, physiological effects and associated health risks of exercise under challenging environmental conditions (Binkley et al., 2002; Bolster et al., 1999; Booth, Marino, & Ward, 1997; Kay & Marino, 2000; Kraning II & Gonzalez, 1991; Morris, Nevill, Lakomy, Nicholas, & Williams, 1998; Nybo & Nielsen, 2001; Sawka, 1992; Sawka et al., 2001). The associated rises in core body temperature often exceed those shown to be beneficial to performance, similar to the warm-up effect (Falk et al., 1998). Rises in core body temperature are associated with increased consumption of muscle energy stores through glycogenolysis (Febbraio, Snow, Stathis, Hargreaves, & Carey, 1994) and increased sweat rate in an attempt to dissipate heat through evaporation. As heat storage accumulates and the demands on evaporative cooling mechanisms increase proportionally, competition for cardiac output arises between the oxygen and substrate demands of the active skeletal muscle and the vasodilated peripheral vasculature. Muscle function may then be inhibited due to changes in muscle metabolism (Morris et al., 1998). Alternatively, Nielsen and Nybo (2003) suggest altered CNS function as an explanatory factor behind decreased exercise capacity in the heat. These researchers theorised that increases in core temperature govern a decrease in neural drive from the CNS, which in turn causes a decrease in sustained muscular force production with no decrement to maximal force development (Nielsen & Nybo, 2003).

The above evidence provides empirical support for the underlying mechanisms and various detrimental effects that thermoregulatory strain induces on exercise capacity. Despite the aforementioned implications of perturbations to core body temperature, an extensive review of literature revealed a dearth of studies that have attempted to report the thermoregulatory demands of singles tennis. Linking the physiological responses to match play with performance of skills integral to tournament success is a suggested line of research. Therefore, if increased core temperature is shown to be a contributing factor to tennis performance deficiencies, strategies (pre-match ice baths or the use of a cooling jacket during breaks in play) should then be researched to counteract the deleterious effects.

Perceptual Skills in Tennis

The time-stressed nature of tennis ensures that well developed perceptual skills are critical to tennis success at the elite level. An extensive body of research has demonstrated the importance of these skills in discriminating between expert and novice players (Goulet, Bard, & Fleury, 1989; Isaacs & Finch, 1983; Jones & Miles, 1978; Rowe & McKenna, 2001; Singer, Cauraugh, Chen, Steinberg, & Frehlich, 1996; Williams, Ward, Knowles, & Smeeton, 2002). Specifically, the research has demonstrated that expert players pick-up anticipatory information earlier than their lesser skilled counterparts. This anticipation is based on information arising from an opponent's pre-contact movement pattern, such as the movement of the racquet arm and racquet. The capability to anticipate is particularly valuable in tennis for a number of reasons. First, in a situation like the tennis return of serve, it may be necessary to begin moving before an opponent has even struck the ball in order to successfully intercept it (Glencross & Cibich, 1977). Second, it provides a player with more time to prepare a response, which may increase the likelihood of successful response execution. Finally, anticipation may also effectively reduce the expert's information-processing load (Rowe & McKenna, 2001).

Methods to assess perceptual skill.

Several experimental paradigms exist to determine the mechanisms that underlie superior visual-perceptual qualities of expert tennis players. Visual search patterns of players attempting to return serve is one area previously investigated. For example, Goulet et al. (1989) demonstrated expert players directed their visual attention toward the racquet and racquet-arm of the server, immediately prior to impact compared to non-experts who fixated on the ball (Shim & Miller, 2003; Williams, Singer, & Weigelt, 1998). However, while many of these studies show some visual search differences between experts and lesser skilled performers the differences are largely trivial, leading to at least some of the authors (e.g., Goulet et al., 1989) concluding that visual search differences cannot alone explain information-processing differences and performance differences. Also prevalent are findings demonstrating the complete absence of a relationship between expertise and visual search patterns (Abernethy & Russell, 1987).

A more prominent approach has been the application of a temporal occlusion paradigm (Farrow, Abernethy, & Jackson, 2005; Isaacs & Finch, 1983; Jones & Miles, 1978). This experimental approach requires participants to view footage of an opponent from an *in situ* perspective. Vision of the opponent's stroke (e.g., service action) is selectively edited to provide differing amounts of advance and ball-flight information. Participants are typically required to predict the direction, depth, or both, of the opponent's shot from the information available to them and a significant change in the prediction accuracy from one occlusion window to the next is assumed to be indicative of information pick-up from within the additional viewing period. This methodology has been repeatedly shown to successfully differentiate the perceptual skills of expert and novice performers and provide information as to which phase of the movement sequence players pick up the most valuable anticipatory information (Abernethy & Russell, 1987; Farrow et al., 2005).

Perceptual-cognitive responses to exercise.

While considerable evidence has been accumulated on the benefits of well developed perceptual skills, the influence of factors such as fatigue or associated stressors on perceptual function have been largely neglected. A point made by Lees (2003) in his relatively recent review of racquet sport research. However, several investigators have examined the effects of exercise on cognitive capacity (Fery, Ferry, Vom Hofe, & Rieu, 1997; Gonzalez, 1997; Gopinathan et al., 1988; S. Hancock & McNaughton, 1986; McMorris & Keen, 1994; McMorris & Graydon, 1996, 1997; Royal et al., 2006) with some interesting findings emerging.

A common methodological theme has been to examine cognition at increasing exercise intensities or levels of fatigue. Application of the findings to sport-specific scenarios has in some cases been limited due to selected cognitive assessment tasks (e.g., literacy, numeracy and simple reaction time tasks) (Fery et al., 1997; Gonzalez, 1997). Improvements in sport-specificity and ecological validity of assessment modalities were made by S. Hancock and McNaughton (1986) and Royal et al. (2006), however the resultant findings were contrasting. The equivocal findings may be explained by the inability of simulated sporting scenarios to induce the mentally draining effects of competition. Experimental exercise protocols are capable of inducing physical fatigue but they do not entirely capture the essence of a contest. Competitive play requires constant information processing and continual concentration, often for extended periods of time and under high stress situations. The collaborative effects of physical and mental fatigue provide a mechanistic explanation for impaired cognitive performance under duress, which is the general consensus of empirical research.

Specific physiological perturbations have also been suggested to underlie impaired cognitive function during exercise or fatigue (Callow et al., 2003; Gopinathan et al., 1988; Shirreffs, O'Connor, Powell, & Durlach, 1997; Welsh et al., 2002; Winnick et al., 2005).

Welsh et al. (2002) and Winnick et al. (2005) proposed hypoglycaemia as a mechanism, as they observed enhanced cognitive function during the latter stages of prolonged intermittent exercise in participants who supplemented with CHO. Hydration status has also been implicated. Gopinathan et al. (1988) reported reductions in mental performance when fluid loss reached 2% of body mass. Callow et al. (2003) later reproduced this finding, but cognitive performance impairments were independent of the degree of dehydration. Others advocate the role of heat stress or hyperthermia in cognitive debilitation (P. A. Hancock, 1981; Hocking et al., 2000a, 2000b; K. G. Johnson, 1987; Maksimovich, 1983; Razmjou, 1996; Shirreffs et al., 1997; Travlos & Marisi, 1996; Vernacchia & Veit-Hartley, 1999). Of particular interest to the current investigation is the reported prevalence of these adverse physiological states in tennis-specific scenarios (Bergeron et al., 1991; E. R. Burke & Ekblom, 1982; Ferrauti et al., 2003; McCarthy et al., 1998; Therminarias et al., 1994) and therefore the perceptual implications.

Biomechanics in Tennis

The biomechanics underlying stroke execution has received much attention in scientific and coaching literature (Elliott, 2006; Elliott, Reid, & Crespo, 2003; Fleisig, Nicholls, Elliott, & Escamilla, 2003; Groppel, 1986; Pluim & Safran, 2004; Singh, 2002). Efforts have largely been directed towards performance of the serve, and both forehand and backhand groundstrokes. Literature typically presents a technical breakdown of these strokes to maximise their quality (power and control), additionally providing a model for skill development, and information on the causative link with injury. Of interest is how stroke mechanics respond to fatigue. Very limited information on this area, specific to tennis, currently exists. This is interesting as biomechanics are recognised to play an integral role in tennis performance (Elliott, 2006).

Anecdotally and empirically the occurrence of fatigue during a tennis match or experimental protocol, is associated with reductions in serve and groundstroke quality (Davey et al., 2002, 2003; Dawson et al., 1985; Vergauwen, Spaepen et al., 1998). At present it can only be speculated, based on research in other domains (Murray, Cook, Werner, Schlegel, & Hawkins, 2001; Myers, Guskiewicz, Schneider, & Prentice, 1999; Royal et al., 2006), if biomechanical or neuromuscular mechanisms underlie the breakdown in performance. In an incrementally fatiguing study of junior elite water polo players, Royal et al. (2006) observed modifications to technical skill proficiency despite no reductions in shot accuracy or velocity. The modified factors were however perceived to be "non-essential" to overall skill performance. The findings were rationalised as a fatigue-coping mechanism where under duress, emphasis is placed on control of vital kinematic components to optimize performance. A more elaborate biomechanical analysis of baseball pitchers revealed significant changes in kinematic and kinetic parameters between early and late innings (Murray et al., 2001). In this instance the researchers also observed a reduction in ball velocity, but could not determine if the biomechanical changes were a protective mechanism or a fatigue response. Myers et al. (1999) conducted a laboratory-based experiment and offered a mechanistic explanation for impaired throwing kinematics when fatigued. After fatiguing the internal and external shoulder rotators of 32 college students the investigators reported no significant reduction in neuromuscular control, but observed reduced proprioception. The findings implicate joint spatial characteristics in the deterioration of throwing-related skills when performed under a state of fatigue.

Given the incidence of fatigue in tennis and the associated implications to stroke quality, future investigators should attempt to discern if a reduction in motor skill proficiency transcends from a disturbance to underlying kinematic processes. If this mechanistic link is identified, strategies may be implemented to reverse or attenuate technical impairment. Some positive results have been achieved through caffeine and CHO supplementation which has been linked to their central and peripheral facilitatory roles (Deslandes et al., 2004; Kalmar & Cafarelli, 1999). It is recommended that investigators explore the ergogenic properties of these strategies for tennis stroke kinematics.

Summary

This review underlines the multifaceted skill requirements of elite tennis performance, the myriad potential stressors players experience during match play and a number of potential strategies that could be employed to mitigate the development of adverse physiological states and their effect on performance. To date, information on tennis physiology is sourced from investigation of simulated match and tournament conditions, or exercise protocols constructed to elicit fatigue (Christmass et al., 1994; Christmass, Richmond, Cable, Arthur, & Hartmann, 1998; Dawson et al., 1985; Elliott et al., 1985; Ferrauti et al., 2003; Novas, Rowbottom, & Jenkins, 2003; Smekal et al., 2001). However, methodological limitations challenge the generalisability of these findings, granted that the demands of actual match play are extremely difficult to replicate in a scientific field-based experiment which places much emphasis on control, standardisation and reliability.

Information obtained thus far under actual tournament conditions is scarce. This is in part due to the lack of current understanding, on behalf of coaches, players and tournament directors, of the potential benefits afforded to tennis through the application of sport sciences services and technologies. In their defence investigation of some devices and experimental strategies during match play may be obtrusive and cause distraction. As a result, more prolific investigations are non-obtrusive notational analysis research providing descriptive and notational features of matches such as rally duration, shots per rally, inter-point time, inter-serve time and comparisons across different court surfaces (Collinson & Hughes, 2003; Hughes & Clarke, 1994; C. D. Johnson & McHugh, 2006; O'Donoghue & Liddle, 1998a, 1998b; O'Donoghue & Ingram, 2001; Reilly & Palmer, 1994).

Of the investigations that have attempted to determine the locus of fatigue under match conditions and the associated performance implications, there is a trend for some expected physiological conditions to present. Fatigue appears to manifest in a number of forms, namely associated with dehydration, hypoglycaemia, hyperthermia and more recently of a neural or central nature. At this point, the most prevalent mechanism is yet to be established, but the variable nature of tennis suggests the cause could be specific to each match or individual and characteristic of the environmental conditions under which the match is played. It could be equally dependent on the type of playing surface or if the match is contested over 3 or 5 sets. This research seeks to identify the performance implications of the aforementioned physiological conditions. This information will drive the development of strategies, applied pre-, during- and post-match, that attenuate the severity of the stressors and enhance performance.

The selection of performance measures has been a major limitation to the results obtained in previous investigations that have attempted to identify the effects of fatigue on performance, or the efficacy of experimental strategies to supersede fatigue. Most attempts to quantify performance implications reside solely in the participants' ability to serve or hit groundstrokes aimed at specified target areas within the court, the resultant performance outcomes being velocity and accuracy of the respective strokes. While the use of a ball-machine, in tests of groundstroke proficiency, increases reliability and standardisation of the skill assessment, it effectively removes any cognitive processing that underscores stroke execution (i.e., in a match situation a player must constantly process the available visual information and generate the appropriate response relative to the position of the opponent at the opposite end of the court). Sensitivity issues pertaining to target sizes and scoring systems have also reduced the capacity to detect subtle performance changes associated with fatigue or experimental interventions. Beyond this, other investigators have measured performance during simulated match play, in terms of the number of games won or lost and the number of errors committed, however this procedure lacks explanatory power and is subject to large variability which is compounded by performance fluctuation of two players.

Without undermining the importance of a demonstrated proficiency in both serve and groundstrokes as significant contributors to match and tournament success, this outcome-based approach to skill assessment does not consider the biomechanical processes that underpin performance of these skills. Additionally, the perceptual aspects of tennis performance are yet to be broached. As previously discussed, a growing body of literature has identified perceptual functions, evidenced in superior anticipation of an opponent's stroke intention, as a strong discriminator of novice and expert tennis players (Goulet et al., 1989; Rowe & McKenna, 2001; Singer et al., 1996; Williams et al., 2002). Whether serve and groundstroke kinematics capitulate under physiological strain, thus precipitating demise in velocity and accuracy, or perceptual motor skill is similarly impaired under duress remains to be explored. As a result of the above factors, a multifaceted approach to performance assessment underpins the experimental chapters of this thesis.

This research provides a platform to gain an understanding of the integration of physiological characteristics and traditionally analysed match statistics. The research is conducted to eliminate the paucity of information addressing the physiological, biomechanical and perceptual variables that occur simultaneously throughout competitive tournament tennis. Research conducted *in situ* or under match-like conditions is emphasised as the added pressures of tournament tennis, where players compete for large sums of money, wildcard entry to tournaments and points toward their world ranking are pertinent elements of performance which cannot be replicated under simulated tournament conditions. This information, invaluable to athletes, coaches and sport scientists identifies which stressor possesses the greatest implications to performance, and drives that exploration of strategies to counteract the development of physiological challenges to sustained performance proficiency.

CHAPTER 3

INVESTIGATION 1

An Integrated Physiological and Performance Profile of Professional Tennis

Abstract

The purpose of this investigation was to describe the physiological responses to tournament tennis in relation with prevailing environmental conditions, match notation and skills that underpin performance. Fourteen male professional tennis players (mean $\pm$ *SD* age: 21.4 $\pm$ 2.6 yr; height: 183.0 $\pm$ 6.9 cm; body mass: 79.2 $\pm$ 6.4 kg; sum of seven skinfolds: 48.1 $\pm$ 11.7 mm; estimated VO_{2max}: 61.65 $\pm$ 4.44 $ml \cdot kg \cdot min^{-1}$) were studied whilst contesting hard and clay court international tennis tournaments. Environmental conditions, match notation (rally duration, shots per rally, inter-point time, inter-serve time etc.) physiological (core temperature, hydration status, heart rate, blood variables) and performance parameters (serve kinematics, serve velocity, error rates) were recorded over the duration of each match. Ambient temperature was greater during matches contested on hard courts (32.0 $\pm$ 4.5 vs. 25.4 $\pm$ 3.8 °C, $p < 0.05$). Hard and clay court tournaments elicited similar peak core temperature (38.9 $\pm$ 0.3 vs. 38.5 $\pm$ 0.6 °C) and average heart rate (152 $\pm$ 15 vs. 146 $\pm$ 19 bpm) but different body mass deficit (1.05 $\pm$ 0.49 vs. 0.32 $\pm$ 0.56%, $p < 0.05$). Average pre-match urine specific gravity was 1.022 $\pm$ 0.004. Time between points was longer during hard court matches (25.1 $\pm$ 4.3 vs. 17.2 $\pm$ 3.3 s, $p < 0.01$). Qualitative analysis of serve kinematics revealed inverse relationships with time and physiological perturbations. Consistency in the height of the tossing arm at ball release (first serve) inversely correlated with progressive match time ($r = -0.74$, $p < 0.05$) and incurred body mass deficit ($r = 0.73$, $p < 0.05$). Consistency in position and height of the ball toss (second serve) also inversely correlated with progressive match

time ($r = -0.73$, $p < 0.05$) and incurred body mass deficit ($r = 0.73$, $p < 0.05$). Participants commenced matches in a poor state of hydration, and experienced moderate thermoregulatory strain and dehydration during competition. These adverse physiological responses may compromise performance and influence notational analyses, however they were dependent on a number of variables such as environmental conditions, court surface and match duration.

Introduction

Tennis performance is multifactorial, reflected by a sophisticated integration of physiological, biomechanical, psychological and perceptual-cognitive elements, all having considerable influence on the outcome of a match (Hohm, 1987). In competition, the integration of these performance facets is challenged by several factors unique to the sport. These include variable environmental conditions, unpredictable match durations, matches played on various court surfaces and different playing strategies. The combination of these factors predispose players to physiological strain that evolves either involuntarily (e.g., hyperthermia; [Therminarias et al., 1994], central fatigue; [Struder et al., 1995]) or through player negligence (e.g., dehydration; [McCarthy et al., 1998], hypoglycaemia; [Ferrauti et al., 2003]).

The consequences of homeostatic disruptions were displayed in historical matches played by Pat Rafter of Australia and Guillermo Coria of Argentina during the 2000 Australian Open and 2004 French Open men's final, respectively. Both players suffered severe muscular cramping during the latter stages of their matches. On both occasions players demonstrated reduced playing intensity, and performance capitulation which ultimately led to the loss of each match. However, a review of literature (searching the keywords: tennis, physiology, notational analysis, match play and performance, on sport science/medicine journal databases, PubMed and SPORTdiscus, search dates unspecified) revealed that integrated physiological and performance analyses of professional tournament tennis had not been attempted. Rather, simulated match and tournament conditions were the prevalent research approach (Christmass et al., 1994; Christmass et al., 1998; Dawson et al., 1985; Elliott et al., 1985; Ferrauti et al., 2003; Novas et al., 2003; Smekal et al., 2001). Those who analysed match play generally applied a notational approach, recording variables such as rally duration, shots per rally, inter-point time, inter-serve time and comparisons across different court surfaces (Collinson & Hughes, 2003; Hughes & Clarke, 1994; C. D. Johnson & McHugh, 2006; O'Donoghue & Liddle, 1998a, 1998b; O'Donoghue & Ingram, 2001; Reilly & Palmer, 1994).

The current investigation first attempted to describe the physiological responses to professional tournament tennis. Specifically, the aim was to identify the prevalence of dehydration, hypoglycaemia, and hyperthermia. The influence of physiology on match notation and performance variables, including serve velocity, accuracy, serve kinematics, and error rates, was also examined. Both court surface and environmental conditions have a significant influence on physiological responses to match play and thus potentially on notational analyses and performance markers, and therefore must be considered when interpreting findings. It was hypothesised that during competition professional tennis players experience various types and degrees of physiological strain. A negative association between physiological strain indices and performance was also proposed. The hypotheses were examined during three international professional tennis tournaments, which were part of the 2003/2004 Australian Summer and Autumn Tennis Circuits.

Methodology

Participants

Fourteen internationally ranked (Association of Tennis Professionals (ATP) average ranking 512, range 125 to 882), male tennis players (mean $\pm$ *SD* age 21.4 $\pm$ 2.6 yr; height 183 $\pm$ 6.9 cm; body mass 79.2 $\pm$ 6.4 kg; sum of seven skinfolds 48.1 $\pm$ 11.7 mm; maximum heart rate 195 $\pm$ 9 bpm) participated in the investigation. Six participants competed in tournaments played on both hard and clay court surfaces. An additional eight participants were studied as they contested tournaments played on either hard courts or clay courts, not both. Participants trained on average for 32 hr per week during out-of-competition phases and had at least 5 years of national level tournament experience. Participants received explicit details of the experimental protocol before voluntarily providing written informed consent. Eleven of the 14 participants undertook comprehensive profiling of anthropometric and tennis-specific physical capacities (during which maximum heart rate was determined), the results are presented in Table 3.1. The study was reviewed and approved by the Australian Institute of Sport and the University of Ballarat Ethics Committees.

Study Design

Physical Capacity Testing

For this phase of research participants presented to Melbourne Park Tennis Centre and underwent a detailed assessment of anthropometric characteristics and tennis-specific physical capacities, that is, speed, agility, power, aerobic endurance, and serve and groundstroke velocity. The standard physiological tennis testing battery administered is widely used and possesses robust validity and reliability (Buckeridge et al., 2000). The tests were conducted largely in accordance with procedures described previously (see Buckeridge et al., 2000). Some protocols were however recently refined, additional tests, as well as minor modifications are subsequently described in brief. The testing was conducted during a rest period between tournaments of the 2004 Australian Uncle Toby's International Circuit, therefore all participants were deemed to be at peak fitness in preparation for competition. This aspect of the investigation was conducted to report comprehensively on the physical characteristics of a cohort of professional male tennis players at the entry level of elite competition.

Field-testing battery.

1. Speed – 5, 10 and 20 m sprint using timing lights.
2. Backwards Speed – 5 m backwards simulated smash test.
3. Agility – Right and left lateral movement, change of direction tests.
4. Leg Power – Right leg, left leg and a double leg counter movement vertical jumps.
5. Upper Body Power – Right and left side rotational throws with a 1 kg medicine ball. Two arms forward overhead throw, similar to a soccer throw-in.
6. Dynamic Balance, Foot Speed, Coordination – Hexagon test, protocol described elsewhere (USTA, 1998).
7. Anaerobic Endurance / Court Speed – Repeated maximal intensity, court-specific running speed. Five consecutive trials, with 20 s rest between each trial.
8. Aerobic Power – 20 m shuttle run test to maximal exhaustion.
9. Serve Velocity – Assessed via a radar gun positioned 3 m behind the centre mark of baseline, at a height of 2.2 m (approximating ball-contact height).
10. Groundstroke velocity – Assessed via a radar gun positioned 2 m to the right or left of the centre mark on the baseline and 3 m behind the baseline, at a height of 1 m (approximating ball-contact height).
11. Anthropometry – Height, weight and sum of seven skinfolds (Triceps, Subscapularis, Biceps, Supraspinale, Abdominal, Front thigh, Medial calf). Calculation of percent body fat using six skinfold sites did not include the Biceps measurement.

Equipment.

Anthropometric measurements.

Height was determined using a portable stadiometer (TTM, Mentone Educational Centre, Victoria, Australia). Body mass was determined using electronic scales (UC-300 Precision Health Scale, AND Mercury Pty Ltd, South Australia). Seven specific skinfold sites were measured using Harpenden skinfold calipers (Mentone Educational Centre, Victoria, Australia) and the sum was retained for subsequent analysis. Measurements were conducted by anthropometrist accredited through the International Society for the Advancement of Kinanthropometry.

Physical testing.

Physical testing was conducted on a hard court, synthetic category 2 (Rebound Ace, A.V. Syntec Pty. Ltd. Queensland, Australia). Vertical jump height was measured using a Yardstick (Swift Performance Equipment, Lismore, Australia). Maximal heart rate attained during the shuttle run test was recorded using a Polar s610i heart rate monitor (Polar Electro Oy, Finland) set to collect HR on 5 s intervals. Peak velocity of serves and groundstrokes were measured using a radar gun (Stalker Professional Sports Radar, Radar Sales, Plymouth, MN). The radar gun was set on “Peak mode” to detect maximal ball velocity between the range of 80 to 400 kph. Prior to using the radar gun a self test was performed, in addition to the factory recommended calibration with a tuning fork. New Slazenger tennis balls (Hydroguard Ultra VIS, Dunlop Sport Equipment, Regents Park, Australia) were used in the analysis of both serve and groundstroke velocity. A stopwatch (Seiko, Japan) was used to record speed of completion of the Hexagon test. All speed and agility components were recorded electronically using light gates (Speedlight Timing System, Swift Performance Equipment, Lismore, Australia).

Table 3.1

Anthropometric and Tennis-Specific Physical Characteristics of Professional Male Tennis Players

Participants	Age (y)	World Ranking at Time of Test	Weight (kg)	Height (cm)	Sum 7 (mm)	Body Fat - Sum 6 (%)	VJ - Double (mm)	VJ - Right (mm)	VJ - Left (mm)	Agility - Lat R (s)	Agility - Lat L (s)	Agility - Hex (s)	Agility Endurance - Mean (s)	Agility Endurance - % Dec	Sprints - 5 m (s)	Sprints - 10 m (s)	Sprints - 20 m (s)	Sprints - 5 m Back (s)	MedBall Throw - Right (m)	MedBall Throw - Left (m)	MedBall Throw - Overhead (m)	Serve Speed - Mean In (kph)	Forehand Speed - Mean 5 (kph)	Backhand Speed - Mean 5 (kph)	Beep Test (Level)	Beep Test (Shuttle)	Beep Test (Decimal)	VO_{2max} Predicted ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)
1	20.1	553	81.40	188.6	43.1	6.8	79	54	54	2.24	2.27	9.78	17.50	3.7	1.08	1.81	3.16	1.13	22.40	22.30	22.80	198	163	145	15	6	15.46	65.6
2	19.0	882	73.30	180.2	43.3	6.8	66	49	47	2.30	2.29	9.97	17.06	4.5	1.14	1.87	3.17	1.27	21.50	19.10	18.10	195	153	147	14	13	15.00	64.0
3	18.6	312	95.40	198.8	69.9	9.6	58	46	43	2.38	2.26	9.66	17.80	9.2	1.13	1.90	3.22	1.22	23.20	24.20	21.00		164	155	12	1	12.08	54.0
4	24.0	718	78.50	180.9	37.4	6.2	83	61	54	2.29	2.21	9.47	16.96	3.0	1.12	1.84	3.13	1.16	20.00	21.30	16.90	195	157	137	14	6	14.46	62.2
5	21.1	565	77.60	181.5	43.5	6.9	66	43	45	2.23	2.32	10.44	17.86	9.2	1.03	1.77	3.08	1.14	20.20	18.80	18.30	192	154	141	12	8	12.67	56.0
6	24.5	204	77.05	182.6	42.9	6.7	71	44	47	2.28	2.29	10.84	16.76	0.7	1.10	1.84	3.17	1.18	19.70	21.70	17.90	192	164	141	15	9	15.69	66.4
7	25.7	496	74.50	172.8	65.0	8.9	64	41	48	2.20	2.26	9.62	17.58	3.7	1.09	1.84	3.15		21.70	19.20	19.50		152	146	14	12	14.92	63.8
8	18.3	678	75.45	188.1	40.1	6.5	71	52	54	2.25	2.48	10.64	18.11	7.0	1.04	1.78	3.14	1.26	17.75	20.70	16.00		141	143	13	5	13.38	58.5
9	23.4	583	75.20	176.7	33.0	5.7	77	43	47	2.37	2.57	9.68	19.35	5.1	1.13	1.88	3.13	1.13	20.70	20.50	15.70	181	158	146	15	1	15.08	64.3
10	20.8	518	85.45	185.4	57.3	8.1																						
11	19.5	125	76.95	180.2	53.5	7.8	58	35	39	2.22	2.17	10.56	16.02	4.8	1.06	1.79	3.02	1.11	22.55	21.10	18.83							
Mean	**21.4**	**512**	**79.16**	**183.3**	**48.1**	**7.3**	**69**	**47**	**48**	**2.28**	**2.31**	**10.07**	**17.50**	**5.1**	**1.09**	**1.83**	**3.14**	**1.18**	**20.97**	**20.89**	**18.50**	**192**	**156**	**145**	**14**	**7**	**14.3**	**61.6**
St. Dev	2.6	224	6.37	6.9	11.7	1.2	8.5	7.4	5.0	0.1	0.1	0.5	0.9	2.7	0.0	0.0	0.1	0.1	1.63	1.65	2.19	6	7	5	1	4	1.3	4.4
Min	18.3	125	73.30	172.8	33.0	5.7	58.0	35.0	39.0	2.2	2.2	9.5	16.0	0.7	1.0	1.8	3.0	1.1	17.75	18.80	15.70	181	141	137	12	1	12.1	54.0
Max	25.7	882	95.40	198.8	69.9	9.6	83.0	61.0	54.0	2.4	2.6	10.8	19.4	9.2	1.1	1.9	3.2	1.3	23.20	24.20	22.80	198	164	155	15	13	15.7	66.4

Note. Only 11 of the 14 participants completed the testing battery (partially or in-full). Hex = Hexagon test; Lat L = Lateral left; Lat R = Lateral right; % Dec = Percent decrement; Sum 6 = Sum of six skinfolds; Sum 7 = Sum of seven skinfolds; VJ = Vertical jump.

Tournament Details

Three tournaments (one clay court and two hard court tournaments) during the 2003/2004 Australian Summer and Autumn Tennis Circuits were the vehicles for investigation. In total 37 data sets were produced from 33 matches (in 4 of the 33 matches analysed both players were participants in the investigation). The tournaments were Uncle Toby's International events where players competed for prize money, points toward their world ranking and ultimately entry into ATP tour events. Matches in all tournaments were best of three sets except for the final of the Australian Open Wildcard (AOW) playoff which was played over five sets. Matches were contested between 0900 and 1700 hr. Matches were played outdoors and all facilities and equipment were defined according to the International Tennis Federation (ITF) handbook for ball and court surface classification (ITF, 2003). Further details of each tournament are presented in Table 3.2.

Table 3.2

Details of the 2004 Australian Open Wildcard Playoff and the Uncle Toby's International Tennis Tournaments

	2004 AOW Playoff	Gosford Satellite	Canberra Challenger
Date	17th – 20th Dec 2003	16th – 22nd Feb 2004	27th Mar – 4th Apr 2004
Main draw players	16	32	32
Qualifying players	N/A	128	128
Surface	Hard courts Synthetic category 2 (Rebound Ace, A.V. Syntec Pty. Ltd. Queensland, Australia)	Hard courts Category 2 (Plexipave, California Products – Plexipave Surfacing Systems, Andover, USA)	Clay courts (European Clay Equivalent, Newcastle, Australia)
Prize money	$A 18 000	$US 6250 + Hospitality expenses	$US 25 000 + Hospitality expenses
Participants	6	6	10

Experimental Match Description

Pre-match.

On match day participants performed their routine game preparation, with a few minor modifications. Participants arrived to the courts with their upon-waking urine sample, having previously ingested (at least 3 hr prior to the start of play) a core temperature measurement capsule. The single use capsule was a tablet-sized electronic device that passes naturally through the digestive system (refer to "*Procedure Measures*" section for more specific details). Immediately prior to the commencement of each match participants emptied their bladder before being weighed nude. Subsequently, participants were seated and fitted with a heart rate (HR) monitor and baseline measurements of HR and core body temperature (T_C) were performed. Pre-match capillary blood sampling was conducted. The total weight of the player's food and fluids carried to the court were ascertained to account for all possible variables influencing changes in body mass. Thereafter, participants walked to their assigned match court and began their pre-game warm-up. Match courts were set up with apparatus to measure environmental conditions, serve speed, match notation and serve biomechanics. Detailed information of the court set up is provided hereafter in respective sections.

During match play.

A standardised set of physiological, biomechanical and descriptive variables were measured. During game and set breaks core body temperature and fluid consumption were monitored. Water and CHO-loaded (6%) sports drinks were available for participants to consume. Collection times were not standardised, rather they were time-dependent on playing duration characteristics (point, game and set length). The procedures were conducted with minimal interruption to the athlete. Serve velocity, serve kinematics and environmental conditions were measured during match play. All matches were filmed for the retrospective computerised notational analysis.

Post-match.

On completion of the match, participants returned immediately to the testing area for assessment of nude body mass (towelled dry) and capillary blood samples. Final weighing of food and fluid consumed on-court was performed. This ensured that all possible influences of body mass change were accounted for.

Procedure Measures

Core body temperature.

Core body temperature was measured during breaks in match play via short range telemetry. Participants ingested a single use capsule (approximate dimensions: 1.5 cm in length and 0.8 cm in diameter) at least 3 hr prior to commencing each match (note: this allowed enough time for the capsule to reside in the gastrointestinal tract which is ideal for accurate measurement). The validity of this method of measurement, in comparison to more traditional methods has been previously published (O'Brien, 1998). The capsule transmitted a frequency to a data logger (BCTM3, Fitsense Technology, USA) attached to the back of the participants' chair used during every change of ends. The radius of the transmission signal was approximately 50 cm from the body. Data was also manually recorded, from the digital display, by a researcher seated courtside behind the player.

Heart rate.

Heart rate was recorded on 5 s intervals from commencement of the warm-up to completion of the match using a Polar Team System monitoring device (Polar Electro Oy, Finland). The Team System enabled HR to be recorded and stored using a chest strap only, thus participants were not required to wear a watch to receive and log the transmission. This procedure proved to have a greater acceptance, as some players disliked wearing a watch during play (note: due to personal reasons some participants did not use a heart rate monitor during match play). On completion of each match data was downloaded to a personal computer for subsequent analysis. The chest strap monitor was fitted immediately after assessment of nude body mass and removed post-match.

Blood metabolites.

Capillary blood sampling was conducted prior to commencement and following completion of each match. The droplet-sized samples were collected from a needle size hole in the participant's earlobe. The blood metabolites measured pre-match included blood glucose (BGL), creatine kinase (CK), creatinine, urea and uric acid. Post-match assessment included BGL, CK and creatinine only. Reduced BGL and elevated CK, creatinine, urea and uric acid have been reported in athletes performing high volumes of training (Parisotto, 1999). Specifically, their measurement provided insight to blood glycogen levels, muscle damage and hydration status in response to the metabolic stress of tournament tennis. These procedures enabled comparison of pre- and post-match values in addition to tracking cumulative changes over the course of the tournament. The participant's earlobe was first cleaned with an alcohol wipe and then pierced by a single use sterile lancet. The first drop of blood was discarded. Blood was drawn into a capillary tube, pipetted onto a measuring strip and analysed immediately using a portable analyser (Reflotron, Boehringer Mannhein, Germany). The Reflotron was utilised during hard court tournaments only. The clay court tournament (Canberra Challenger) was located in close proximity to the Australian Institute of Sport (AIS). Logistically this enabled blood collection to occur at the tournament venue and blood analysis at the AIS using laboratory-based equipment (Hitachi 911 Automatic Analyser, Hitachi Ltd. Tokyo, Japan). Between collection and analysis, samples were stored on ice. Reported correlations coefficients between the two methods of analyses ranged 0.992 to 0.998 (Roche Diagnostics, 2004; personal communication). Blood glucose was analysed at all tournaments using a HemoCue Blood Glucose Analyser (HemoCue AB, Angelholm, Sweden). All blood testing apparatus were calibrated according to the manufacture's guidelines on the morning of every testing session.

Urine specific gravity.

Urine specific gravity was measured from upon-waking samples provided by participants on the morning of each match. This procedure was conducted to assess pre-match hydration status and post-match rehydration efficacy. Cumulative hydration status was also monitored in players who progressed through a number of rounds. Measurement was conducted by two means, either using a Bayer Multistix test strip (8SG, Bayer Diagnostics Manufacturing, South Wales) dipped into the urine or alternatively, using a Digital Urine S.G. Refractometer (UG-1, Atago Co. LTD, Tokyo, Japan). Distilled water was used to calibrate the refractometer prior to each measurement. A correlation coefficient ($r = 0.725$) has been previously reported for the two methods of urinalysis (Brandon, 1994).

Body mass.

Body mass measurements were conducted pre- and post-match as an index of sweat rate, fluid loss and percent change in body mass. For accuracy of assessment participants were ideally weighed nude or wearing minimal clothing (shorts only). Measurements were obtained without risk of invading the participant's privacy. Post-match measurement required participants to towel down to remove any sweat lying on the skin surface, that would otherwise underestimate sweat loss. Players who required toilet breaks during matches were weighed pre- and post-faecal or urinary excretion wearing all tennis apparel. On completion of the match players proceeded immediately to the testing area for post-match analysis. All measurements were conducted using electronic scales (UC-300 Precision Health Scale, AND Mercury Pty Ltd, South Australia). The sensitivity of the scales was 50 g. The scales were recently calibrated for accuracy using weights of known mass.

Hydration status.

Fluid consumption was measured by weighing player drink bottles before, during and after matches. Measurements were conducted on a set of digital electronic kitchen scales (Portion Power, InterTAN Australia LTD.) that displayed sensitivity to 1 g and a range of 0 to 2000 g. For the analysis conducted during breaks in play the scales were positioned court-side, next to the tester and behind the player. The procedure provided no distraction to players. Careful instructions were given to participants to ensure that they did not tip water out of the drinking bottle for any reason (i.e., to splash on ones' face) as this could potentially lead to an overestimation of fluid consumption. In order to account for all possible changes in body mass, the weight of all food and fluid was calculated prior to commencement of the match and recorded as consumed. This procedure accounted for partially consumed food or fluids, whereby athletes were instructed to store all items which were weighed post-match.

Serve speed.

Peak velocity of first and second serves was measured using a radar gun (Stalker Professional Sports Radar, Radar Sales, Plymouth, MN). The radar gun was set on "Peak mode" to detect maximal ball velocity ranging 80 to 400 kph. Radar gun function was checked on each day of competition by entering the "self test" mode and performing the factory recommended tuning fork calibration. The radar was positioned on the back fencing, aligned with the approximate height of ball contact (~2.2 m) and directed down the centre of the court.

Serve kinematics.

A qualitative biomechanical assessment of the first and second service action was conducted retrospectively from serves filmed during match play. A digital video camera (Sony Blue Tooth DCR-TRV950E, Japan) was used to film the anterior plane of the participant executing the serve. The camera was placed to the side of the court along an imaginary extension of the baseline, where it was mounted on a tripod at a height approximately 1.5 m above the ground. Footage was captured from one end of the court, hence only every second service game was analysed. The footage was subsequently downloaded and converted to video files for the qualitative analysis.

The serve technique checklist was devised (refer to Appendix A) through discussions with elite coaches, biomechanists and sections extracted from an advanced coaching manual (Singh, 2002). The checklist was developed to identify salient processes of the serve that may be prone to fatigue-induced impairment. Each component of the checklist was qualitatively observed for each individual serve of a game and a consistency score was produced. To obtain a consistency score, the number of times a technical modification appeared during one complete service game was recorded and converted to a percentage. Two elite coaches from the AIS and Tennis Australia (TA) conducted the analysis. Coaches were instructed to view the footage in real-time and remain objective. Slow motion analysis was also permitted to enhance qualitative assessment. In order to eliminate the influence the knowledge of time at which serves occurred, coaches were blinded to any order and instructed that serve sequences were randomised. Coaches were briefed and required to perform several familiarisation trials to minimise inter- and intra-tester variability.

Notational analysis.

Matches were filmed using a digital video camera (Sony Digital Handycam DCR-VX2000E PAL, Japan) for the purposes of a retrospective notational match analysis. The camera was fitted with a wide angle lens to ensure the entire court was within the field of view and secured to the upper fence railing at one end of the court, approximately 3 – 4 m above the court surface. Information extrapolated from the footage was descriptive match characteristics including rally lengths, shots per rally, inter-point time, inter-serve time, the number of direction changes per rally and error rates. An attempt was made to classify errors as forced or unforced. If the errors were deemed unforced, an attempt was then made to determine the cause (e.g., technical: poor stroke execution; or decision making: wrong stroke selection). The statistical match analysis was conducted using customised software (TenTimer V1.1, AIS, Canberra) developed specifically for purposes of the investigation.

Environmental conditions.

Environmental conditions, including ambient temperature, relative humidity (RH), wind speed, and wet bulb temperature (T_{WB}), were monitored using a portable digital weather tracker (Kestrel 4000, Nielsen-Kellerman, Australia). The Kestrel 4000 was positioned approximately 1 m above the ground on the side fencing. Court temperature was measured using a digital temperature analyser (Testo 610, Testo Sense PTY LTD. Bayswater, VIC, Australia) placed approximately 50 cm inside the court fencing, on the court surface, in a position unimpeded by shade. Measurements were recorded every 5 min from commencement to conclusion of each match.

Statistical Analyses

Data from the two hard court tournaments were pooled, whereas data from the single clay court tournament is presented individually. Data were analysed using SPSS for Windows^{TM} version 11.0 (SPSS Inc., USA). Standard descriptive statistics characterised the 14 participants. Six participants competed in tournaments on both surfaces. Data of only those six participants was used for the statistical analyses. It was deemed appropriate to do this as, first it provided a true representation of an evenly distributed data set, and second results of the six repeated participants mirrored those of all players. Alternatively, Appendixes B - E present data of all matches, however, participants appear in the data set on only one occasion (i.e., one set of match data was randomly selected and included if participants progressed through a number of rounds). Although reducing the sample size (n = 10), this procedure was required to eliminate the existence of statistical contamination by eliminating individually-biased responses. Under these circumstances, participants repeatedly expressing a dominant physiological response confounded the potential to observe a true distribution of results when dealing with a relatively small sample size.

As a result of significant differences in environmental conditions, comparisons across the different court surfaces were not warranted. Instead the purpose was to present physiological profiles of tournament tennis and in doing so, infer a role of physiological perturbation on match outcomes. However, in some cases paired t-tests were used to compare environmental conditions, physiological responses, and notational analyses between matches played on different court surfaces and pre- versus post-match responses. Where data expressed significant non-normality, non-parametric statistics were used to examine statistical significance (Wilcoxon sign-ranked test). A correlation matrix was used to identify relationships between physiological responses, skill performance and match notation over the duration of a match. First, correlations were conducted using only measurements up to the duration of the shortest match. This procedure is statistically sound, however it does not represent the true effects of an entire match and prolonged tennis play. A second correlation matrix was conducted which included full match data, regardless if the match finished in 1 hr or 3 hr, for example. These results are presented in the Appendixes F - L. Correlations were conducted using pooled data of all matches, on both court surfaces. For identification of findings specific to different court surfaces, correlations were also conducted using data from only hard court matches and data from only clay court matches. A positive correlation reflects a positive relationship, in instances where both values are positive (i.e., increasing match time and increasing serve velocity would be a positive relationship). Statistical significance was identified where $p < 0.05$.

Results

Comprehensive Participant Demographics

Reported previously (Table 3.1, page 55) are individual and group normative data of the anthropometric and physical testing battery performed by participants in the weeks prior to commencing the 2003/2004 Australian Summer and Autumn Tennis Circuits.

Environmental Conditions

Environmental conditions during hard court and clay court matches are presented in Table 3.3. Values are based on the matches contested by the six repeat participants only. Ambient temperature ($t = -2.988$, $p = 0.031$), T_{WB} ($t = -3.59$, $p = 0.016$) and court temperature ($t = -2.731$, $p = 0.041$) were significantly higher during the hard court tournaments, relative to the clay court tournament. Further comparisons of physiological responses, match notation and performance characteristics across court surfaces are limited due to the influence of environmental conditions. Values recorded from all matches, with participants appearing in the data set on one occasion only, can be sourced in Appendix B.

Table 3.3

Environmental Conditions during the Hard and Clay Court Tennis Tournaments

	Hard court		Clay court	
	mean $\pm$ *SD*	min - max	mean $\pm$ *SD*	min - max
Temperature (°C)	32.0 $\pm$ 4.5*	24.9 - 43.1	25.4 $\pm$ 3.8	19.6 - 33.8
Relative humidity (%)	38 $\pm$ 14	12 - 62	32 $\pm$ 5	21 - 43
Wind speed ($m \cdot s^{-1}$)	1.2 $\pm$ 1.7	0.0 - 10.8	1.2 $\pm$ 1.1	0.0 - 5.3
T_{WB} (°C)	21.7 $\pm$ 1.9*	17.1 - 26.5	16.1 $\pm$ 2.6	11.9 - 23.7
Court temperature (°C)	40.4 $\pm$ 5.3*	31.4 - 51.5	34.1 $\pm$ 4.3	24.6 - 42.7

Note. Values presented are mean $\pm$ *SD*, minimum and maximum (* represents a significant difference between the hard and clay court tournaments at a level of $p < 0.05$). T_{WB} = Wet bulb temperature.

Physiological Responses

Both court surface and environmental conditions are variables that have a significant influence on physiological responses to match play and thus potentially on notational analyses and performance markers. The purpose here was simply to present physiological profiles to tournament tennis and in doing so, infer a role of physiological perturbation on match outcomes. Out of interest, comparative analyses were conducted on some variables to further explore the influence of court surface and environmental conditions on overall match characteristics. Physiological responses to hard court and clay court tennis tournaments are presented in Table 3.4. Values presented are those of the six repeat participants only. Equipment failure hampered the collection of creatine kinase during the hard court tournaments. Post-match body mass deficits were significantly greater during hard court matches (hard courts vs. clay courts; 1.05 $\pm$ 0.49% vs. 0.32 $\pm$ 0.56%, z = -2.201, $p < 0.05$). Only eccrine and urinary/faecal losses were considered in the calculation of changes in body mass. No attempt was made to calculate respiratory and metabolic body weight losses over the course of a match which potentially attracted a 10% margin of error (Cheuvront & Haymes, 2001). Pre- versus post-match analysis of blood variables revealed that blood glucose concentration ($t = -3.202$, $p = 0.008$), creatine kinase ($t = 4.835$, $p = 0.005$) and creatinine (Wilcoxon z = -3.062, $p = 0.002$) were all significantly higher post-match, refer to Table 3.4 below (note: to increase statistical power, data from both hard and clay court tournaments was pooled for this analysis). Values recorded from all matches, with participants appearing in the data set on one occasion only, can be sourced in Appendix C.

Table 3.4

Physiological Responses to Matches Played on Hard and Clay Courts

	Hard court		Clay court	
	mean ± *SD*	min - max	mean ± *SD*	min - max
Peak core temperature (°C)	38.9 ± 0.3	38.6 - 39.3	38.5 ± 0.6	37.9 - 39.5
Sweat rate ($kg \cdot hr^{-1}$)	2.04 ± 0.44	1.53 - 2.77	1.51 ± 0.32	1.08 - 1.86
Body mass deficit (%)	1.05 ± 0.49*	0.39 - 1.59	0.32 ± 0.56	-0.47 - 0.95
Fluid consumed vs. fluid lost (%)	77 ± 12	63 - 90	89 ± 26	68 - 133
Average heart rate (bpm)	152 ± 15	137 - 173	146 ± 19	130 - 167
Pre-match BGL ($mmol \cdot L^{-1}$)	5.2 ± 0.6	4.5 - 5.7	6.4 ± 2.4	3.8 - 10.4
Post-match BGL ($mmol \cdot L^{-1}$)	6.7 ± 2.2	3.6 - 8.6	8.4 ± 1.9	6.3 - 11.1
Pre-match CK ($U \cdot l^{-1}$)	-	-	255 ± 73	134 - 344
Post-match CK ($U \cdot l^{-1}$)	-	-	312 ± 87	161 - 414
Pre-match creatinine ($umol \cdot L^{-1}$)	70 ± 7	60 - 79	81 ± 6	71 - 89
Post-match creatinine ($umol \cdot L^{-1}$)	87 ± 14	70 - 107	96 ± 8	90 - 113
Pre-match urea ($mmol \cdot L^{-1}$)	5.6 ± 1.0	4.4 - 7.0	6.3 ± 0.5	5.4 - 6.9
Pre-match uric acid ($umol \cdot L^{-1}$)	321 ± 89	176 - 385	342 ± 43	298 - 412
Urine specific gravity	1.023 ± 0.004	1.015 - 1.025	1.021 ± 0.004	1.017 - 1.028

Note. Values presented are mean ± *SD*, minimum and maximum (* represents a significant difference between the hard and clay court tournaments at a level of $p < 0.05$). BGL = Blood glucose; CK = Creatine kinase.

Match Performance Characteristics

Despite the significant environmental differences between hard and clay court tournaments match performance characteristics were similar. First and second serve velocity, first serve percentage, the percentage of points won emanating from first and second serves, and the percentage of unforced errors committed per match are presented in Table 3.5. No significant differences were identified between performance variables across court surfaces. Values presented are those of the six repeat participants only. Values recorded from all matches, with participants appearing in the data set on one occasion only, can be sourced in Appendix D.

Table 3.5

Quantitative Performance Indicators of Men's Professional Tennis Matches Played on Hard and Clay Courts

	Hard court	Clay court
	mean ± *SD*	mean ± *SD*
First serve velocity (kph)	178 ± 9 (*N* = 445)	172 ± 14 (*N* = 375)
Second serve velocity (kph)	135 ± 10 (*N* = 199)	134 ± 12 (*N* = 147)
First serve accuracy (%)	56 ± 24	55 ± 24
Points won on first serve (%)	72 ± 32	76 ± 25
Points won on second serve (%)	63 ± 34	61 ± 35
Unforced errors (%)	24 ± 13	24 ± 17

Note. Values (mean ± *SD*) are specific to the player participating in the investigation. No data was collected on the opposing player. Values presented in parentheses (*N*) represent the number of data from which mean and standard deviation are derived.

Notational Analysis

Match statistics for hard and clay court tournaments are presented in Table 3.6. Values presented are those of the six repeat participants only. Time between points was significantly longer during hard court matches (hard vs. clay: 25.1 ± 4.3 s vs. 17.2 ± 3.3 s, $t = -6.886$, $p < 0.01$). No other match statistic differed significantly between court surfaces. See Appendix E for results of the all recorded matches. The larger sample size ($n = 10$) returned more expected findings, for example the number of shots per rally was greater on clay courts and difference between match duration was less (see Appendix E).

Table 3.6

Notational Analyses of Men's Professional Tennis Matches Played on Hard and Clay Courts

	Hard court		Clay court	
	mean ± *SD*	min - max	mean ± *SD*	min - max
Match duration (min)	119 ± 36	84 - 171	79 ± 13	61 - 101
Rally duration (s)	6.7 ± 2.2	3.1 - 15.0	7.5 ± 3.0	2.8 - 17.9
Shots per rally	4.7 ± 1.4	2.4 - 8.4	4.5 ± 2.0	2.3 - 11.8
Direction changes per rally	2.5 ± 0.9	1.0 - 4.6	2.4 ± 1.3	1.2 - 8.4
Time between games (s)	59.9 ± 18.1	23.9 - 108.6	50.0 ± 18.5	8.0 - 117.5
Time between points (s)	25.1 ± 4.3**	16.7 - 34.4	17.2 ± 3.3	10.2 - 27.5
Time between serves (s)	11.7 ± 3.2	5.2 - 22.1	10.6 ± 2.5	7.6 - 24.4

Note. Values (mean $\pm$ *SD*) presented are those of the six repeated participants only (** represents a significant difference between the hard and clay court tournaments at a level of $p < 0.01$).

Correlations over Time between Physiological Responses, Performance and Notational Analyses (Pooled Data)

Correlations were conducted on data pooled from all hard court and clay court matches analysed. Only data up to the duration of the shortest match was used, the results are presented below.

Quantitative performance.

Physiological manifestations did not correlate with any of the quantifiable performance measures listed in Table 3.5 (see page 70). First serve velocity negatively correlated with court temperature ($r = -0.772$, $p < 0.05$). Second serve velocity correlated with RH ($r = 0.708$, $p < 0.05$), and negatively correlated with ambient temperature ($r = -0.739$, $p < 0.05$) and T_{WB} ($r = -0.734$, $p < 0.05$). Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix F.

Qualitative performance.

A longitudinal assessment of serve kinematics revealed correlations between technical inconsistencies, a number of match variables and physiological responses. Consistency in the height of the tossing arm at ball release was the predominant fatigue-susceptible characteristic of the first serve, inversely correlating with both progressive match time ($r = -0.741$, $p < 0.05$) and incurred body mass deficit ($r = 0.730$, $p < 0.05$). Second serve analyses revealed that consistency in position and height of the ball toss tended to deteriorate as physiological strain imposed, inversely correlating with progressive match time (r = -0.729, $p < 0.05$) and incurred body mass deficit (r = 0.725, $p < 0.05$). Consistency of the second serve ball toss height correlated with court temperature (r = 0.708, $p < 0.05$) and inversely correlated with ambient temperature (r = -0.728, $p < 0.05$) and T_{WB} (r = -0.804, $p < 0.05$). These observations limit interpretation of relationships between environmental stresses and serve kinematics. Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix F.

Notational analysis.

Core body temperature was the only physiological strain index that displayed a relationship with notational analyses; time between games (r = 0.908, $p < 0.01$), time between points (r = 0.815, $p < 0.05$), shots per rally (r = 0.728, $p < 0.05$) and rally duration (r = 0.794, $p < 0.05$). No significant correlations were reported between environmental conditions and match statistics. Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix H.

Correlations over Time between Physiological Responses, Performance and Notational Analyses (Hard Court Matches)

A correlation matrix of physiological responses, match notation, performance and environmental conditions was conducted for hard court matches only. Tournaments were analysed separately as hard court matches were played under more challenging environmental conditions. The data from both hard court tournaments were pooled.

Quantitative performance.

First serve percentage inversely correlated with both elapsed match time (r = -0.700, p < 0.05) and progressive body mass deficits (r = 0.695, p < 0.05). No other physiological perturbations correlated with quantifiable performance measures. Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix I.

Qualitative performance.

A longitudinal assessment of serve kinematics did not reveal any significant relationship between physiological stressors when matches were played under more challenging environmental conditions.

Notational analysis.

A number of correlations were observed between physiological responses, notational analyses and environmental conditions (see Table 3.7). The correlation matrix was conducted using data from only hard court matches and up to the duration of the shortest match. Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix I.

Table 3.7

Correlations between Physiological Variables, Notational Analyses and Environmental Conditions

	Notational analyses and environmental conditions							
Physiological variables	Inter-game time	Inter-point time	Inter-serve time	Shots per rally	Rally duration	Direction changes per rally	Relative humidity	Court temperature
Elapsed time	0.286	0.796**	-0.579	0.366	0.394	0.545	-0.707*	0.642*
Core temperature	0.652	0.984**	-0.728*	0.666*	0.654	0.795**	-0.409	0.451
Body mass deficit	-0.207	-0.791*	0.576	-0.356	-0.382	-0.537	0.705*	-0.645*
Heart rate	0.916**	0.851**	-0.627	0.811**	0.834**	0.872**	-0.064	-0.138

Note. Correlations were conducted on hard court matches only (values represent r, * represents $p < 0.05$, ** represents $p < 0.01$).

Correlations over Time between Physiological Responses, Performance and Notational Analyses (Clay Court Matches)

A correlation matrix of physiological responses, match notation, performance and environmental conditions was conducted for clay court matches only. Tournaments were analysed separately as clay court matches were played under cooler environmental conditions, relative to matches played on hard courts.

Quantitative performance.

Heart rate was the only physiological index that displayed a relationship with quantifiable performance characteristics, inversely correlating with second serve velocity (r = -0.739, $p < 0.05$). Second serve velocity also correlated with RH (r = 0.721, $p < 0.05$) and inversely with both ambient temperature (r = -0.739, $p < 0.05$) and T_{WB} (r = -0.739, $p < 0.05$). Correlations conducted using full match data, regardless if the match finished in 1 hr or 3 hr, for example, are presented in Appendix J.

Qualitative performance.

The longitudinal correlation matrix between serve kinematics and physiological stressors revealed inverse relationships between consistency of the landing position within the court after racquet-ball contact (second serve) and elapsed match time (r = -0.755, $p < 0.05$) and progressive body mass deficit (r = 0.724, $p < 0.05$). More significant relationships were revealed when correlations were conducted using full match data (see Appendixes K and L; first serve and second serve, respectively).

Notational analysis.

Core body temperature was the only physiological strain index that displayed a relationship with notational analyses, correlating with time between games (r = 0.918, p < 0.01). Wet bulb temperature correlated with shots per rally (r = 0.722, p < 0.05) and inversely correlated with time between games (r = -0.776, p < 0.05). Court temperature correlated with the time between points (r = 0.732, p < 0.05). A number of relationships were observed between physiological responses, performance parameters and notational analyses when correlations were conducted using full match data (see Appendix J).

Discussion

Physiological Profile and Potential Performance Implications

The aim of this investigation was to produce a collaborative notational analysis and physiological profile of professional tournament tennis. A secondary aim was to establish a link between adverse physiological conditions that manifest during match play and performance degradation. The findings revealed that professional tennis players competed while experiencing moderate thermoregulatory strain and hypohydration. Alongside these findings are increases in cardiovascular demand and indications of skeletal muscle damage. Collectively, the effects of hot and humid ambient conditions, repeated ballistic actions and intermittent exercise over a prolonged period are predisposing factors to homeostatic disruption and ultimately performance impairment. Specific to the thermoregulatory response, a number of players exhibited core body temperatures exceeding 38.5 °C and 39.0 °C, shortly after match commencement. These observations demonstrate that players experience various facets of physiological strain for substantial periods of match play. Identification of interventions to reduce physiological compromise is therefore a fruitful research domain. In this instance, performance implications were technical modifications of the service motion, however the effects on stroke velocity and accuracy were difficult to quantify under match conditions, specifically as one cannot control a players' stroke intentions. Consequently, match play conditions are not conducive to valid and reliable assessment of these stroke outcomes and thus, further research in a controlled setting with standardised skill assessment is required. The subsequent experimental phase of this thesis (Investigation 2, Chapter 4) extends these initial findings and seeks to confirm the mechanistic link between impaired stroke kinematics and deterioration of stroke quality.

These findings illustrate the need to implement strategies to attenuate perturbations in core temperature that may predispose players to premature fatigue (Gonzalez-Alonso et al., 1999; Low, Purvis, Reilly, & Cable, 2005), performance decrements (Cotter, Sleivert, Roberts, & Febbraio, 2001; P. A. Hancock, 1993) and heat illness (Binkley et al., 2002). Pre-match body cooling is an experimental modality which addresses this locus of fatigue (Quod, Martin, & Laursen, 2006). Trialled in other sports and proven to delay the onset of fatigue and enhance endurance performance, the application to tennis demands investigation. Investigation 2 of this thesis (Chapter 4) illustrates the continued exploration of this suggested research direction.

Match Preparation and Hydration Status

Analysis of pre-match hydration status reaffirmed the poor hydration practices of tennis players (Bergeron, Waller, & Marinik, 2006). It is generally recommended that U_{sg} should be less than 1.020 for optimum pre-exercise hydration, particularly for prolonged activities in hot and humid conditions (Bergeron, Armstrong et al., 1995; Popowski et al., 2001). In the current investigation some athletes returned upon-waking U_{sg} values as high as 1.030, which implies poor pre-match hydration and post-match rehydration player practices. Whether players' hydration status changed between waking and the start of play was not, however, assessed. Several thermoregulatory benefits have been ascribed to commencing exercise in a hyperhydrated state, relative to a euhydrated state (Grucza, Szczypaczewska, & Kozlowski, 1987). Grucza et al. (1987) observed earlier onset of sweating and mitigated increases in core body temperature in hyperhydrated cyclists during only 45 min of submaximal exercise in a thermoneutral environment. Tennis matches are often played under thermally challenging conditions which would augment the above responses, placing players at risk of performance deterioration and compromised health. Extensive research exists which demonstrates compromised cognitive (Callow et al., 2003; Gopinathan et al., 1988; Shirreffs et al., 1997) and motor/physical (Devlin et al., 2001; Walsh, Noakes, Hawley, & Dennis, 1994) performance under a state of hypohydration. These findings emphasise the need to educate coaches and athletes on the importance of following appropriate pre- and post-match hydration regimens. Individualised hydration strategies will optimise one element of match preparation, decreasing the incidence of heat strain and dehydration-induced performance deficits. Post-match strategies will facilitate recovery by restoring total body water volume and electrolyte balance in addition to reducing the effects of cumulative body mass losses over the duration of a tournament.

Examination of post-match body mass deficits further emphasises the need to educate players on the importance of adhering to adequate hydration strategies during matches contested in warm conditions. During all of the hard court matches studied (17 data sets containing repeat participants), played under moderate environmental conditions, on 13 occasions participants incurred greater than 1% body mass deficit. Average fluid consumption per match was 2329 ± 1104 ml, equivalent to 66 ± 18% of total fluid loss. Comparatively, during all of the clay court matches studied (20 data sets containing repeated participants), played in temperate conditions, equivalent levels of dehydration were reported on only one occasion. Average fluid consumption per match was 1908 ± 694 ml, equivalent to 97 ± 26% of body fluid loss. These observations reaffirm the poor hydration practices of tennis players (Bergeron, Maresh et al., 1995; McCarthy et al., 1998), particularly when matches are played during intemperate conditions. Suboptimal behaviours of players are further exemplified by a number of participants who incurred body mass deficits greater than 2% over the course of 2 to 3 sets. Evidently, some deficits were less than 0.5%, illustrating some positive hydration practices. Irrespective, it is postulated that the magnitude of body mass change would multiply during matches contested over 5 sets or during thermally challenging conditions. It is therefore imperative that future efforts are made to rectify the prevalence of similar levels of body fluid loss. The body mass deficits observed in this investigation are comparable to previous tennis research (Bergeron, 1996, 2003; E. R. Burke & Ekblom, 1982; Davey et al., 2002, 2003; Vergauwen, Brouns et al., 1998) and are easily offset through adherence to prescriptive hydration regimens.

Notwithstanding the implications of dehydration, hypomagnesemia is another condition linked to body fluid losses. Hypomagnesemia is defined by depleted serum magnesium and is its victims experience cramps, tetany, neuromuscular dysfunction and carpopedal spasm (Liu, Borowski, & Rose, 1983). The condition is not uncommon to tennis players, and has been reported on a number of occasions during prolonged exercise (Liu et al., 1983; Therminarias et al., 1994). Therminarias et al. (1994) reported four related episodes, in 23 female tennis players, during 2 hr of fluid-restricted (500 ml) simulated match play in warm conditions (28.3 ± 0.7 °C). All conditions caused premature cessation of activity and were associated with an average post-match body mass deficit of 2.7%. In this respect, it would have been interesting to determine the serum magnesium concentrations of participants during the current investigation. These findings reiterate the importance of adequate hydration and the physiological and performance consequences of poor hydration. Additionally, hydration beverages should contain electrolytes to replenish those lost in sweat and reduced the likelihood of cramping. These issues, among others, will be examined in the next phase of this research investigation.

From a different perspective, of particular interest was one participant who weighed more on completion of each match than prior to commencing the match. Despite counteracting dehydration, the extent of the player's aggressive fluid consumption (mean body mass gain equated to 0.79%, and ranged 0.45 to 1.09%) may render the athlete at risk of hyponatremia or fluid intoxication. Significant reductions in blood sodium concentration, below the normal range of 136 to 143 $mmol \cdot L^{-1}$, is characteristic of hyponatremia (Wilmore & Costill, 1999). The symptoms that manifest include muscle cramps, weakness, disorientation, seizures, pulmonary oedema and coma (Nelson et al., 1988; Toy, 1992; Wilmore & Costill, 1999). The primary aetiology of this condition appears to be a combination of voluntary hyperhydration with hypotonic solutions and excessive loss of electrolytes in sweat. Interestingly, observation of fluid consumption strategies by this participant during matches reported in the current investigation, noted that he elected to consume large volumes of water as opposed to an available sports drink. The player did not report any symptoms of hyponatremia but was informed of risks associated with aggressive hydration practices. It is recommended that players consume carbohydrate-electrolyte beverages and water, individualised to replace sweat loss. To assist with maintenance of hydration status over the duration of a match, ideally players could weigh themselves during each break in play although the practicality of this suggestion is debatable. Notwithstanding the consequences of fluid intoxication, these findings confirm that it is possible to maintain fluid balance during tennis match play, contradicting previous suggestions (Bergeron, Armstrong et al., 1995). It is actually poor, or alternatively over-zealous, attempts to hydrate that predispose players to adverse physiological conditions. Evidently, individualised hydration guidelines need to be devised, specific to environmental conditions. These will ensure players maintain euhydration without risk of developing the aforementioned adverse physiological responses.

Substrate Availability and Hypoglycaemia as a Fatigue Mechanism

The findings of this investigation suggest performance deterioration during extended tennis matches cannot be explained by insufficient availability of energy substrates. In agreeance with previous investigations of moderate (Bergeron et al., 1991) and prolonged tennis play (Mitchell et al., 1992), the current investigation revealed that hypoglycaemia does not manifest during match play. Participants displayed relatively high post-match blood glucose concentrations which are comparable to studies of simulated match play (Christmass et al., 1994; Therminarias, Dansou, Chirpaz-Oddou, Gharib, & Quirion, 1991; Therminarias et al., 1994). It appears that ingestion of CHO beverages is sufficient to maintain blood glucose concentration to match the increased uptake of glucose by active musculature. However the moderate duration 2 and 3 sets matches studied in the current investigation may not be sufficient to challenge and lower blood glucose levels. Significant rises in core body temperature were recorded during both tournaments which would increase CHO oxidation (Febbraio, Snow, Hargreaves et al., 1994; Febbraio, Snow, Stathis et al., 1994). Further research of prolonged tennis match play, equivalent to 5 set matches, is required before hypoglycaemia can be ruled out as a mechanism inducing performance deterioration.

Despite the maintenance of adequate blood glucose concentration during the current investigation, it is conceivable that hypoglycaemia could occur and compromise performance in matches of longer duration. Previous attempts have been made to identify the tennis-specific benefits of CHO supplementation but no conclusions have been consolidated (E. R. Burke & Ekblom, 1982; Magal et al., 2003; Mitchell et al., 1992; Vergauwen, Brouns et al., 1998). The presence of serve technique incongruities in euglycaemic players of the current investigation lends no resolution to this problem. However, similar to previous investigations test sensitivity, match or simulated match intensity and duration are examples of methodological variants that could potentially confound the findings. This suggestion is empirically supported by Hawley et al. (1997), who purported that the benefits of CHO loading or supplementation are observed only as exercise duration exceeds 90 min (Hawley et al., 1997). Therefore, in an attempt to establish the benefits afforded to tennis through CHO supplementation, future researchers should apply strategies over protocols of longer duration with tightened test sensitivity. This is attempted in Investigation 2 (Chapter 4) of this thesis which provided a logical extension to previous investigations.

To identify the aetiology of fatigue and performance decrements in tennis it is suggested that investigators may need to look beyond blood glucose concentration. Depleted muscle glycogen content has been reported (Hawley et al., 1997) as the mechanism underlying fatigue despite participants displaying blood glucose concentrations indicative of euglycaemia (5 mmol·L^{-1}). On this premise, it seems imperative that future tennis research involves a periodic assessment of blood and muscle glycogen. The inclusion of this procedure is however very unlikely due to the intrusive nature of muscle glycogen assessment and the equivocal benefits currently ascribed to CHO supplementation in tennis.

Match Intensity

The estimated playing intensity averaged 78% and 75% of maximum HR for matches played on hard and clay courts, respectively. These values support the estimates of previous researchers (Bergeron et al., 1991; Christmass et al., 1994; Christmass et al., 1998; Smekal et al., 2001; Therminarias et al., 1991). The intensity estimated was derived from average match play HR measurements and calculated as a percentage of maximum HR values that were obtained when participants performed a 20-m shuttle run test as part of the comprehensive participant description. Peak HR attained during play on hard and clay courts respectively, equated to 93% and 94% of maximum HR. These observations, in addition to confirming the high-intensity intermittent nature of tennis, confirm that cardiovascular strain also presents a physiological challenge to sustained performance during match play. Despite no measurement of recovery rate in this study, it appears that the time between points and games is sufficient for players to recover from the high-intensity periods of play, nullifying the previously reported dramatic effects of cardiovascular duress (volitional exhaustion) on tennis skill performance (Davey et al., 2002).

Muscle Damage Associated with Match Play

Creatine kinase is an enzyme important to muscle energy production, but its proliferation post-exercise is also indicative of muscle damage (Wilmore & Costill, 1999). In the current study, post-match CK increased mildly, but significantly, relative to pre-match values. This response, which could be attributed to changes in plasma volume, occurred despite the players being conditioned to the ballistic movements (disruptive stimulus) of tennis, which is said to reduce muscle trauma (Evans & Cannon, 1991). It is proposed that greater tissue damage would accumulate during a prolonged match and over the course of a tournament. This response could increase a player's susceptibility to performance impairment and acute or chronic injuries. These observations emphasise the need for players to employ effective recovery strategies between matches. It is envisaged that this would minimise the cumulative effects of muscle damage and ultimately ensure that players are able to perform at optimum capacity over the duration of a match and tournament. In order to do this, research must first establish which prophylactic or therapeutic strategies are most effective in reducing the response to the ballistic and repetitive actions of tennis. Post-exercise cryotherapy strategies and compression garments have recently returned positive results in other sports (Coffey, Leveritt, & Gill, 2004; Dawson, Gow, Modra, Bishop, & Stewart, 2005; Gill, Beavan, & Cook, 2006), and hence exploration of their efficacy is encouraged in tennis.

Notational Analysis

The standard match statistics of the current investigation are comparable to those of previous researchers (Collinson & Hughes, 2003; O'Donoghue & Liddle, 1998a; O'Donoghue & Ingram, 2001; Richers, 1995). O'Donoghue and colleagues reported average rally lengths 6.3 $\pm$ 1.8 s and 7.7 $\pm$ 1.7 s, inter-point times 18.7 $\pm$ 1.9 s and 19.5 $\pm$

2.1 s, and inter-serve times 9.3 $\pm$ 1.5 s and 9.2 $\pm$ 1.3 s, for men's Grand Slam tournament matches played at the Australian Open (hard courts) and the French Open (clay courts), respectively. One exception was the length of inter-point time on different court surfaces. O'Donoghue and Ingram (2001) reported longer recovery times during clay court matches and reasoned it was due to the longer rally lengths, whereas players in the current investigation required longer recovery times during the hard court matches. The different findings are likely to be related to the different environmental conditions. Additionally, this investigation revealed that increasing core body temperature and significant body fluid loss also influenced match notation, highlighting the need to consider the many variables that determine match notation. Unfortunately, O'Donoghue and Ingram (2001) did not measure physiological parameters in concert with match notation making it difficult to discern the mechanisms behind their findings. The similarity in match notation between Grand Slam and entry level professional tennis tournaments infers that elite players experience equivalent physiological challenges.

The disparity in reported notational analyses and the lack of a definitive explanation illustrates the need for future investigations to adopt a more comprehensive approach when conducting descriptive analyses of tournament tennis. This was applied in the current investigation and created a greater understanding of the physiological responses that underlie match characteristics and performance. The reluctance of players to participate in investigations of this nature (tournament analysis) hampers the rate at which information on elite level performance is obtained. Construction of an experimental tennis tournament will address this issue and serve as a vehicle for investigation by various sport science disciplines. The feasibility and suggested methodologies of this proposal is discussed in the future directions section of this thesis (Chapter 5).

Correlations over Time between Physiological Responses, Performance and Notational Analyses

Performance.

This is the first investigation identified in tennis that has attempted to correlate the increasing physiological demand of match play with skills that underscore performance. This procedure revealed significant findings that warrant further exploration. The qualitative analysis of first and second serves indicated that as matches progressed and adverse physiological conditions developed (e.g., elevated heart rate, body mass deficits, heat strain), elements of the service action were negatively impacted. This finding is consistent with other investigations of elite sports (Murray et al., 2001; Royal et al., 2006) and is suggestive of a relationship between physiological strain and diminished technical skill performance. Specifically, consistency in the height of the arm at ball release, the position and height of the ball toss and the landing position inside the court after racquet-ball impact were the most overt technical inconsistencies. These technical flaws were largely common to all methods in which correlations were conducted (i.e., using complete match data or only match data up to the duration of the shortest match and tournaments played on different court surfaces). General fatigue, possibly modulated through hyperthermia or hypohydration, may also explain performance deterioration, but this possibility could not be confirmed nor discarded based on the available data.

While it could be expected that modifications to coordination and timing of the movement pattern would compromise the outcome of the stroke (Elliott et al., 2003), this was not realised under match conditions as there were no prevailing reductions in serve velocity and accuracy. These findings are in agreement with those of Royal et al. (2006) who observed altered technical proficiency but unchanged shooting velocity and accuracy with increasing levels of physiological strain in water polo players. This suggests either the kinematic components that demonstrated inconsistency with physiological strain are not integral to sustained stroke velocity and accuracy or, that highly skilled athletes are able to maintain performance proficiency under duress.

These findings ultimately afford some certainty to the implication of fatigue to skills that underlie performance. Future investigations should employ more elaborate performance assessment tools (e.g., Swinger™ or Dartfish™ computer software) and extend the analysis to include groundstrokes and volleys. Usage of computer software would effectively decrease the subjectivity of the analyses, adding a quantitative aspect to the performance assessment. Subjectivity was identified as a limitation to the current study design. Post-analysis discussions with coaches indicated that the serve technical checklist (see Appendix A) was perhaps too generalised to identify subtle technical alterations.

The influence of environmental conditions on performance parameters was again realised when hard court and clay court matches were analysed independently. Analysing hard and clay court data collaboratively revealed few prevailing reductions in outcome performance measures (serve velocity and percentage) despite the qualitative technical incongruities. Under hot and humid conditions (hard court tournaments), several correlations were identified between first and second serve velocity, progressive match time and associated disruptions to physiological equilibrium. These observations are consistent with previous suggestions that increasing levels of dehydration and cardiovascular strain impair motor skill proficiency (Davey et al., 2002; Devlin et al., 2001). Considering the serve is one of the most important strokes in the game (Elliott, 2001), any disruption to its functional integrity, in terms of velocity, accuracy or consistency, could influence the outcome of the match. Notwithstanding the limitations and variability of performance assessment *in situ*, the link between suboptimal physiological status and performance degradation encourages further investigation into strategies to counteract the manifestation of undesirable homeostatic disruptions. Previous researchers have attempted investigations of this nature with mixed performance results, which could be explained by the sensitivity and reliability of performance measures (Ferrauti et al., 1997; Magal et al., 2003; Vergauwen, Brouns et al., 1998). The subsequent experimental phase of this thesis (Chapter 4) built on the methodologies of previous investigators using a multifaceted approach to performance assessment.

Notational analysis.

Incremental disruptions to homeostasis during match play appeared to have significant influence on notational analyses. Increases in core temperature, body mass deficits and heart rate, as match time progressed were often associated with increases in the time taken by players between serves, points and games, and the duration and number of shots per rally. The findings suggest that as indices of physiological strain intensified individuals required longer time to complete points and longer recovery time. These observations were particularly evident during hard court matches which were played in thermally challenging conditions. It is likely that these responses would compound over the course of a prolonged match, the implications extending beyond notational analyses to performance impairment. Quantifying performance *in situ* is however a complex task and limits the ability to interpret the effects of physiological strain on performance. The methods applied in the current investigation were a step forward, but performance assessment in a controlled environment (i.e., simulated match play) or during matches using advanced technologies (e.g., Hawk-Eye™) with precise measurement accuracy is encouraged to increase the understanding of this interaction.

Summary

This investigation provides a comprehensive profile of entry level professional tennis (3 set matches), where match notation reflected that of elite tournaments. Simultaneous measurement of performance and physiological parameters infers implications of physiological status on match outcomes. While not directly measured in this investigation it is proposed that standardised assessment of performance variables in a controlled setting would identify skill deterioration associated with physiological strain. Inadequate pre-match hydration, body fluid deficits incurred during play, heat strain and early signs of acute muscle damage stand as the dominant adverse responses during competition. The severity of each condition is not extreme and in is most cases specific to the individual and match variables (i.e., court surface, match duration, environmental conditions). However, it is envisaged that the magnitude of these responses would increase during Grand Slam tournaments (5 set matches). In some instances stroke kinematics were negatively impacted by physiological stress warranting a more detailed examination of this relationship and the resultant effect on stroke outcome measures (velocity and accuracy). Variability of match play, no predetermined intensity or match duration, and having no control over player intentions challenged reliable performance assessment. These findings therefore set the scene for investigation of ergogenic strategies and their capacity to enhance tennis performance and prevent physiological compromise. The subsequent phase of this thesis (Chapter 4) provides a logical extension to the findings of the current investigation and attempts to address, and build on, methodological issues in previous investigations.

CHAPTER 4

INVESTIGATION 2

Caffeine, Carbohydrates and Cooling: Are These Strategies Beneficial to Tennis Performance?

Abstract

Neuromuscular fatigue, hypoglycaemia and hyperthermia may induce a decline in tennis performance. The purpose of this investigation was to determine the effects of prolonged simulated tennis on measures of performance, and the ergogenic potential of caffeine, carbohydrates and cooling. Twelve highly trained male tennis players (mean ± *SD* age 18.3 ± 3.0 yr; height 178.8 ± 8.5 cm; body mass 73.95 ± 12.3 kg; sum of seven skinfolds 62.3 ± 20.9 mm) performed four prolonged (2 hr 40 min) simulated tennis matches, against a ball machine, on an indoor (average temperature 21.2 ± 0.3 °C) hard court. The four counterbalanced experimental trials involved: caffeine supplementation (3 $mg \cdot kg^{-1}$), carbohydrate supplementation (6% solution), pre- and intermittent-cooling and a placebo-control. Physiological markers, subjective responses, stroke velocity and accuracy, serve kinematics and tennis-specific perceptual skill quantified the efficacy of interventions. Significant effects of time ($p < 0.01$) reflected increased physiological demand, reduced serve velocity and groundstroke velocity and accuracy, and slowing of the racquet-arm acceleration phase of the serve. Caffeine was associated with increased serve velocity (165 ± 15 kph) in the final set of the match (condition by time effect, $p = 0.014$) compared to the placebo (159 ± 15 kph, $p = 0.008$) and carbohydrate (158 ± 13 kph, $p = 0.001$) conditions. Significant interactions between condition and time, and effect sizes at specific times suggested a stimulatory effect of caffeine on serve kinematics and reduced perceptions of effort. The carbohydrate and cooling conditions afforded homeostatic

advantage (increased blood glucose concentration over the duration of the simulated match ($p < 0.01$) and reduced thermal sensation at rest ($p < 0.01$), but did not effect performance, relative to the placebo condition. Prolonged simulated tennis of match-like intensity induced significant decrements in tennis skills, despite only mild disruption to selected measures of homeostasis. Caffeine supplementation prevented deterioration of, and increased serve velocity, specifically during the latter stages of the protocol. Facilitative effects on serve kinematics appeared to underscore this response. In this instance carbohydrate and cooling strategies did not afford ergogenic properties; however, methodological limitations may have precluded such observations.

Introduction

Based on the results of Investigation 1, the next phase of research involved a controlled assessment of tennis performance skills (stroke velocity and accuracy, serve kinematics and return of serve anticipation) under the constraints of physiological perturbations and in response to potential ergogenic strategies. Physiological perturbation is a common explanation for overt performance reductions during tennis match play. Several controlled experiments have attempted to quantify the effects of fatigue on tennis skills (Davey et al., 2002; Dawson et al., 1985; Vergauwen, Spaepen et al., 1998) but performance deterioration has not been consistently reported. At volitional exhaustion Davey et al. (2002) observed deterioration of groundstroke accuracy, but after a short rest performance was restored. A tennis skills test conducted pre- and post-fatigue intervention, revealed reduced serve accuracy to the right service box only. Comparatively, Vergauwen, Spaepen et al. (1998) observed reduced serve velocity and accuracy and groundstroke velocity following 2 hr of strenuous training. The level of fatigue induced in both investigations (i.e., beyond that of match play) challenges the validity of the findings and encourages examination of performance under match-like conditions (for a review of physiological responses to match play see (Fernandez, Fernandez-Garcia, Mendez-Villanueva, & Terrados, 2005) or Investigation 1, Chapter 3).

Previous investigations that attempted to either determine the locus of fatigue or reduce its influence through ergogenic strategies typically have only quantified performance outcomes (serve and groundstroke velocity and accuracy). Yet, evidence from other sports encourages exploration of the mechanics that underlie skill proficiency or capitulation (Murray et al., 2001; Royal et al., 2006). From a coaching and injury prevention perspective, stroke kinematics in tennis has received much attention (Elliott, 2006; Groppel, 1986; Pluim & Safran, 2004). However, understanding the mechanics of strokes and their proficiency under duress has comparatively received very little exploration. In baseball, Murray et al. (2001) reported subtle changes in the pitchers' mechanics, and in concert observed slower pitch speed (8 kph) when comparing early and late innings. Similarly, tennis-specific perceptual skill, evidenced in a player's ability to anticipate the stroke intentions of their opponent, consistently discriminates players of differing skill levels (Goulet et al., 1989; Rowe & McKenna, 2001; Williams et al., 2002). However, little is understood pertaining to the functionality of anticipatory skill under duress, or how it is affected by known psycho-physiological and central stimulants, such as caffeine and carbohydrates (Davis et al., 1992; van Duinen, Lorist, & Zijdewind, 2005). As the playing field levels and the nature of the game evolves, players constantly search for strategies or devices to enhance performance and provide an advantage over opponents. Nutritional supplements, such as caffeine and carbohydrates, and cooling modalities are examples currently used by tennis players. The application of these strategies in tennis remains contentious as their capacity to prevent fatigue and enhance performance is not well established (Magal et al., 2003; Struder et al., 1999; Vergauwen, Brouns et al., 1998). The lack of diversity in performance measures and other common methodological shortcomings (i.e., protocols to induce fatigue and test sensitivity) are suggested reasons for the current equivocal nature of findings. The current investigation aimed to address this paucity of information by adopting a multifaceted approach to performance assessment.

The purpose of the investigation was to first induce match-equivalent physiological perturbations and simultaneously measure the effect on various facets of performance. Second, an attempt was made to examine the capacity of potentially ergogenic strategies (commonly used at all levels of tennis) to counteract detrimental homeostatic disruptions. In a counterbalanced order, participants performed the simulated match on four separate occasions; 1 x placebo-control trial (PLA), 1 x pre- and intermittent-cooling trial (cooling), 1 x carbohydrate supplementation trial (CHO) and 1 x caffeine supplementation trial (CAF).

Using the statistical data gathered from the notational analysis completed in Investigation 1 (i.e., average rally duration, shots per rally, changes of direction per rally, time between points, time between serves and time between games) a prolonged simulated match was constructed. The experimental protocol was similar to previous investigations (E. R. Burke & Ekblom, 1982; Davey et al., 2003; Vergauwen, Spaepen et al., 1998) in that a ball machine was utilised for standardisation and repeatability; however, multifaceted performance assessment was introduced. Standard measurement of serve and groundstroke velocity and accuracy was conducted. Serve kinematics were quantified by means of a temporal phase analysis and return of serve anticipation accuracy was assessed using a tennis-specific perceptual skills test. Inclusion of outcome and process facets of performance into the testing battery reflects a significant extension of previous research and a positive movement in the final application of the findings. Both performance components are integral to success yet have been the focus of very little scientific exploration in response to fatigue or the application of common ergogenic agents.

The purpose-built testing protocol was carefully developed to simulate match play and induce equivalent physiological responses to tournament tennis (see Literature Review and Investigation 1 – Chapters 2 and 3). Participants performing the simulated match were the vehicles to implement experimental strategies to reduce physiological perturbations and enhance performance. Interventions were implemented separately to focus on, and counteract, specific physiological stressors. Specifically, the three experimental strategies were applied to reduce central fatigue (CAF), hypoglycaemia (CHO), and hyperthermia (cooling), respectively. It was proposed that this methodology would reveal the efficacy of individual interventions to attenuate specific facets of fatigue - that occur under match conditions - and enhance performance. The multifaceted approach to performance was applied to provide unique insight to the effects of different interventions on specific performance skills.

The experimental strategies were first selected as they are commonly used by players at all levels of tennis participation, and second for their specific address of physiological disturbances that are likely associated with performance impairment during match play. Caffeine was selected for its central stimulatory mechanisms, CHO for its glycemic properties and cooling for its influence on thermogenics. All interventions have demonstrated benefits in other sports and exercise modalities (Coggan & Coyle, 1987; Juhn, 2003; Quod et al., 2006); however, their efficacy in tennis has not been previously articulated.

The purpose of this investigation was to examine the ergogenic potential of caffeine, carbohydrates, and cooling strategies in tennis. In addition to stroke velocity and accuracy quantification, measurement of serve kinematics, perceptual skill, and an ecologically valid experimental protocol were key methodological features designed to extend the existing literature. It was hypothesised that the interventions would counteract the various manifestations of match fatigue, in concert preventing deterioration of skills central to tennis success or ultimately enhancing performance. It was envisaged that this information would appeal to the wider audience (scientists, coaches and athletes) through provision of evidence-based support for the use of these common practices in preparation for or during tennis training and match play.

Methodology

Participants

Twelve highly trained, male tennis players (mean ± *SD* age 18.3 ± 3.0 yr; height 178.8 ± 8.5 cm; body mass 73.95 ± 12.30 kg; sum of seven skinfolds 62.3 ± 20.9 mm) participated in the investigation. Two of the participants were 2004/2005 Australian Institute of Sport tennis scholarship holders and were ranked within the top 600 ATP players. Participants trained at least 15 – 20 hr per week and had at least 5 years of competitive tournament experience. The professional players, who took part during their out-of-competition phase, trained at least 32 hr per week. It was desirable, but not essential, that participants possessed a current or former world ranking (junior or senior). Participants (and parents) received explicit details of the experimental protocol before voluntarily providing written informed consent. The study was reviewed and approved by the Australian Institute of Sport Ethics Committee and the University of Ballarat Ethics Committee.

Preliminary Testing

Prior to experimental trials, 8 of the 12 participants performed the national fitness testing battery. Details of the tests are described previously (see Chapter 3, *Physical Capacity Testing*). Tests were conducted to explicitly describe participant demographics and for comparative purposes with the cohort of professional tennis players who participated in Investigation 1; results are presented in Table 4.1.

Table 4.1

Anthropometric and Tennis-Specific Physical Characteristics of the Highly Trained Tennis Players who Participated in the Investigation

Participants	Age (y)	Weight (kg)	Height (cm)	Sum 7 (mm)	Body Fat - Sum 6 (%)	VJ - Double (mm)	VJ - Right (mm)	VJ - Left (mm)	Agility - Lat R (s)	Agility - Lat L (s)	Agility - Hex (s)	Agility Endurance - Mean (s)	Agility Endurance - % Dec	Sprints - 5 m (s)	Sprints - 10 m (s)	Sprints - 20 m (s)	Sprints - 5 m Back (s)	MedBall Throw - Right (m)	MedBall Throw - Left (m)	MedBall Throw - Overhead (m)	Serve Speed - Mean In (kph)	Forehand Speed - Mean 5 (kph)	Backhand Speed - Mean 5 (kph)	Beep Test (Level)	Beep Test (Shuttle)	Beep Test (Decimal)	VO_{2max} Predicted ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$)
1	19.9	73.50	180.5	39.8	6.5	59	47	47	2.20	2.28	10.67	17.31	2.3	1.08	1.85	3.13	1.26	19.20	20.20	16.3	195	149	141	14	7	14.54	62.4
2	19.1	73.85	180.3	49.2	7.4	64	50	46	2.17	2.23	11.63	17.87	4.3	1.06	1.76	2.98	1.12	24.00	22.30	15.5	192	139	140	12	12	13.00	57.1
3	15.1	61.10	164.2	51.4	7.5	50	38	40	2.35	2.42	10.03	17.69	5.0	1.13	1.94	3.35	1.19	16.30	16.00	14.5	162			12	6	12.50	55.4
4	15.0	64.65	179.0	56.7	8.2	45	24	34	2.53	2.48	10.34	18.53	2.3	1.24	2.01	3.38	1.32	16.00	15.40	11.5	163						
5	14.5	50.50	160.8	40.0	6.5	50	38	30	2.35	2.45	9.37	17.53	1.4	1.20	2.05	3.52	1.25	13.75	12.20	11.7	154			13	12	13.92	60.3
6	25.4	75.75	175.0	88.1	11.3	60	39	41	2.44	2.40		18.84	2.3	1.15	1.91	3.21	1.28	16.60	17.60	14.00	146	117	99	12	1	12.08	54.0
7	23.0	86.95	182.3	100.6	12.6	54	31	30	2.58	2.63		20.66	6.3	1.25	2.12	3.55	1.48	17.70	17.00	14.50	168	130	122	7	5	7.50	38.1
8	16.2	76.40	185.5	64.8	8.9	53	37	38	2.39	2.40		17.88	3.3	1.05	1.81	3.15	1.30	13.65	13.70	13.0	157	127	125	11	2	11.17	50.8
Mean	**18.5**	**70.34**	**176.0**	**61.3**	**8.6**	**54**	**38**	**38**	**2.38**	**2.41**	**10.41**	**18.29**	**3.4**	**1.15**	**1.93**	**3.28**	**1.28**	**17.15**	**16.80**	**13.8**	**167**	**132**	**125**	**12**	**6**	**12.1**	**54.0**
St. Dev	4.1	11.18	8.9	22.2	2.3	6.3	8.2	6.6	0.1	0.1	0.8	1.1	1.7	0.08	0.12	0.20	0.10	3.33	3.29	1.7	18	12	17	2	4	2.3	8.0
Min	14.5	50.50	160.8	39.8	6.5	45.0	24.0	30.0	2.2	2.2	9.4	17.3	1.4	1.05	1.76	2.98	1.12	13.65	12.20	11.5	146	117	99	7	1	7.5	38.1
Max	25.4	86.95	185.5	100.6	12.6	64.0	50.0	47.0	2.6	2.6	11.6	20.7	6.3	1.25	2.12	3.55	1.48	24.00	22.30	16.3	195	149	141	14	12	14.5	62.4

Note. Only 8 of the 12 participants completed the testing battery (partially or in-full). Hex = Hexagon test; Lat L = Lateral left; Lat R = Lateral right; % Dec = Percent decrement; Sum 6 = Sum of six skinfolds; Sum 7 = Sum of seven skinfolds; VJ = Vertical jump.

Testing Protocol

Investigation 1 revealed a number of limitations of *in situ* performance assessment. The accuracy, reliability and validity of performance measures were confounded by variable match intensity and duration, environmental conditions, and ability of the opposing player. For this investigation, the aim was to extend on the methods of previous researchers who attempted to identify the effects of fatigue and fatigue-resisting strategies on tennis performance in a simulated and controlled setting (E. R. Burke & Ekblom, 1982; Davey et al., 2002, 2003; Ferrauti et al., 1997; Magal et al., 2003; Mitchell et al., 1992; Struder et al., 1999; Vergauwen, Brouns et al., 1998; Vergauwen, Spaepen et al., 1998). These researchers suggested that fatigue is detrimental to tennis performance; but, the specific locus of fatigue has not been articulated, and in all cases a one-dimensional approach to performance assessment is evident. Several investigators attempted to employ interventions to minimise or eliminate performance impairment; however, the findings are fraught with contention as reported in Chapters 1 and 2.

The prolonged simulated tennis match - 4 sets (~2 hr 40 min) - was developed using match statistical data obtained during Investigation 1 (Figure 4.1 illustrates the timeline of the testing protocol; see page 102). Participants presented to the testing area (National Tennis Centre, Melbourne Park, Australia), prior to commencing the study and received explicit detail of all experimental procedures. After obtaining voluntary written consent, anthropometric profiling and familiarisation with testing devices was conducted. At this stage, participants were informed of the strict dietary and training controls that were enforced prior to each testing session. Participants were instructed to consume no caffeine during the 24 hr prior to testing. Participants kept a 24-hr dietary and training record and replicated this prior to each session. Participants were encouraged to consume 500 ml of water immediately prior to presentation at the testing area to encourage euhydration. All participants had prior exposure to hitting against a ball machine; thus, it was deemed that a 5-min warm-up period, prior to commencing each experimental trial, was sufficient for familiarisation. Experimental sessions firstly involved participants participating in the appropriate intervention or placebo strategy and being fitted with all measuring devices. Baseline physiological measurements (heart rate [HR], core body temperature [T_C], thermal sensation [TS]) were then collected, as well as collection of capillary (blood glucose [BGL], blood lactate [BLa], creatine kinase [CK]) and venous (prolactin) blood samples; details of procedures are described subsequently. Once all measuring devices were fitted, blood samples were obtained and the standardised 30-min resting/cooling period had elapsed, participants were then accompanied to the court to commence the experimental protocol.

Once courtside, participants sat and performed the perceptual skill test, followed immediately by a standardised 5-min warm-up in accordance with the rules of the International Tennis Federation (ITF, 2004). The warm-up involved approximately 3 min of “hitting up” against the ball machine, where participants performed several types of forehand and backhand groundstrokes. Participants subsequently served at increasing intensities and familiarised themselves with the target area until the 5-min period had elapsed. On completion of the warm-up, physiological (HR and T_C) and subjective (rating of perceived exertion [RPE] and TS) responses were recorded; details of the RPE and TS scales are described below (see *Subjective Analyses*). Participants then performed six first serves (see *Performance Assessment*) from the deuce court, before commencing the first of 12 games comprising the simulated match.

Each simulated match followed an identical protocol and was separated by 48 hr to 7 days. Trials differed only by the experimental strategy employed, to which participants were blinded (except for the cooling trial, see *Simulated Match Experimental Strategies*). Interventions were implemented ultimately to counteract performance decrements occurring during prolonged matches. Mechanistically and logistically, interventions were selected based on the potential to attenuate physiological, metabolic and neural perturbations, their feasibility for application during a tennis match and previous or current usage by professional tennis players.

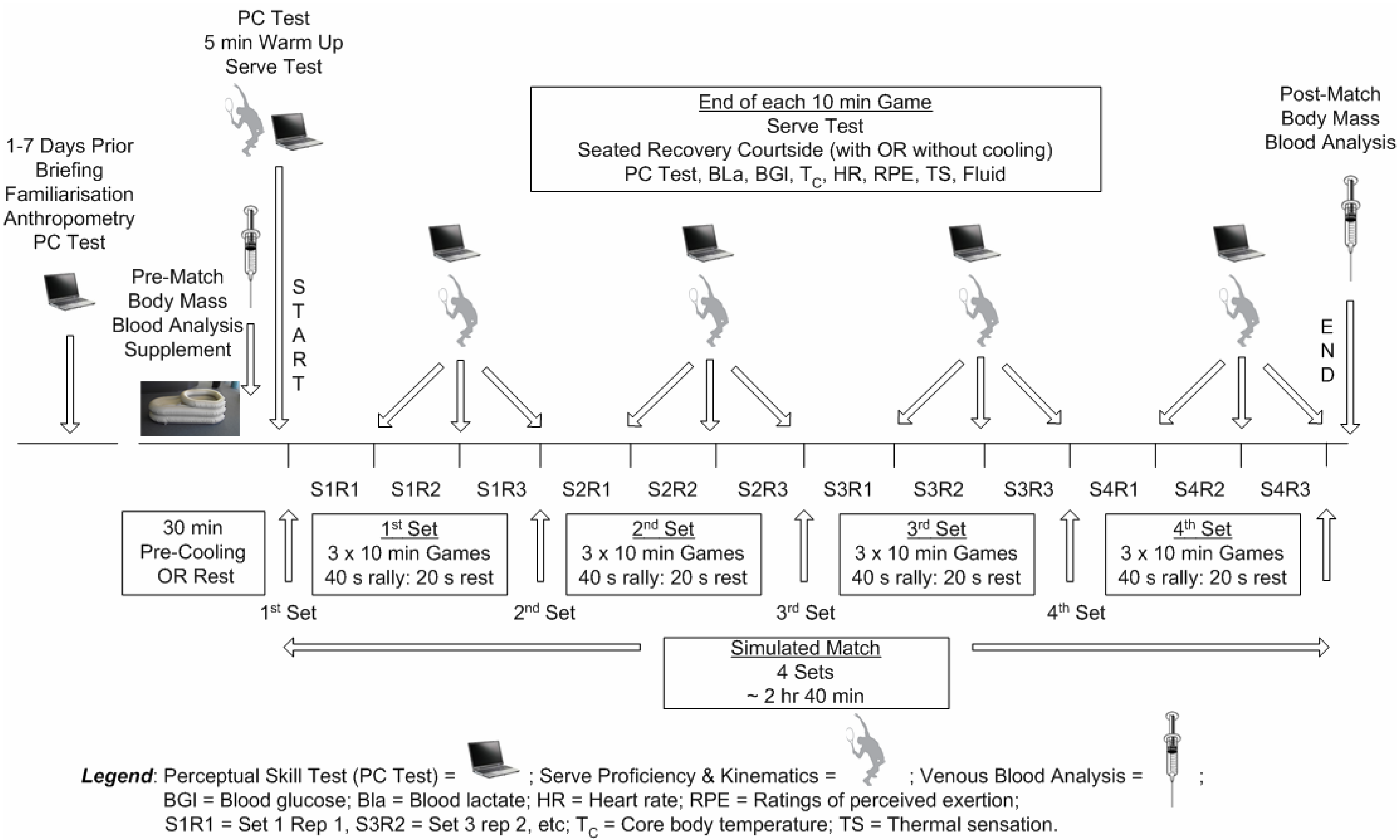

Figure 4.1. A schematic illustration of the testing protocol.

The protocol, first rally, and first set commenced with the ball machine projecting 17 tennis balls in a pre-programmed random sequence over a duration of 40 s. The balls landed approximately 1.5 m to the left and right of the centre mark of the baseline, and at a depth approximating the midpoint between the baseline and service line. The participants' role was to return the balls to designated areas at the opposite end of the court (Figure 4.2). Participants were given a different hitting sequence prior to each game (e.g., cross court only, one shot to the left two shots to the right, etc.). On completion of the rally, participants rested at the baseline for 20 s, after which the next 40 s rally immediately commenced. This process continued until 10 rallies were completed (10 min). Thereafter, players served six first serves then sat and recovered courtside for 90 - 120 s (essentially a change of ends). During this time participants performed a computer-based return of serve test to examine perceptual skill. Physiological variables were recorded (T_C, HR, RPE and TS) and experimental strategies were applied. Once all required parameters had been recorded, participants were informed of the next hitting sequence then walked to the baseline and commenced the subsequent 10-min groundstroke assessment. Therefore, one "game" (~13-min block) comprised: groundstroke performance assessment (~10 min: 40-s rally, 20-s rest); first serve analysis (6 serves, ~1 min); perceptual skill test (12 trials, ~90 – 120 s, also recovery). Three completed games constituted one "set" and four sets constituted the simulated match. The successive sets replicated the format of the first set, with the only variation being the instructions to players regarding the direction balls were to be returned. Participants were instructed to attempt to maintain an intensity equivalent to that during match play.

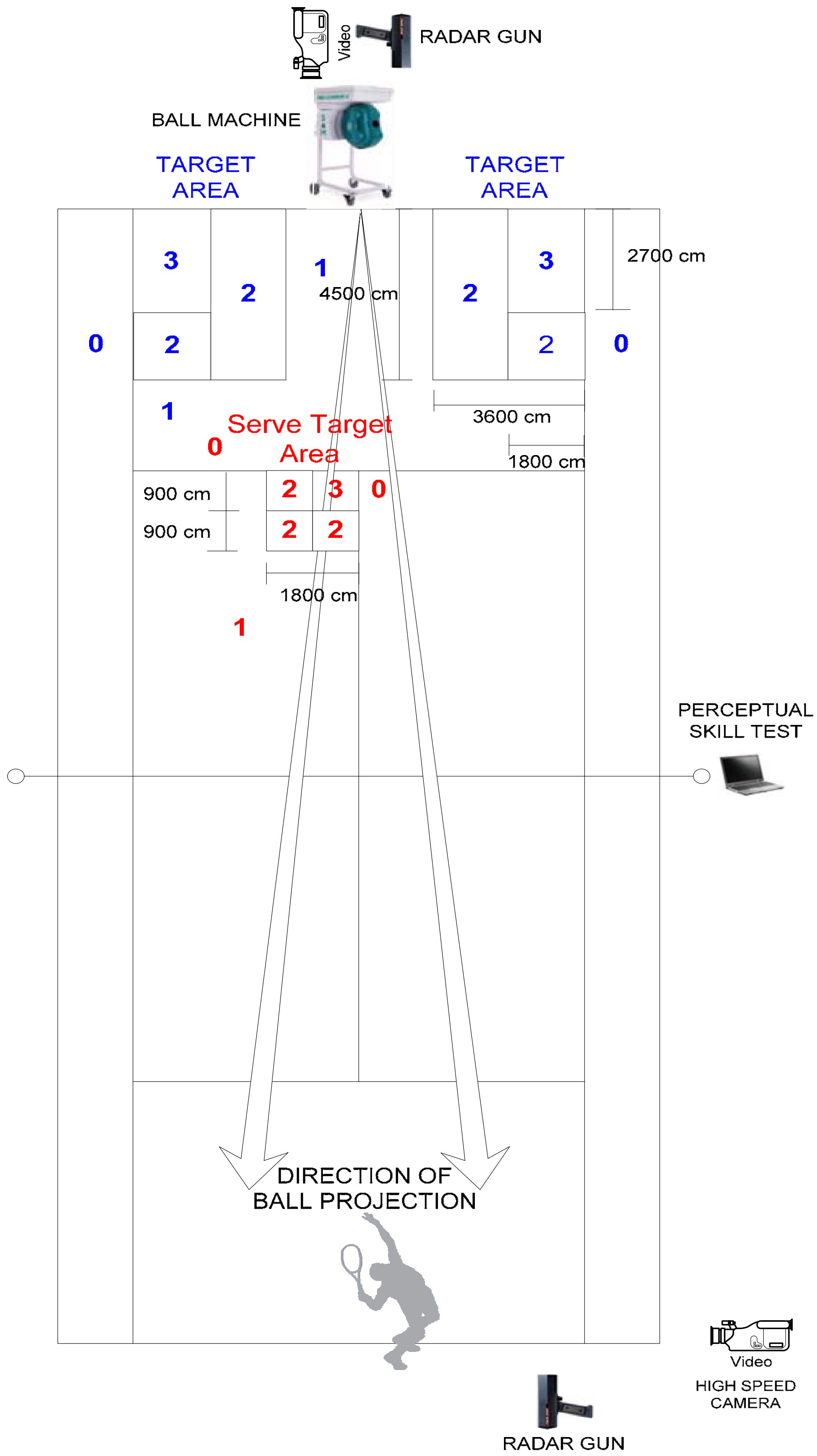

Figure 4.2. A schematic representation of the tennis performance test and target area dimensions.

The work-to-rest ratios of the experimental protocol were set in attempt to simulate the recovery periods of tournament matches conducted in accordance with the rules of the ITF; that is, 90-s recovery after every second service game from completion of the third game, and 120 s between sets (ITF, 2004). Additionally, players performed the recovery period between games and sets seated at the side of the court, as they would during a match. The rationale in selecting the duration of rally lengths (40 s), sets (~40 min) and the experimental protocol (~2 hr 40 min) was deduced from results of Investigation 1 and the previous work of Hughes and Clarke (1994) and O'Donoghue and Liddle (1998a). These authors reported notational analyses of Grand Slam tournament matches played on grass (Wimbledon, 1992), and synthetic (Australian Open, 1992) surfaces. To ensure the protocol induced physiological perturbations similar to those experienced under match conditions the rally duration was selected towards the longer end of the scale. Additionally, the experimental protocol reflected the average duration of a four set match played on a synthetic court.

Protocol and Intra-Rater Reliability

Three participants completed two PLA trials for the purpose of determining reliability of the protocol. Similar to the experimental trials, reliability trials were separated by at least 48 hr. Participants were blinded to the nature in which the trials were conducted (i.e., placebo-control or intervention). The relative typical error of measurement (TE%) for each environmental, physiological and performance characteristic was calculated by comparing the values recorded during both PLA trials, and is later presented in each respective section. Additionally, intra-rater reliability tests were conducted on performance measures that were subject to error during the recording process. The intra-rater value (TE%), herein presented in relevant sections, was calculated by selecting the performance measures of six participants and twice conducting the analysis. This value reports the measurement error of the tester and was conducted for the temporal analysis of the serve and groundstroke accuracy.

Performance Assessment

Serve and groundstroke velocity and accuracy.

During each experimental trial, a number of elements indicative of stroke quality were measured. The elements included ball velocity and ball landing proximity to sidelines (in this instance target areas), both of which are considered important markers of performance (Vergauwen, Spaepen et al., 1998). Velocity was recorded in real time during each trial and accuracy was recorded retrospectively from video footage. For this procedure, a VHS camera (Panasonic MS5, Australia), positioned to film the entire court, captured the duration of each trial. The intra-tester reliability for the retrospective analysis of groundstroke accuracy was 1.47%.

Accuracy analysis.

The accuracy scores for both serve and groundstrokes were determined by counting the number of times the ball landed within the designated target perimeter (exact measurements of both target areas are presented in Figure 4.2). Target dimensions were designed considering similar methodologies, available resources, through discussion with coaches and athletes and preliminary trials. Shots landing within the court perimeter and target areas were ranked according to a 3, 2, 1 scoring system (see Figure 4.2, page 104). Balls failing to pass over the net or landing outside the perimeter of the court (i.e., errors) received a 0 score. A total score, expressed as a percentage of the maximum, was recorded for each game. As illustrated in Figure 4.2 (page 104), the target area for serve was inside the intersection of the service line and the centre line. Participants served from the deuce court and were instructed to “serve first serves flat and down the T”.

Groundstroke performance assessment required participants to hit ball machine-fed balls to targets positioned inside the intersection of the singles sideline and baseline on both the right- and left-hand sides of the court. The ball machine (SAM Millennium II, Maximum Sports, Victoria), utilised to ensure protocol standardisation and repeatability, was positioned on the baseline at the opposite end of the court to the player. New tennis balls (Slazenger Hydroguard Ultra VIS, Dunlop Sport Equipment, Regents Park, Australia) were projected in a pre-programmed sequence, at approximately 100 kph. Tennis balls were replaced after either being used during four successive trials or after seven days had elapsed. Ideally, balls should have been replaced after each trial, but a limited research budget did not afford this luxury. Given that ecological validity is compromised in a field research setting, an attempt was made to ensure a level of a cognitive demand throughout the protocol. Ball feeds were randomised in direction, but instructions to participants regarding the direction of returned strokes were fixed, either; (1) down the line only, (2) cross court only, (3) two shots to the right and one to the left or (4) one shot to the right and two to the left. This procedure ensured that players maintained a degree of concentration and that a variety of forehand and backhand strokes were performed.

Velocity analysis and radar specifications.

Peak velocity of first serves and groundstrokes (that is, peak ball velocity measured post racquet-ball impact) was measured using multiple radar guns (Stalker Professional Sports Radar, Radar Sales, Plymouth, MN). Radar guns were set on “Peak mode” to detect maximal ball velocity between the range of 80 to 232 kph. Before each experimental session, the radar guns were calibrated in accordance with the manufacturer's specifications. For assessment of serve velocity the radar was positioned on the centre of the baseline at the opposite end of the court to the server, aligned with the approximate height of ball contact (~2.2 m), and pointing down the centre of the court. Equipment restraints meant that it was only possible to measure forehand groundstroke velocity. For this measurement the radar gun was positioned on the forehand side of the court, behind the participant. The radar was mounted on a tripod 1.3 m above the ground, 3 m behind the baseline, 1.5 m inside the singles sideline and pointed at net height down the singles sideline.

Instructions to participants.

Participants were instructed to attempt to maintain an intensity equivalent to that which they would produce under real match conditions. Participants were therefore discouraged from pacing, despite prior knowledge of the prolonged duration of the protocol, as this is not reflective of match play and may be a mechanism of delaying physiological perturbations. Participants were permitted to hit topspin or slice groundstrokes, however they were informed of the implications to velocity of hitting with slice rather than hitting topspin. Figure 4.3 illustrates one of the participants performing the groundstroke proficiency test.

Figure 4.3. A participant performing the groundstroke proficiency test.

Serve kinematics.

To gain further insight into how serve characteristics are affected by physiological perturbations, building on the findings of Investigation 1, a quantitative temporal analysis of the serve was conducted. The players' first serve service action was captured on high-speed video, downloaded and converted to video files. The files were subsequently viewed using a sport analysis tool (Swinger Plus, Webbsoft Solutions, Melbourne, Australia) and divided into the following temporal phases. Figure 4.4 illustrates the specific moments in the service action that defined the start and end of each phase.

- Phase 1 = Preparation to ball release (from the moment the ball leaves the shaft of the racquet to moment the ball is released from the hand).
- Phase 2 = Ball release to maximum height of the ball toss.

- Phase 3 = Maximum height of the ball toss to racquet-ball impact.
- Phase 4 = Racquet-ball impact to follow through (from the moment the racquet contacts the ball to the moment the racquet head passes the left leg, for a right-handed participant).
- Phase 5 = Entire serve sequence (from the moment the ball leaves the shaft of the racquet to the moment the racquet head passes the left leg, for a right-handed participant).

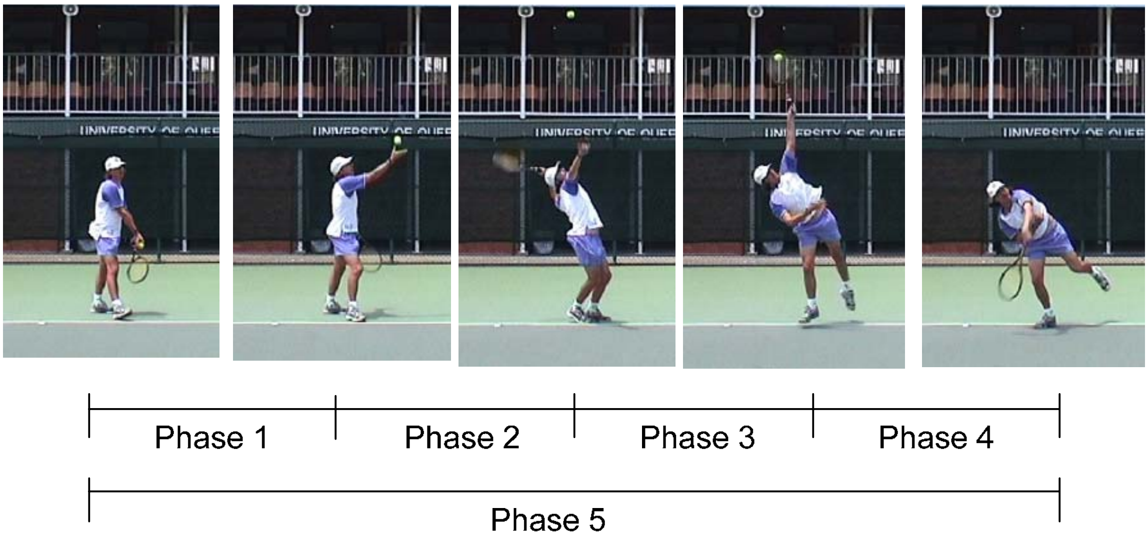

Figure 4.4. An illustration of the five phases used to conduct the serve temporal analysis.

Individual idiosyncrasies in preparation and follow through meant that phases 1, 4 and 5 were generalised in the above statements. Hence, specific characteristics of initiation and completion of the serve, pertaining to each participant, were identified prior to analysis. By dividing the serve into sections, frames were then counted to determine the length of each respective phase and the total duration of the serve. The intra-tester reliability for this procedure was 1.54%. This method of assessment was preferred to the qualitative technique analysis used in Investigation 1, as it eliminated the subjectivity and it produced quantitative measurements of serve kinematics. More elaborate three-dimensional modes of analysis could not be feasibly conducted during the data collection phase, simply due to the availability of equipment and a trained biomechanist. The temporal analysis was therefore based on motor control literature which infers that, with fatigue, the coordination and timing of motor patterns is susceptible to impairment (Apriantono, Nunome, Ikegami, & Sano, 2006; Johnston, Howard, Cawley, & Losse, 1998). Phases 2 and 3 represent the racquet-arm acceleration phases. It was proposed that a lengthening of these phases would indicate reduced racquet-head velocity, and thus a reduction in serve speed (potentially caused by physiological perturbations). This would decrease the advantage afforded to the serve and increase an opponent's capability to execute an effective return of serve. At present, very little research has been conducted on the effects of fatigue on racquet skills (Lees, 2003). It is envisaged that this fundamental research will generate further exploration of the field.

Footage was captured using a high-speed digital video camera (Phantom, USA) which recorded at a rate of 100 frames per second. The camera was mounted on a tripod 1.5 m above the ground and placed along an imaginary extension of the baseline, viewing the anterior plane of the participant during the service action. Figure 4.5 illustrates the positioning of the high-speed camera and a participant performing the serve test.

Figure 4.5. Positioning of the high-speed camera and setup for the serve kinematic analysis.

Perceptual skill.

This test was designed to measure tennis-specific perceptual skill processes and how they respond to physiological perturbations and potential ergogenic strategies. Developed specifically for tennis, the test possessed greater ecological validity than non-sport specific numeracy and literacy tests of cognition. Participants viewed 12 clips, displayed on a laptop computer screen, of a professional player serving. The footage was captured from the perspective of a player attempting to return the serve. The participant was instructed to assume the role of a receiving player and attempt to anticipate the direction of a serve from the footage shown.

Two temporal conditions were presented to manipulate the time available to the participant to predict the direction of the serve. One condition presented the complete service action, where the image was occluded as the ball passed over the net, while the other condition occluded the vision at the point of racquet-ball contact. Participants used the computer mouse to click on the side of the service box they believed was the intended service direction. A response accuracy percentage was then generated from the 12 trials presented (six randomly ordered trials of each occlusion condition). Five equally challenging tests (12 trials in each) were used to avoid the possibility of participants recalling answers.

The underlying skill inherent to this task is the ability to identify the direction of an oncoming serve, using salient postural and technical cues presented by the server prior to impact. These skills are critical to the return of serve in that they allow elite players more time for response selection and stroke execution. The test was performed prior to commencement of the warm-up component of the simulated match and on completion of each game and set thereafter. Each time the test was performed, participants were seated at the side of the court as if resting during a game or set break (see Figure 4.6). The test took approximately 90 s, which is equivalent to the allocated time between games in a tournament match. In this time participants were also permitted to drink allocated beverages. Attempts were made to minimise distractions to the participant while the perceptual test was performed.

Figure 4.6. A participant performing the perceptual skill assessment.

Simulated Match Experimental Strategies

Participants performed the simulated match on four occasions, each time using a different experimental strategy. The four trials (1 x placebo-control and 3 x interventions) were conducted in counterbalanced order. Participants were blinded to three of the four trials performed (placebo-control, caffeine, carbohydrates) however the selected cooling intervention did not permit complete masking. No indication of performance or experimental strategy used was revealed until participants completed all trials.

Placebo-control trial.

Participants presented to the Melbourne International Tennis Centre on the day of the trial having prepared as for a normal match. Upon arrival participants' upon-waking urine sample was collected, they were weighed nude then rested on a massage table for 30 min. The 30-min pre-match resting period was standardised across trials, in accordance with the 30-min pre-match cooling procedure performed during the cooling trial. Heart rate, T_C, and TS were recorded every 5 min throughout the resting period. Pre-trial capillary and venous blood samples were collected and a gelatine capsule, containing a caffeine placebo was ingested. Prior to breakfast on the day of the trial or during the night on the eve of each trial, participants ingested a core temperature capsule for analysis of core body temperature (refer to Investigation 1 "*Procedure Measures*" for details; page 59).

Measurement of nude body mass was self-performed in an internally locked room, so there was no risk of invasion of privacy. Participants were instructed to record the exact measure of body mass that appeared on the electronic scales (UC-300 Precision Health Scale, AND Mercury Pty Ltd, South Australia). The measured blood parameters, obtained from capillary samples, included BGL, CK, and BLa. Prolactin (PRL), measured as a surrogate index of central fatigue, was analysed from venous blood. Urine was analysed for specific gravity as a marker of pre-match hydration status. The procedure was conducted using a Digital Urine S.G. Refractometer (UG-1, Atago Co. LTD, Tokyo, Japan). In addition to measuring each variable pre- and post-match, BLa, BGL, HR, T_C, RPE and TS were monitored throughout the simulated match.

Following collection of pre-exercise data participants proceeded immediately to the indoor court, which was set up as detailed previously and illustrated in Figure 4.2 (page

104). Prior to commencing the standardised warm-up and simulated tennis match, participants performed the perceptual test. During periodic breaks in play, that is game and set breaks, the perceptual test was performed prior to assessment of subjective (RPE and TS) and physiological responses (BLa, BGL, HR, T_C). Measurements were conducted within the designated 90 - 120 s period between games and sets. Participants then proceeded to the baseline to commence the subsequent groundstroke assessment.

In the event that participants required a toilet break during the simulated match, they were permitted one in accordance with the regulations of the ITF (ITF, 2004). The stoppage could occur only during a set break and participants were weighed pre and post to account for faecal and urinary losses in the calculation of pre- and post-match body mass changes.

Over the course of each trial, in order to maintain hydration status, participants were given a calculated volume (14 $ml \cdot kg^{-1} \cdot hr^{-1}$) of fluid (a carbohydrate beverage or placebo) to consume. Those participants who ingested greater or less than the calculated fluid volume in their initial trial, were given that exact volume in each subsequent trial.

On completion of the protocol participants walked back to the laboratory where nude body mass, capillary and venous blood sampling were conducted. Environmental conditions were monitored every 5 min throughout the trial using a portable digital weather tracker (Kestrel 4000, Nielsen-Kellerman, Australia).

Pre- and intermittent-cooling trial

Procedures for the cooling trial were identical to those of the control trial, except that participants performed a pre-match cooling manoeuvre and were cooled during game and sets breaks. The intervention was employed to attenuate perturbations in core body temperature that were reported during tennis matches played in moderate environmental conditions (Investigation 1) and in the literature (Therminarias et al., 1994). A number of the participants in Investigation 1 experienced core body temperatures in excess of 39.0 °C, in both temperate and intemperate conditions. Researchers have reported impaired cognitive function and task performance (i.e., information processing, attention, perceptual function, reaction time), as thermal stress intensifies (Gonzalez, 1997; P. A. Hancock, 1993; Razmjou, 1996). Perceptual-cognitive skills underpin functional tennis performance. As the playing environment is often intemperate, offsetting core temperature perturbations should sustain the proficiency of functional and cognitive performance parameters.

On presentation to the laboratory participants were weighed nude and fitted with a HR monitor prior to full-body water immersion in an inflatable plastic plunge pool (Figure 4.7). The plunge pool (Portacovery™, Canberra ACT, Australia) held approximately 420 L of water and its dimensions were 1.6 m x 0.6 m x 0.8 m. Participants sat submersed in water, to the level of the sternum, for 30 min. The water temperature, continuously monitored with a Testo 781 thermometer (Testo Term, Germany), was progressively reduced over the 30 min period from 29 °C to 24 °C by the addition of ice to the bath. Heart rate, T_C, and TS were recorded every 5 min during the immersion. On completion of the cooling period participants towelled dry, changed into tennis attire and all remaining preliminary physiological measurements were conducted. Participants then proceeded to the court where they commenced the simulated match as previously described.

Figure 4.7. The portable ice bath used to pre-cool participants, prior to commencing the simulated match.

During every periodic recovery, between games and sets, participants were cooled using a waist length, sleeveless, cooling jacket and hood (RMIT, Melbourne, Australia). The jacket and hood (Figure 4.8) were constructed from a polyester blend outer shell with a phase-change material (PCM) sewn on the inside. The PCM changes form, from liquid to solid (i.e., phase-change), at a temperature of 20 °C. Both were frozen overnight, removed from the freezer as the participant completed the water immersion period, then stored courtside in an ice-packed esky for the duration of the trial. The jacket and hood were applied immediately as players reached the side of the court, after completing the 10 min bout of hitting and serving six first serves. The cooling devices, applied over the shirt and directly on the head, were removed after the perceptual test had been completed and the physiological and subjective measures were recorded (90 – 120 s). The jacket and hood were then returned to the esky to ensure that the PCM maintained its cooling capacity for the duration of the protocol.

Figure 4.8. The cooling jacket and hood worn by participants during game and set breaks.

Carbohydrate supplementation trial.

The procedures for the CHO trial were identical to those of the PLA trial. The only (masked) difference being that participants consumed a commercially available CHO-loaded beverage**,** Lemon Lime flavoured Gatorade® (Pepsico Australia Holdings Pty Ltd., Sydney, Australia), instead of the placebo fluid. Gatorade® was supplied in a powder form and made-up according to the instructions on the packet, so that participants consumed a 6% CHO solution. The calculated fluid volume was made-up on the day prior to the trial and fridge-stored overnight. During all other trials participants consumed a flavoured placebo substance, Gatorade® Lemon Lime Placebo (Pepsico Australia Holdings Pty Ltd., Sydney, Australia). Participants were unable to discriminate between placebo and CHO beverages. In concert with the CHO supplement, the placebo was also supplied in powder form and was made-up according to the instructions on the packet, on the night prior to the trial.

The CHO intervention was primarily employed to offset the incidence of hypoglycaemia. As an adjunct, the volume of fluid prescribed (14 $ml \cdot kg^{-1} \cdot hr^{-1}$) minimised body mass deficits and prevented significant dehydration. Episodes of both conditions (hypoglycaemia and dehydration) have been previously reported in competitive tennis environments (Ferrauti et al., 2003; McCarthy et al., 1998). The need to offset the occurrence of dehydration in particular, is evidenced through the findings of Gopinathan et al. (1988) who previously established that fluid loss equivalent to a deficit of only 2% body mass has the capacity to induce impairments in mental performance. Body mass deficits in excess of 2% were recorded during Investigation 1 of this thesis, emphasising the need to implement strategies of this nature and offset excessive body fluid losses.

Caffeine supplementation trial.

The procedures for the CAF trial were identical to those of the PLA trial, except that participants ingested caffeine instead of a placebo supplement prior to commencing the simulated match. The current pre-exercise caffeine dosage recommended by the AIS Department of Nutrition, and administered in this investigation was 3 $mg \cdot kg^{-1}$ of body mass. The caffeine supplement used in the current investigation was Nō-Dōz® Awakeners (Key Pharmaceuticals Pty Ltd, Rhodes, Australia), a commercially available and doping agency approved caffeine supplement (Australian Sports Anti-Doping Authority and AIS

Supplementation Information Scheme). This modest dosage is equivalent to consuming 1 – 2 cups of coffee and has previously been shown to possess ergogenic properties without inducing adverse side-effects (Magkos & Kavouras, 2004). The dosage utilised is far below that administered in previous investigations (6 – 9 $mg \cdot kg^{-1}$) where participants had an increased likelihood of experiencing ill effects, such as anxiety, insomnia, tachycardia and cramping, from the superfluous supplementation (Birnbaum & Herbst, 2004). It should also be noted that the ergogenic properties of caffeine are non-dose dependant (Graham & Spriet, 1995).

Participants consumed the supplement upon presentation to the laboratory, approximately 30 – 45 min before commencement of the simulated match. This time span ensured peak levels remain in the blood until completion of the trial; note the purported half-life of caffeine elimination from the plasma compartment is 3.5 to 8 hr post-oral ingestion (Haller, Jacob III, & Benowitz, 2002; Magkos & Kavouras, 2005). Caffeine and caffeine-placebo supplements (Polycose®, Ross Nutrition, Abbott Laboratories, Ohio, USA) were ingested in a gelatine capsule.

Blood Analyses

Venous blood samples (10 ml) were collected into clot activating/serum separator tubes, before and after the experimental protocol. Samples were extracted from a superficial vein from the Cubital Fossa of the forearm using the Vacutainer system. Samples subsequently sat upright, at room temperature, until centrifuged at 4500 revolutions per minute for 6 min. Following centrifugation, and frozen storage (- 20 °C) for up to three months, the supernatant was removed and analysed for PRL concentration. The analysis was performed using an Immulite (Diagnostic Products Corporation, Los Angeles, California, USA). Peripheral PRL concentration has formerly been acknowledged as a surrogate index on central serotonergic activity (Yatham & Steiner, 1993) and an indirect measure of central fatigue. In this instance PRL was sampled to assess its proliferation during prolonged match play and primarily to measure the efficacy of interventions to mitigate the response. Blood lactate and blood glucose pre-, during-, and post-match measurements were analysed using a Lactate Pro (Arkray Factory Inc. Shiga Japan) and a HemoCue (Angelholm Sweden), respectively. Creatine kinase concentration, measured pre- and post-match, was analysed using a Reflotron (Roche Diagnostics, Indianapolis IN USA). Pre-exercise (baseline) blood samples were obtained 1 to 1.5 hr after participants consumed a standardised meal, presented to the testing area and rested supine for 5 min. Post-exercise samples were collected immediately after participants completed the final perceptual test, left the court and rested supine for 5 min in the blood analysis area. Prolactin intra-assay statistics were calculated for samples from the results of 20 replicates in a single run, the results are presented in the precision table (see Table 4.2).

Table 4.2

Prolactin Intra-Assay Reliability

Control Sample	mean ($u \cdot l^{-1}$)	*SD*	CV (%)
1	169.6	11.5	6.8
2	345.6	21.2	6.1
3	775.9	43.9	5.7

Note. SD = standard deviation; CV = coefficient of variation.

Subjective Analyses

Rating of perceived exertion.

The RPE 15-point scale (6 “minimal exertion” - 20 “maximal exertion”), modified from the original 10 point scale (Borg, 1970), measures the intensity at which the participant believes they are performing. Increasing numeric values, from 6 - 20, represent levels of intensity which have been shown to reliably correlate with increasing cardiovascular strain (Garcin, Wolff, & Bejma, 2003; Skinner, Hutsler, Bergsteinova, & Buskirk, 1973). When presented with the scale participants rated their whole-body level of exertion at that specific point in time.

Thermal sensation.

The thermal sensation scale (Young, Sawka, Epstein, Decristofano, & Pandolf, 1987) is a 17 point scale (0.0 to 8.0) which measures how cold, comfortable, or hot the participant perceives their body temperature to be. Numeric values represent comfort levels along the continuum, starting at 0.0 (unbearably cold) and increasing in half units to 8.0 (unbearably hot). When presented with the scale participants rated their whole-body level of comfort at that specific point in time.

Statistical Analyses

The experiment used a repeated measures design (with each participant undertaking one trial under each condition), with longitudinal data collected throughout each trial. The data were analysed using linear mixed modelling, with provision for fixed effects of trials and time, random effects for participants, and either constant correlation or autoregressive correlation between the random errors within each trial. For each dependent variable, model building was undertaken using maximum likelihood methods, and the parameters of the final model were estimated using restricted maximum likelihood (REML). Normality and homoscedasticity assumptions were checked by analysis of residuals, and where necessary logarithmic or other mathematical transformations were used to reduce skew and stabilise variance. This procedure was conducted to assess the differences in participant performance and physiological responses to the experimental strategies that occurred over the duration of the simulated match. Where overall significant differences were detected, subsequent Bonferroni-adjusted post-hoc analyses were conducted to determine the pattern of significance.

Data were analysed using SPSS for Windows™ version 12.0 (SPSS Inc., USA) and Microsoft® Excel XP (Microsoft Corporation, USA). Results are reported as mean ± standard deviation, unless stated otherwise, and significance was identified where $p < 0.05$. Effect sizes were also calculated for all measured variables. Inclusion of effect sizes complimented *p* values as an estimate of the magnitude of change in means. Interpretation of the magnitude of changes was conducted as previously described (Hopkins, 2002), with effect sizes of <0.2 classified as trivial, 0.2 – 0.6 as small, 0.6 – 1.2 as moderate, 1.2 – 2.0 as large, and >2.0 as very large. Protocol and intra-tester reliability was calculated using the relative typical error of measurement.

Results

The following tables (Table 4.3 and Table 4.4) present environmental, physiological and performance data (mean ± *SD*) measured over the course of each simulated match and compared across experimental conditions.

Table 4.3

Environmental Conditions and Physiological Responses during the Simulated Match

	Placebo	Carbohydrates	Caffeine	Cooling
Temperature (°C)	21.0 ± 4.8	21.6 ± 3.9	21.2 ± 4.6	21.0 ± 4.6
Relative humidity (%)	50.9 ± 12.0	50.5 ± 8.2	50.6 ± 11.0	49.7 ± 9.9
T_C resting (°C)	36.9 ± 0.3	36.8 ± 0.2	36.7 ± 0.3	37.1 ± 0.2
T_C exercising (°C)	37.6 ± 0.5	37.7 ± 0.4	37.7 ± 0.4	37.5 ± 0.4
HR resting (bpm)	67 ± 12	66 ± 12	65 ± 11	64 ± 11
HR exercising (bpm)	154 ± 14	154 ± 17	156 ± 14	156 ± 16
TS resting/cooling	4.0 ± 0.1	4.1 ± 0.3	4.0 ± 0.2	2.3 ± 0.6
TS exercising	5.5 ± 0.7	5.6 ± 0.9	5.4 ± 0.7	5.1 ± 0.6
RPE	14 ± 1	14 ± 2	14 ± 1	14 ± 1
BM pre (kg)	73.83 ± 12.45	73.74 ± 12.60	74.14 ± 12.45	74.26 ± 12.40
BM post (kg)	73.51 ± 12.36	73.60 ± 12.23	73.64 ± 12.07	74.10 ± 12.14
BM difference (kg)	0.33 ± 0.57	0.14 ± 0.58	0.50 ± 0.54	0.16 ± 0.58
BM change (%)	-0.4 ± 0.8	-0.1 ± 0.8	-0.6 ± 0.7	-0.2 ± 0.7
TFL (ml)	2818 ± 1089	2673 ± 920	3014 ± 1005	2687 ± 895
U_{sg}	1.022 ± 0.004	1.024 ± 0.004	1.022 ± 0.005	1.022 ± 0.006
Average BGL ($mmol \cdot L^{-1}$)	5.5 ± 1.5	5.9 ± 1.0	5.3 ± 0.7	5.1 ± 0.7
Average BLa ($mmol \cdot L^{-1}$)	1.3 ± 0.5	1.4 ± 0.4	1.3 ± 0.4	1.2 ± 0.4
CK pre-match ($U \cdot L^{-1}$)	220.6 ± 135.5	213.1 ± 147.8	214.1 ± 121.5	188.0 ± 100.0
CK post-match ($U \cdot L^{-1}$)	314.5 ± 120.3	301.4 ± 152.2	347.2 ± 174.4	310.8 ± 131.3
CK difference ($U \cdot L^{-1}$)	94.0 ± 121.4	88.3 ± 78.8	133.1 ± 110.6	122.8 ± 64.1
PRL pre-match ($U \cdot L^{-1}$)	254.8 ± 90.9	211.0 ± 79.7	243.6 ± 56.5	208.7 ± 99.3
PRL post-match ($U \cdot L^{-1}$)	258.2 ± 108.8	266.8 ± 118.3	313.1 ± 189.4	373.5 ± 399.6
PRL difference ($U \cdot L^{-1}$)	3.4 ± 98.0	55.8 ± 130.0	69.9 ± 180.6	164.7 ± 347.5

Note. Values presented are mean ± *SD*. Values for ambient temperature, relative humidity, core temperature (T_C), heart rate (HR), thermal sensation (TS), rating of perceived exertion (RPE), blood lactate (BLa) and blood glucose (BGL) are averaged over the duration in which they were recorded. BM = Body mass; CK = Creatine kinase; PRL = Prolactin; TFL = Total fluid loss; U_{sg} = Urine specific gravity.

Table 4.4

Measures of Tennis Performance Skills Averaged over the duration of the Simulated Match and Compared across Conditions

	Placebo	Carbohydrates	Caffeine	Cooling
Serve velocity (kph)	161 ± 15	160 ± 11	164 ± 14	161 ± 15
Serve accuracy (%)	26 ± 14	29 ± 15	28 ± 15	26 ± 13
Groundstroke velocity (kph)	120 ± 8	120 ± 7	120 ± 8	117 ± 7
Groundstroke accuracy (%)	36 ± 5	35 ± 5	36 ± 4	36 ± 5
Decision accuracy - occluded (%)	78 ± 23	77 ± 21	78 ± 23	79 ± 20
Decision accuracy - unoccluded (%)	82 ± 19	80 ± 20	81 ± 20	84 ± 19
Serve kinematics - Phase 1 (ms)	1581 ± 389	1562 ± 360	1542 ± 363	1572 ± 332
Serve kinematics - Phase 2 (ms)	1629 ± 218	1620 ± 225	1587 ± 226	1610 ± 232
Serve kinematics - Phase 3 (ms)	1095 ± 296	1090 ± 280	1050 ± 297	1077 ± 281
Serve kinematics - Phase 4 (ms)	652 ± 125	663 ± 149	651 ± 132	663 ± 136
Serve kinematics - Phase 5 (ms)	4957 ± 708	4932 ± 625	4825 ± 623	4939 ± 593

Note. Values presented are mean ± *SD*. Values for all variables represent averages over the duration in which they were recorded.

Environmental Conditions

Ambient temperature and relative humidity were recorded at 5 min intervals over the duration of the testing protocol. The between trial reliability for ambient temperature and relative humidity was 13.22% and 14.19%, respectively. Some small effect sizes were revealed, at a number of times over the duration of the experimental protocol, for inter-condition comparisons of both measures. When conditions were averaged over the course of the trial, only effect sizes of trivial magnitude were revealed. Means and effect sizes can be sourced from Appendixes N and O, ambient temperature and relative humidity respectively.

Ambient temperature.

Illustrated in Figure 4.9, ambient temperature increased in a linear fashion over the course of each trial. The average temperature in each condition is also presented in Table 4.3. Across all trials and conditions the ambient temperature averaged 21.2 ± 0.3 °C.

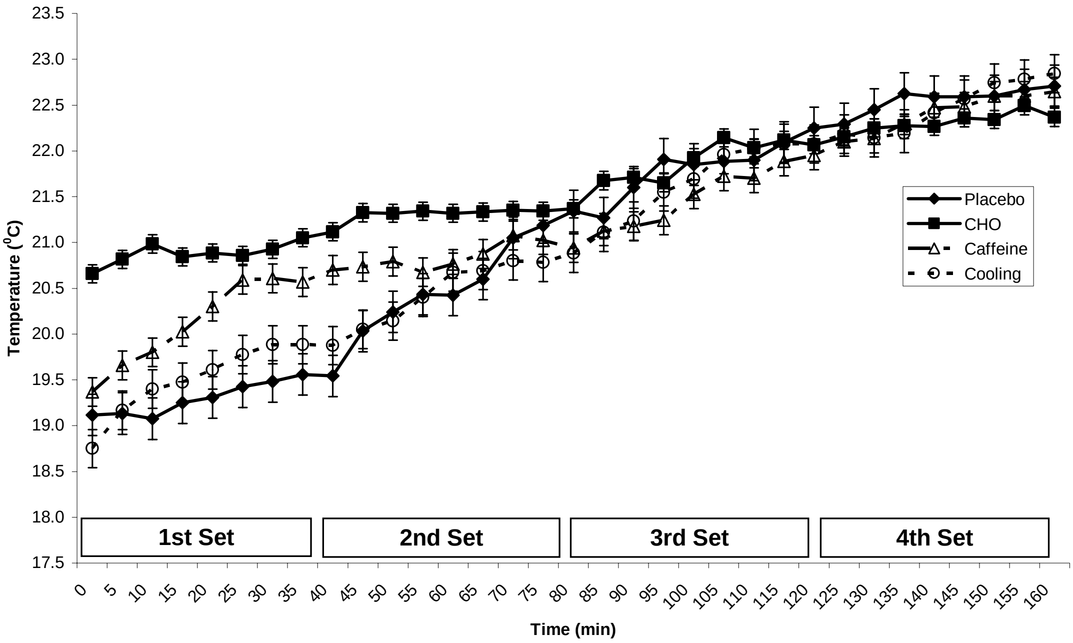

Figure 4.9. Ambient temperature over the duration of the simulated match. Values presented are mean ± *SE*.

Relative humidity.

Illustrated in Figure 4.10, relative humidity decreased in a linear fashion over the course of each trial. The average relative humidity in each condition is also presented in Table 4.3. Across all trials and conditions the relative humidity averaged 50.4 ± 0.5%.

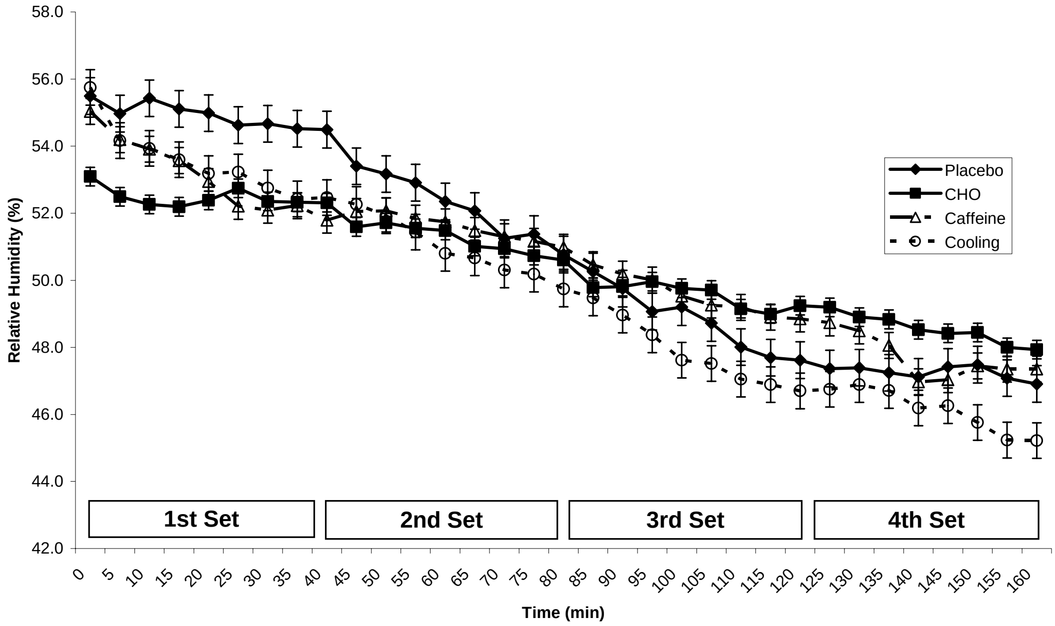

Figure 4.10. Relative humidity over the duration of the simulated match. Values presented are mean ± *SE*.

Physiological Responses

Physiological markers were measured for two purposes, first to verify the capacity of the devised simulated tennis match to induce responses similar to that observed under real match conditions and second to identify the effect of the experimental strategies on relevant physiological states.

Core body temperature.

Core body temperature was monitored every 5 min during the 30 min pre-match (resting or cooling) period, once post-warm-up, and during every standardised recovery period between games and sets thereafter. Due to the nature of the data, and the potential for interventions to affect both resting and exercising responses, herein, resting/cooling and exercise data were analysed individually. Reliability of T_C obtained over the course of the trial, however, was 1.01%. Figure 4.11 illustrates the T_C response during the resting/cooling phase and over the duration of the simulated match.

Resting.

Indicated in Figure 4.11, pre-match T_C was significantly higher ($p = 0.005$) when participants performed the pre-match cooling manoeuvre (average core temperature over the 30 min resting/cooling period was 37.1 ± 0.2 °C). However, the cooling procedure induced significant differences only when compared to the CHO (36.8 ± 0.2 °C, p = 0.014) and CAF (36.7 ± 0.3 °C, $p = 0.008$) conditions, not PLA (36.9 ± 0.3 °C, p = 0.225). Moderate, large and large effect sizes were recorded, for the PLA, CHO and CAF conditions (ES = -0.82, ES = -1.35, ES = -1.37, respectively), when the average pre-match T_C was compared against that of the cooling condition. Further statistical exploration also revealed a significant effect of time ($p = 0.019$) and a first order interaction of condition by time ($p = 0.012$).

During exercise.

Upon commencement of the warm-up, T_C in the cooling condition relative to the other conditions, decreased sharply although significant differences between conditions were not achieved. Evidenced in Figure 4.11 was the trend for T_C, in the cooling condition to remain slightly lower than other conditions until commencement of the second set, and this was supported statistically by examination of effect sizes (Appendix P). Comparisons of average T_C over the course of the simulated match produced small (*ES* = 0.26), small (*ES* = 0.57) and moderate (*ES* = 0.62) effect sizes for the PLA, CHO and CAF trials, respectively. The variables time and temperature also achieved statistical significance ($p < 0.01$ and $p = 0.014$, respectively) which is reflective of the metabolic cost of the prolonged exercise and the influence of environmental conditions on T_C.

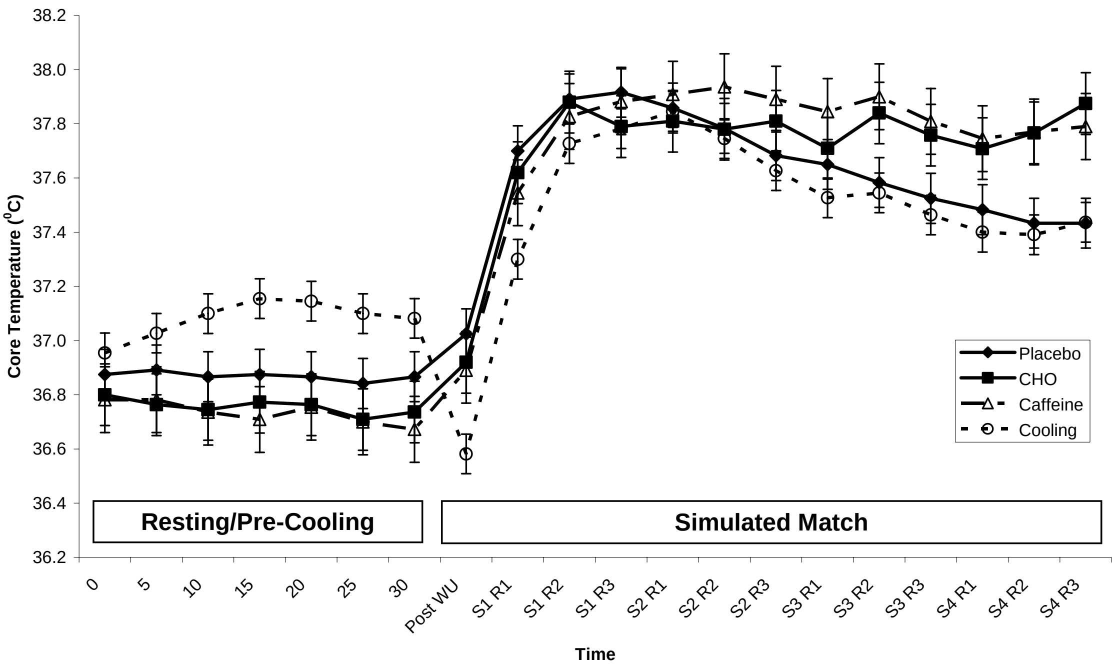

Figure 4.11. Core body temperature over the duration of the experimental protocol. Values presented are mean ± *SE*.

Heart rate.

Heart rate was monitored every 5 min during the 30 min pre-match (resting or cooling) period, once post-warm-up, and during every standardised recovery period between games and sets thereafter. Due to the nature of the data, problems occurred with normality when resting and exercising data were analysed collaboratively. Herein, resting/cooling and exercise data were analysed separately. Reliability of HR obtained over the course of the trial, however, was 8.60%. Figure 4.12 illustrates the HR response during the resting/cooling phase and over the duration of the simulated match.

Resting.

Depicted in Figure 4.12, the HR response to both rest and the exercise protocol was largely mirrored in all conditions. At rest, all covariates (i.e., temperature, relative humidity and the initial resting HR data point) significantly affected HR (p = 0.004, p = 0.009, $p < 0.01$, respectively). Examination of effect sizes revealed only small and trivial responses for inter-condition comparisons. Noteworthy, for the analysis of HR it was deemed that the initial HR value collected would serve as a covariate, as this value was not affected by any of the applied experimental strategies.

During exercise.

In concert with the HR response during the resting/cooling phase, HR during exercise was significantly affected by temperature, relative humidity and the initial resting HR data point (p = 0.001, p = 0.003, p = 0.005, respectively). In addition, exercising HR was also significantly affected by time ($p < 0.01$). Examination of effect sizes, of average HR measured longitudinally across the match phase of the protocol, revealed only trivial magnitudes for inter-condition comparisons (Appendix Q).

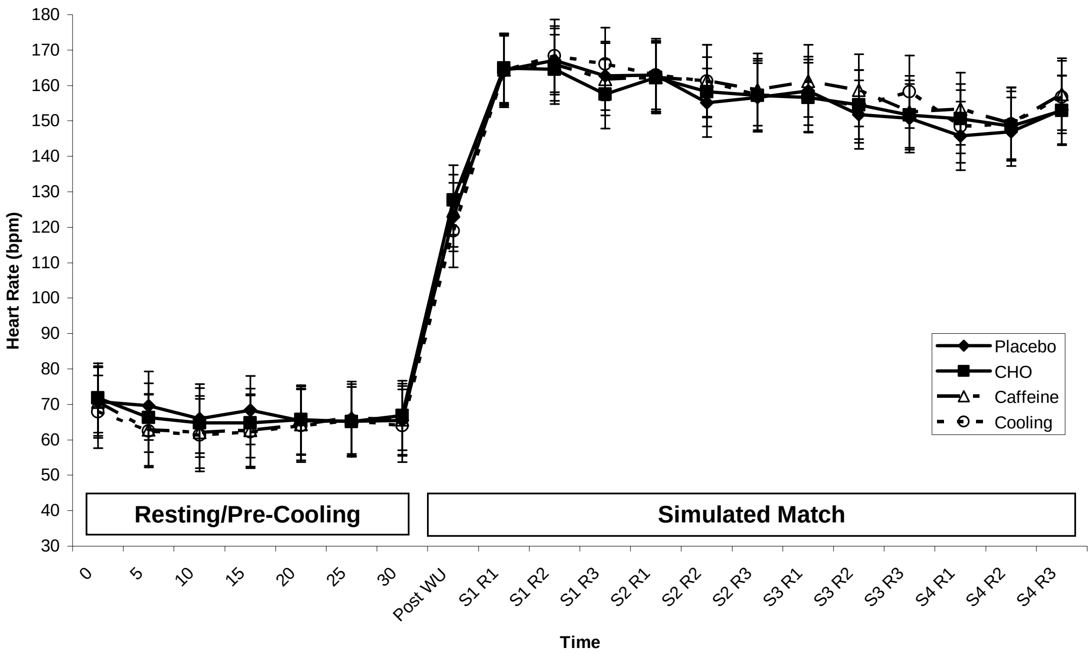

Figure 4.12. Heart rate over the duration of the experimental protocol. Values presented are mean ± *SE*.

Blood glucose.

Resting blood glucose measurements were obtained immediately upon arrival to the laboratory. For this reason it was deemed that no conditions would effectively influence the value, and thus the initial BGL measurement was treated as a covariate throughout statistical analyses. Subsequent measurements were obtained after completion of each set. Statistical analyses revealed main effects for condition ($p < 0.01$), time ($p < 0.01$), temperature ($p = 0.013$), resting BGL ($p = 0.02$) and an interaction effect for temperature by time ($p = 0.005$). The effects of condition and time are evident in Figure 4.13 and verified through the Bonferroni-adjusted post-hoc analyses. Comparison of longitudinal condition means revealed that BGL in the CHO condition (5.9 $\pm$ 1.0 $mmol \cdot L^{-1}$) was significantly greater than the PLA (5.5 $\pm$ 1.5 $mmol \cdot L^{-1}$, $p < 0.01$) and CAF (5.3 $\pm$ 0.7 $mmol \cdot L^{-1}$, $p < 0.01$) conditions. Data instabilities rendered the cooling condition as not estimable, however comparisons of means (5.1 $\pm$ 0.7 $mmol \cdot L^{-1}$) would suggest that this condition also differed significantly from the CHO trial. A moderate effect size (*ES* = 0.96), detected for this analysis, was supportive of the assumption. Furthermore, small and moderate effect sizes were also revealed for the PLA (*ES* = -0.37) and CAF (*ES* = 0.72) conditions, validating the ability of the supplementation strategy to enhance BGL concentration over the duration of the protocol. The reliability of BGL concentration over the duration of the protocol and between trials was 14.55%.

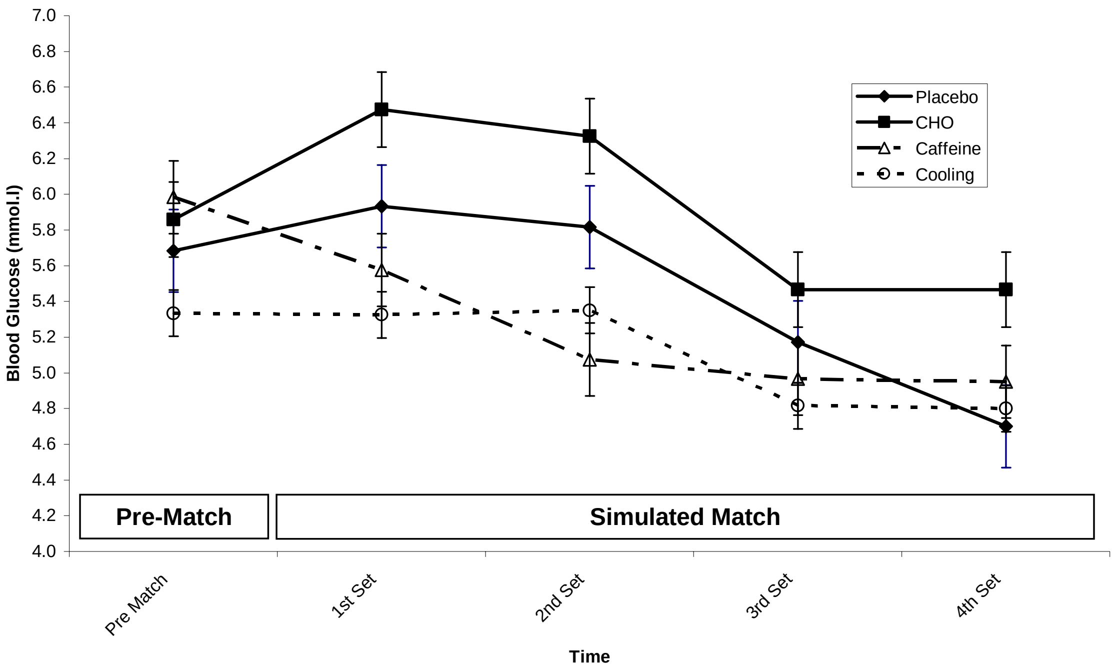

Figure 4.13. Blood glucose concentration over the duration of the experimental protocol. Values presented are mean $\pm$ *SE*.

Blood lactate.

Resting blood lactate concentrations were obtained immediately upon arrival to the laboratory. Similarly with BGL, for this reason it was deemed that no conditions would effectively influence the value, and thus the initial BLa measurement was treated as a covariate throughout statistical analyses. Subsequent measurements were obtained after completion of each set. Illustrated in Figure 4.14, BLa barely increased above resting levels and this was reflected in the statistical analysis where no significant effects of either condition or time were identified. Comparison of means returned effect sizes of only small and trivial magnitudes. Only interactions between variables produced significant effects, these being condition by time (p = 0.013) and temperature over time (p = 0.03). The reliability of BLa concentration over the duration of the protocol and between trials was 14.75%.

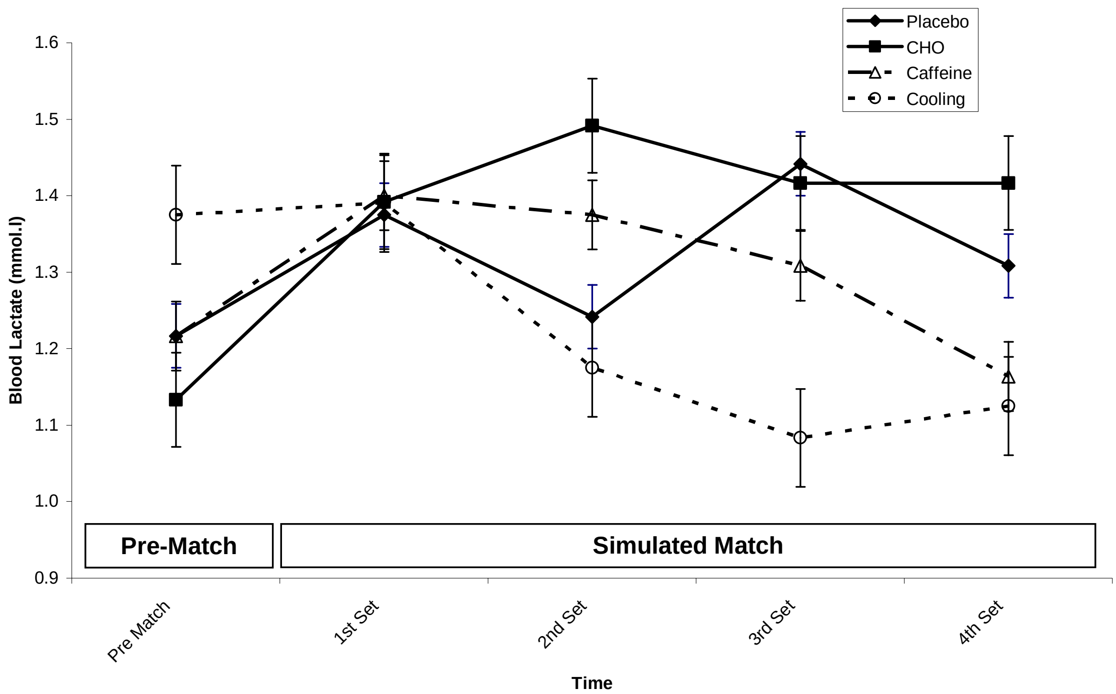

Figure 4.14. Blood lactate concentration over the duration of the experimental protocol. Values presented are mean ± *SE*.

Creatine kinase.

Creatine kinase was measured pre- and post-exercise. Figure 4.15 illustrates the blanket increase in CK post-match. This response was statistically affirmed as time produced the sole significant effect ($p < 0.01$). Analysis of inter-condition post-match means revealed small effect sizes when all conditions were compared against caffeine (*ES* = 0.22, 0.28, 0.24, for PLA, CHO, and cooling, respectively). Refer to Table 4.3 and Appendix R for means and effect sizes of inter-condition pre- versus post-match concentration differences. The reliability of CK concentration over the duration of the protocol and between trials was 17.97%.

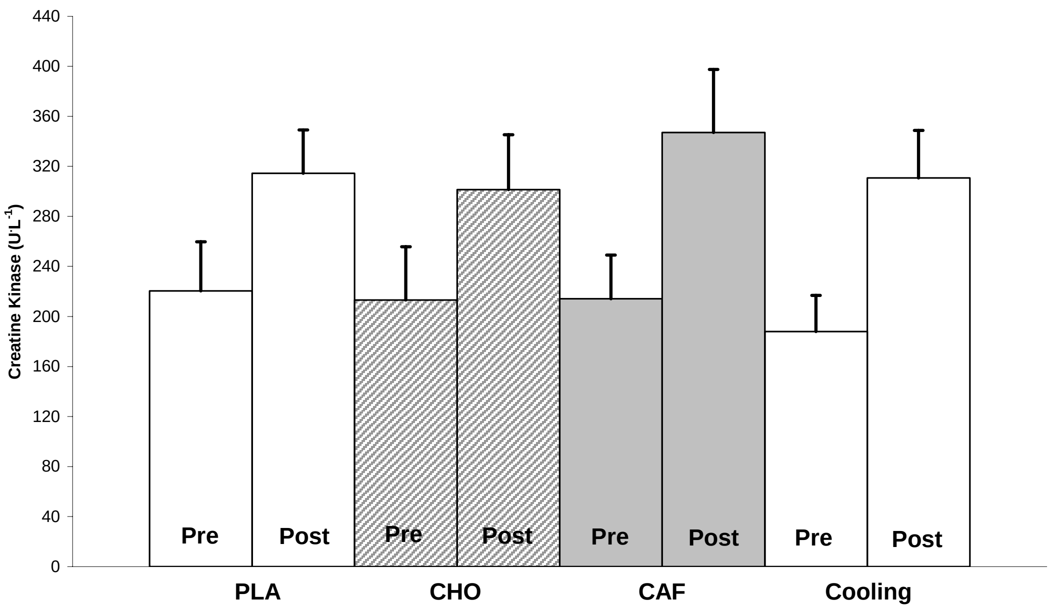

Figure 4.15. Creatine kinase concentration measured pre- and post-match. Values presented are mean ± *SE*. CAF = Caffeine, CHO = Carbohydrate, PLA = Placebo.

Prolactin.

Peripheral prolactin concentration was measured pre- and post-exercise as a surrogate index of central fatigue. Figure 4.16 illustrates a trend (non significant; $p = 0.149$) for elevated PRL post-match. Analysis of inter-condition, pre- versus post-match concentration changes, revealed moderate and small effect sizes when all conditions were compared against cooling (*ES* = 0.72, 0.46, 0.36, for PLA, CHO, and CAF, respectively). Refer to Table 4.3 and Appendix R for means and other related effect sizes. The reliability of peripheral PRL concentration over the duration of the protocol and between trials was 23.44%.

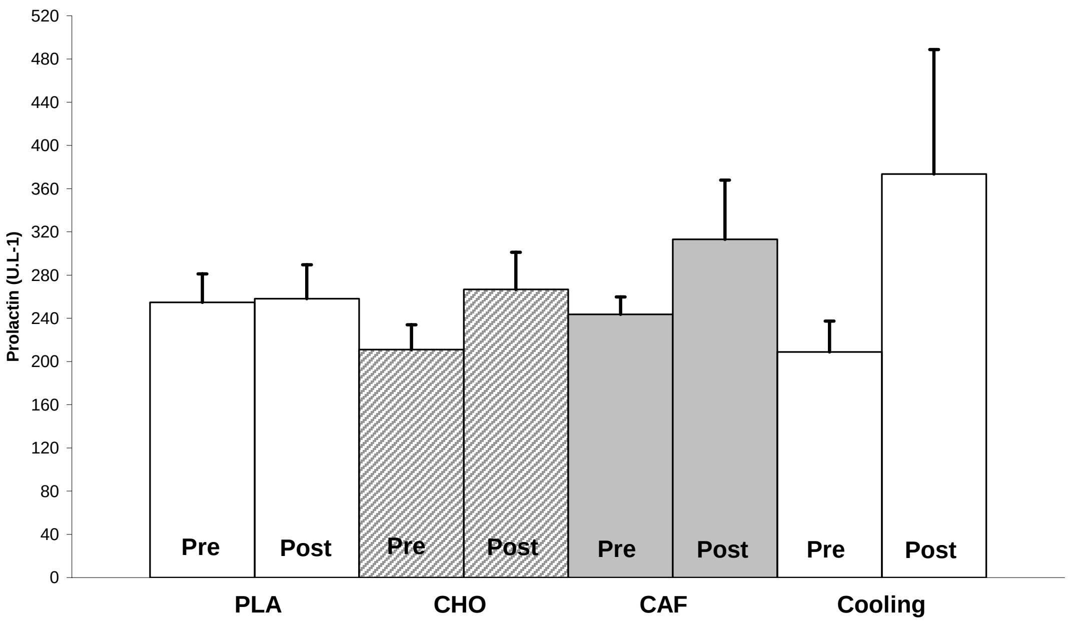

Figure 4.16. Prolactin concentration measured pre- and post-match. Values presented are mean ± *SE*. CAF = Caffeine, CHO = Carbohydrate, PLA = Placebo.

Body mass and hydration status.

Body mass, measured pre- and post-match, served as a means to ensure that participants presented in a similar hydrated state for each trial and additionally to ensure that the prescribed fluid consumption maintained an appropriate level of hydration. Representative of achieving these aims are measures of body mass change, expressed as percent deficit (Figure 4.17), where on average participants lost less than 0.6% of their body mass (0.5 kg) and total fluid losses differed only marginally between conditions (Figure 4.18). Statistical analyses verified the consistency of changes in body mass across conditions as no significant differences were identified. Further advocating the consistency of pre- and post-match body mass were measures of reliability, 0.75% and 0.31% respectively.

Analysis of fluid losses revealed similar findings with temperature producing the only significant effect ($p = 0.014$). Interestingly, small effect sizes were detected when average fluid losses incurred during the CAF trial (3014 + 1005 ml) were compared against the CHO (2673 ± 920 ml, ES = 0.35) and cooling trials (2687 + 985 ml, ES = 0.33). The marginal differences between trials are illustrated in Figure 4.18. The inter-trial reliability for TFL over the duration of the simulated match was 19.78%.

Upon-waking urine specific gravity was measured to ensure that participants presented in the same state of hydration for each trial. Negligible differences were observed for comparison of U_{sg} between conditions. Ultimately, the marginal differences identified did not reach statistical significance ($p = 0.611$) but did produce some moderate and small effect sizes; CHO versus PLA (1.024 ± 0.004 vs. 1.022 ± 0.004, ES = 0.60), CHO versus CAF (1.024 ± 0.004 vs. 1.022 ± 0.005, ES = 0.45) and CHO versus cooling (1.024 ±

0.004 vs. 1.022 ± 0.006, ES = 0.31). Between trial reliability comparisons returned a supportive value (0.63%).

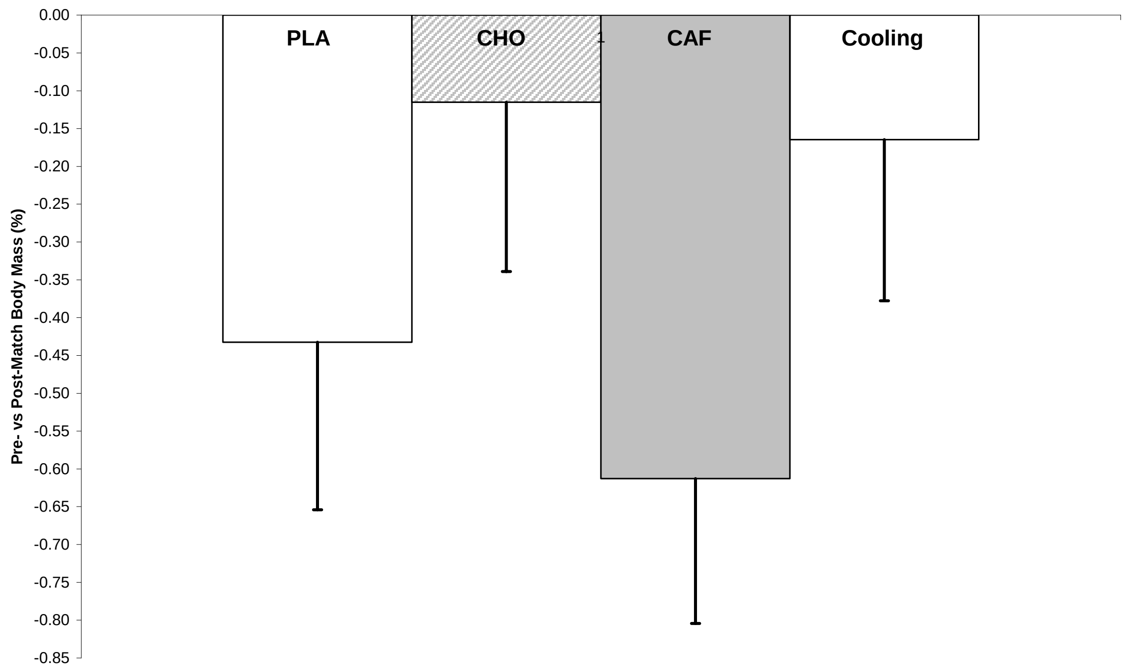

Figure 4.17. Pre- versus post-match body mass expressed as a percent deficit. Values presented are mean ± *SE*. CAF = Caffeine, CHO = Carbohydrate, PLA = Placebo.

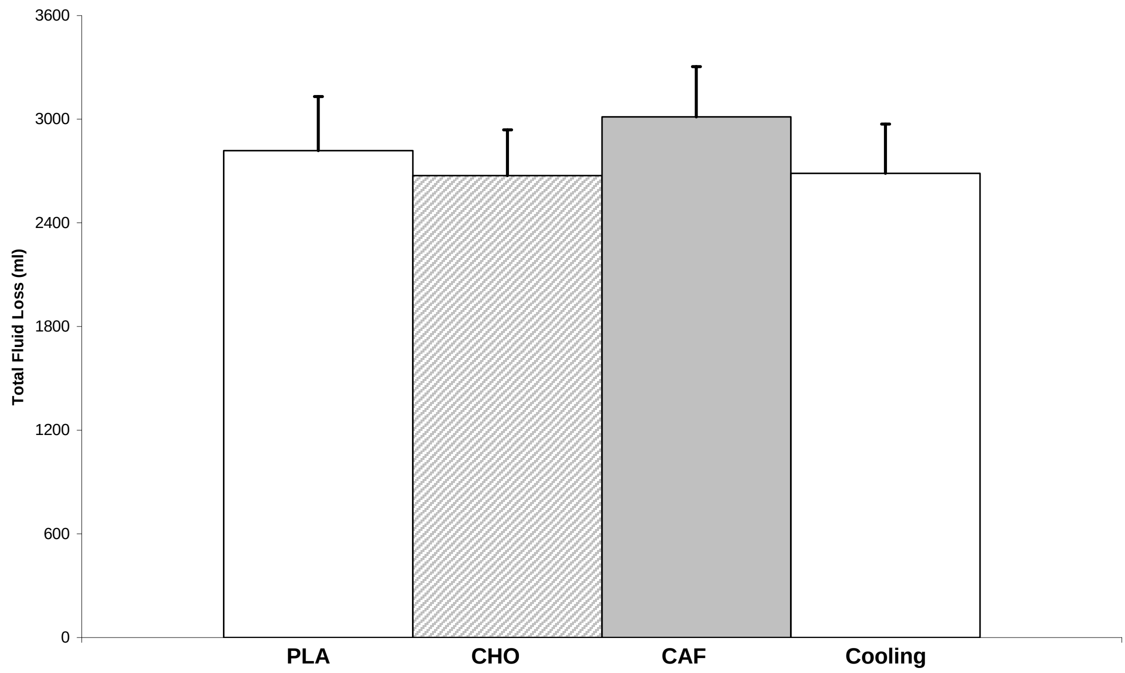

Figure 4.18. Total fluid loss compared across conditions. The measurement was deduced from absolute changes in body mass, fluid volume consumed and urinary losses. Values presented are mean ± *SE*. CAF = Caffeine, CHO = Carbohydrate, PLA = Placebo.

Subjective Responses

Rating of perceived exertion.

Rating of perceived exertion was collected during every recovery period between games and sets, during the simulated match. Illustrated in Figure 4.19, RPE increased in a linear fashion over the duration of the match, thus all RPE measurements were significantly greater than the initial measurement ($p < 0.01$). The effects of time ($p < 0.01$) and ambient temperature ($p = 0.001$) were also significant. No condition had the capacity to mitigate the effects of time or temperature on RPE. However, Figure 4.19 illustrates an obvious deviation of RPE values in the CAF trial away from the increasing trendline of all other conditions. The capacity for CAF to reduce RPE toward the latter stages of the match is evidenced in analysis of inter-condition effect sizes (see Table 4.5 below). For comparisons of individual means and effect sizes over the duration of each trial, refer to Appendix S. Average RPE compared longitudinally and across conditions also revealed small effect sizes for the CHO (14 ± 2, ES = 0.23) and cooling (14 ± 1, ES = -0.23) trial against the CAF trial (14 ± 1). The inter-trial reliability for RPE over the duration of the simulated match was 4.50%.

Table 4.5

Rating of Perceived Exertion at Specific Times during the Simulated Match and Respective Effect Sizes

	Caffeine	Placebo	Carbohydrates	Cooling
Set 3 Rep 1	14 ± 1	-	15 ± 1 (0.29)	15 ± 1 (0.32)
Set 3 Rep 2	15 ± 1	15 ± 1 (0.34)	15 ± 1 (0.20)	15 ± 1 (0.46)
Set 3 Rep 3	14 ± 1	15 ± 1 (0.34)	15 ± 2 (0.57)	15 ± 1 (0.73)
Set 4 Rep 2	14 ± 1	15 ± 1 (0.90)	15 ± 2 (0.66)	15 ± 1 (0.79)
Set 4 Rep 3	15 ± 1	16 ± 1 (0.58)	15 ± 2 (0.32)	15 ± 2 (0.42)

Note. Values presented are mean ± *SD* and effect magnitudes in parentheses. All conditions are compared against the caffeine condition. Only comparisons that returned small (*ES* = 0.2 – 0.6) and moderate (*ES* = 0.6 – 1.2) effect sizes are reported (- denotes trivial magnitudes).

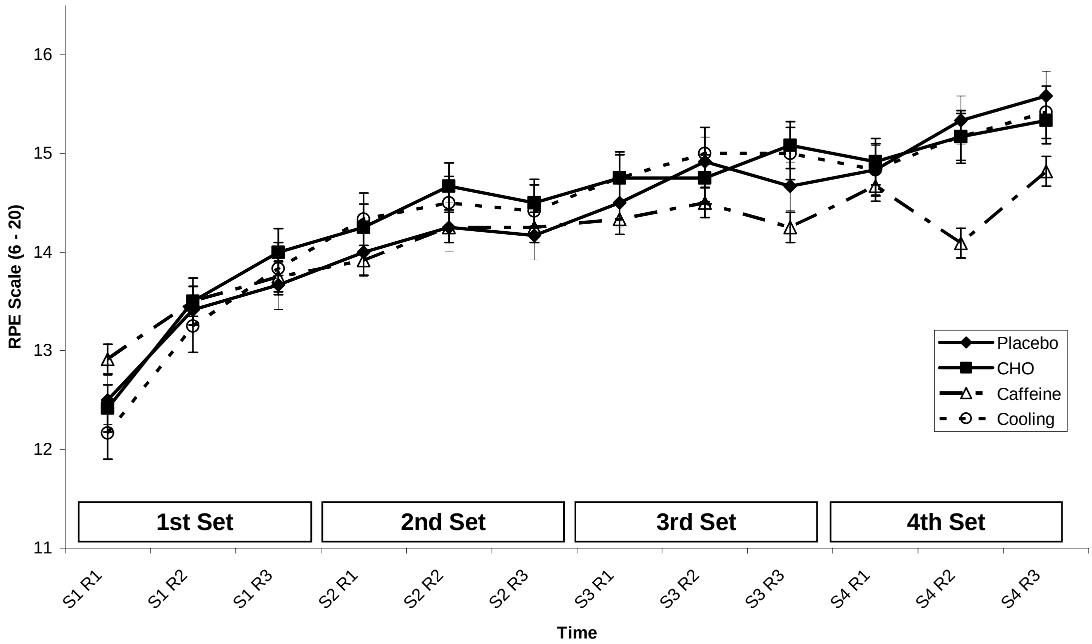

Figure 4.19. Rating of perceived exertion over the duration of the simulated match. Values presented are mean + *SE*.

Thermal sensation.

Thermal sensation was monitored every 5 min during the 30 min pre-match (resting or cooling) period, once post-warm-up, then during every standardised recovery period between games and sets thereafter. Due to the nature of the data, when resting and exercising data were analysed collaboratively, problems occurred relative to normality, therefore resting/cooling and exercise data were herein analysed individually. Figure 4.20 illustrates the reported thermal sensations during both rest/cooling and exercise. The inter-trial reliability for TS from commencement of the resting/cooling phase, to completion of the simulated match was 6.40%.

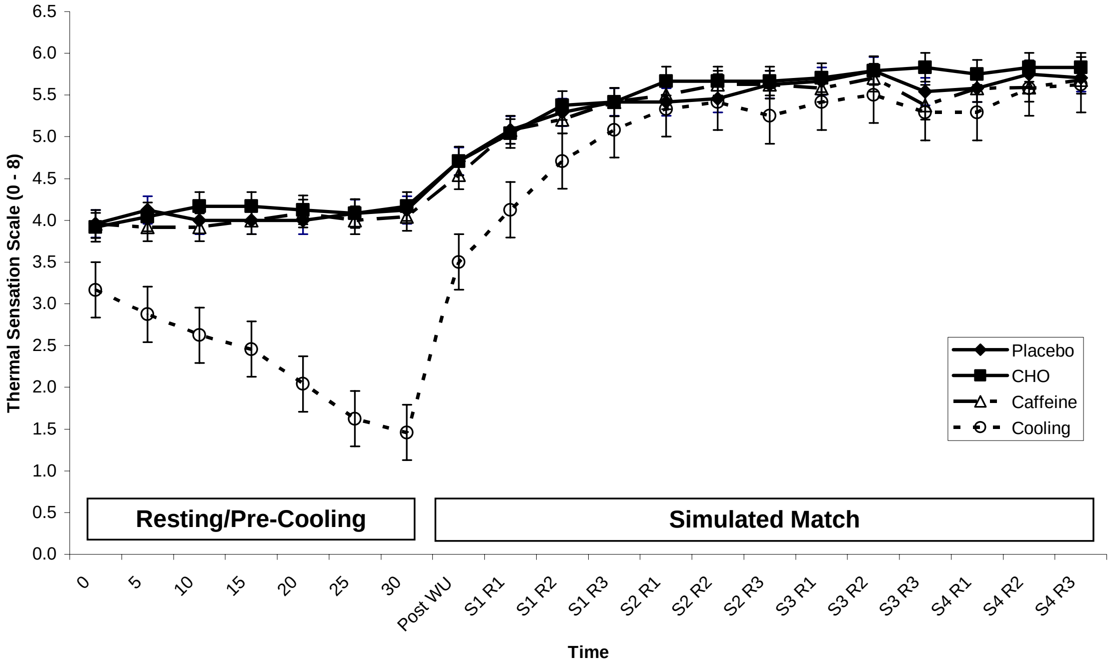

Figure 4.20. Thermal sensation ratings over the duration of the experimental protocol. Values presented are mean ± *SE*.

Resting.

Illustrated in Figure 4.20, the ice bath pre-cooling protocol, implemented to decrease a players predisposition to heat strain during hot and humid playing conditions, effectively reduced ratings of TS (4.0 ± 0.1, 4.1 ± 0.3, 4.0 ± 0.2, 2.3 ± 0.6; mean resting thermal sensation for PLA, CHO, CAF, and cooling respectively). Condition, time and the interaction of condition by time all returned a high level of statistical significance ($p < 0.01$). Effect sizes of a very large magnitude further supported the cooling procedure as an effective mechanism to reduce TS (PLA vs. cooling, ES = 4.68; CHO vs. cooling, ES = 3.90; CAF vs. cooling, ES = 4.21).

During exercise.

The pre-match cooling manoeuvre and the application of the cooling jacket and hood during the standardised breaks in play were not capable of significantly lowering thermal sensation below that of the other conditions over the duration of the simulated match. Residual effects of the applications are evident in Figure 4.20, and reinforced by effect magnitudes. Comparison of average TS over the course of the exercise period revealed small (PLA: 5.5 ± 0.7, ES = 0.59; CAF: 5.4 ± 0.7, ES = 0.53) and moderate effects (CHO: 5.6 ± 0.9, ES = 0.65) when these conditions were compared to the cooling trial (5.1 ± 0.6). Despite no condition-induced effects, time ($p < 0.01$), temperature ($p < 0.01$) and relative humidity ($p = 0.005$) returned significance.

Further investigation of effect sizes revealed large differences between all conditions, relative to the cooling condition, when TS was measured immediately post-warm-up (cooling: 3.5 ± 0.6, PLA: 4.7 ± 0.8, CHO: 4.7 ± 0.7, CAF: 4.5 ± 0.5, ES = 1.74, 1.78, 1.77, respectively), and at the completion of set 1 rep 1 (cooling: 4.1 ± 0.4, PLA: 5.1 ± 0.7, CHO: 5.0 ± 0.8, CAF: 5.1 ± 0.7, ES = 1.83, 1.51, 1.83, respectively). In keeping with these findings moderate effect sizes were revealed for all conditions, relative to the cooling trial at the completion of set 1 rep 2 (cooling: 4.7 ± 0.5, PLA: 5.3 ± 0.6, CHO: 5.4 ± 0.9, CAF: 5.2 ± 0.7, ES = 1.00, 0.92, 0.81, respectively). A number of additional moderate and small effects were identified over the duration of the simulated match (see Table 4.6). For comparisons of individual means and effect sizes over the duration of each trial, refer to Appendix T.

Table 4.6

Thermal Sensation Ratings at Specific Times during the Simulated Match and Respective Effect Sizes

	Cooling	Placebo	Carbohydrates	Caffeine
Set 1 Rep 3	5.1 ± 0.6	5.4 ± 0.7 (0.51)	5.4 ± 0.9 (0.42)	5.4 ± 0.7 (0.49)
Set 2 Rep 1	5.3 ± 0.6	-	5.7 ± 0.8 (0.47)	5.5 ± 0.5 (0.32)
Set 2 Rep 2	5.4 ± 0.6	-	5.7 ± 0.8 (0.36)	5.6 ± 0.6 (0.36)
Set 2 Rep 3	5.3 ± 0.4	-	5.7 ± 0.7 (0.75)	5.6 ± 0.6 (0.77)
Set 3 Rep 1	5.4 ± 0.4	5.7 ± 0.4 (0.58)	5.7 ± 0.8 (0.50)	5.6 ± 0.7 (0.30)
Set 3 Rep 2	5.5 ± 0.7	5.8 ± 0.7 (0.43)	5.8 ± 0.8 (0.38)	5.7 ± 0.8 (0.29)
Set 3 Rep 3	5.3 ± 0.6	5.5 ± 0.7 (0.38)	5.8 ± 0.9 (0.75)	-
Set 4 Rep 1	5.3 ± 0.5	5.6 ± 0.8 (0.43)	5.8 ± 1.0 (0.61)	5.6 ± 0.7 (0.47)
Set 4 Rep 2	5.6 ± 0.8	-	5.8 ± 0.9 (0.28)	-
Set 4 Rep 3	5.6 ± 0.8	-	5.8 ± 1.1 (0.22)	-

Note. Values presented are mean ± *SD* and effect magnitudes in parentheses. All conditions are compared against the cooling condition. Only comparisons that returned small (*ES* = 0.2 – 0.6) and moderate (*ES* = 0.6 – 1.2) effect sizes are reported (- denotes trivial magnitudes).

Performance

Outcome Measures

Serve velocity and accuracy.

Measurement of first serve velocity and accuracy was conducted immediately post-warm-up and on completion of each game thereafter (i.e., immediately prior to the standardised recovery period between games). Both main effects and first order interactions were detected for serve velocity, being condition (p = 0.016), time (p = 0.011), temperature (p = 0.003) and condition by time (p = 0.014). Further examination of the significant main effects for condition revealed that CAF produced the fastest serve velocity over the course of the trial. However the Bonferroni-adjusted post-hoc analyses revealed significant differences only between CAF (164 ± 14 kph) and CHO (160 ± 11 kph) conditions (p = 0.008). This finding was supported by a small effect size (*ES* = 0.33) whereas the difference between CAF (164 ± 14 kph), PLA (161 ± 15 kph, p = 0.215) and cooling (161 ± 15 kph, p = 0.259) trials returned trivial effects (*ES* = 0.19 and ES = 0.19). A number of other small effects were recognised, specifically between the CAF condition and other conditions, these can be sourced from Appendix U. Further examination of a significant (p = 0.014) condition by time interaction revealed that players served significantly faster in the fourth set under the CAF condition (165 ± 15 kph), compared to the PLA (159 ± 15 kph, p = 0.008) and CHO (158 ± 13 kph, p = 0.001) conditions, but not cooling (162 ± 14 kph, p = 0.213). Figure 4.21 illustrates the reduction in serve velocity over time and how this response is reversed in the CAF trial. The inter-trial reliability for first serve velocity measured over the duration of the simulated match was 3.06%.

First serve accuracy was not significantly affected by condition, time or any other variable. There was however a trend, illustrated in Figure 4.22, for participants undertaking the CHO condition (29 $\pm$ 15%) to exhibit greater proficiency over the course of the simulated match, relative to the PLA (26 $\pm$ 14%) and cooling (26 $\pm$ 13%) conditions (*ES* = 0.25 & 0.26 respectively). Game to game performance fluctuations rendered further data interpretation difficult, thus individual effect sizes are only reported in Appendix V. The inter-trial reliability for accuracy of the first serve (46.57%), measured over the duration of the simulated match reflects the measurement variability.

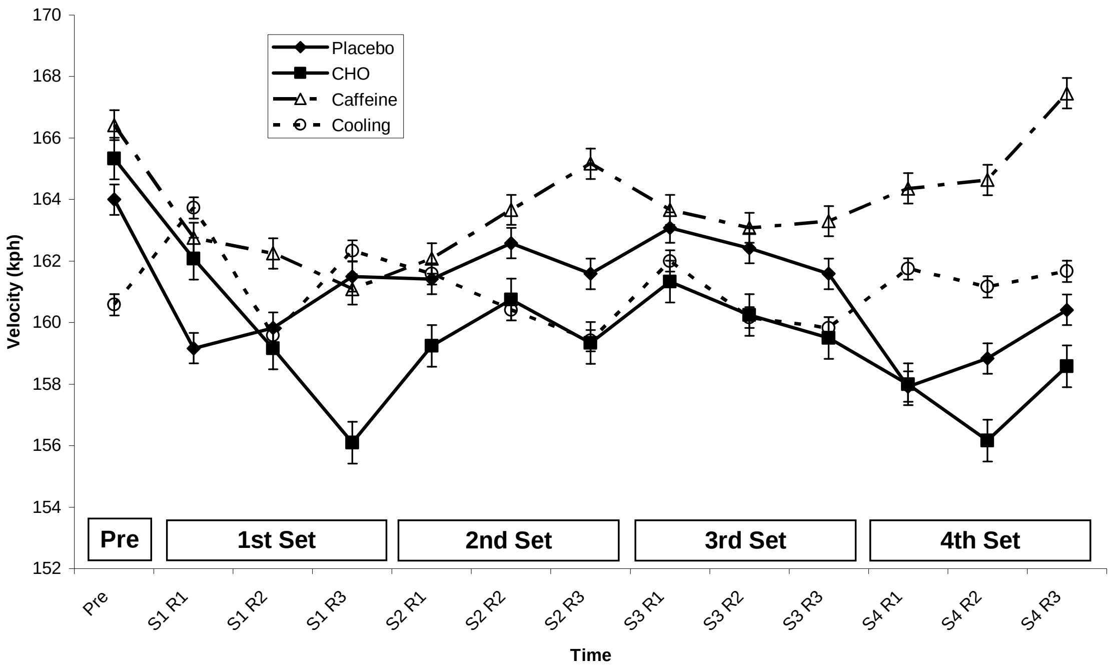

Figure 4.21. First serve velocity over the duration of the simulated match. Values presented are mean $\pm$ *SE*.

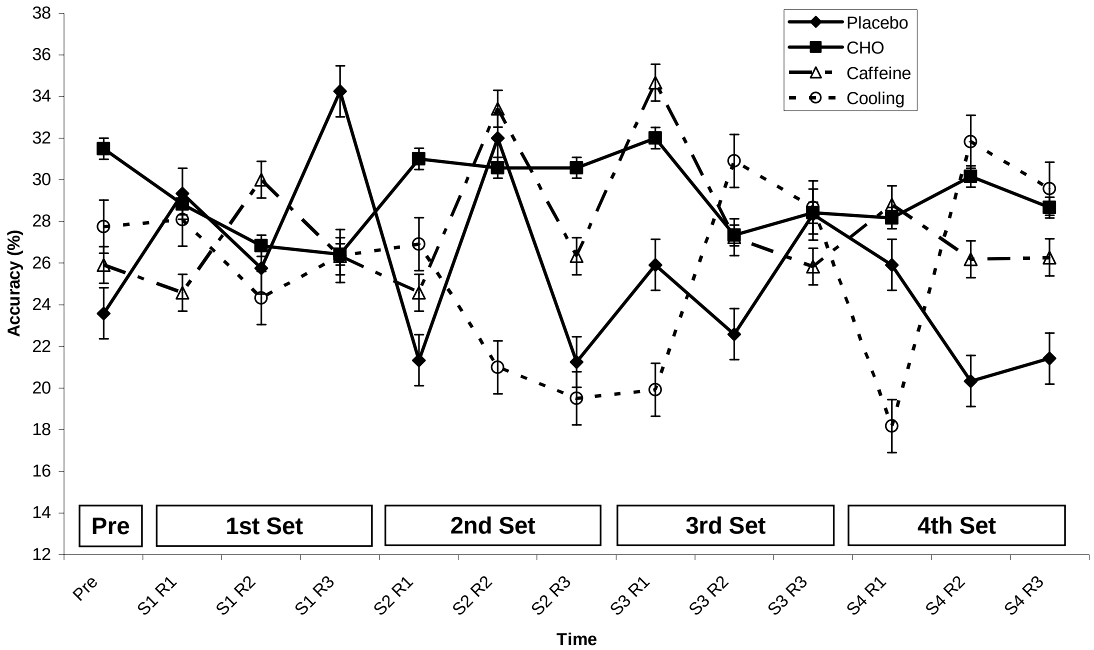

Figure 4.22. First serve accuracy over the duration of the simulated match. Values presented are mean $\pm$ *SE*.

Groundstroke velocity and accuracy.

Groundstroke velocity and accuracy were measured concomitantly during every rally of each game or repetition. Despite the apparent reduction in groundstroke velocity displayed by participants undertaking the cooling condition (Figure 4.23), statistical significance was not achieved ($p = 0.263$), but was however achieved for time ($p < 0.01$) and the interaction of temperature by time ($p = 0.008$). Inter-condition comparisons of mean velocity over the duration of the simulated match returned small effect sizes for all conditions compared against the cooling trial (117 $\pm$ 7 kph), (PLA: 120 $\pm$ 8 kph; CHO: 120 $\pm$ 7 kph; CAF: 120 $\pm$ 8 kph; ES = 0.38, 0.37, 0.47, respectively). This finding is reinforced by several small and moderate effects over the duration of the simulated match; these can be sourced from Appendix W. The inter-trial reliability for groundstroke velocity measured over the duration of the simulated match was 1.88%.

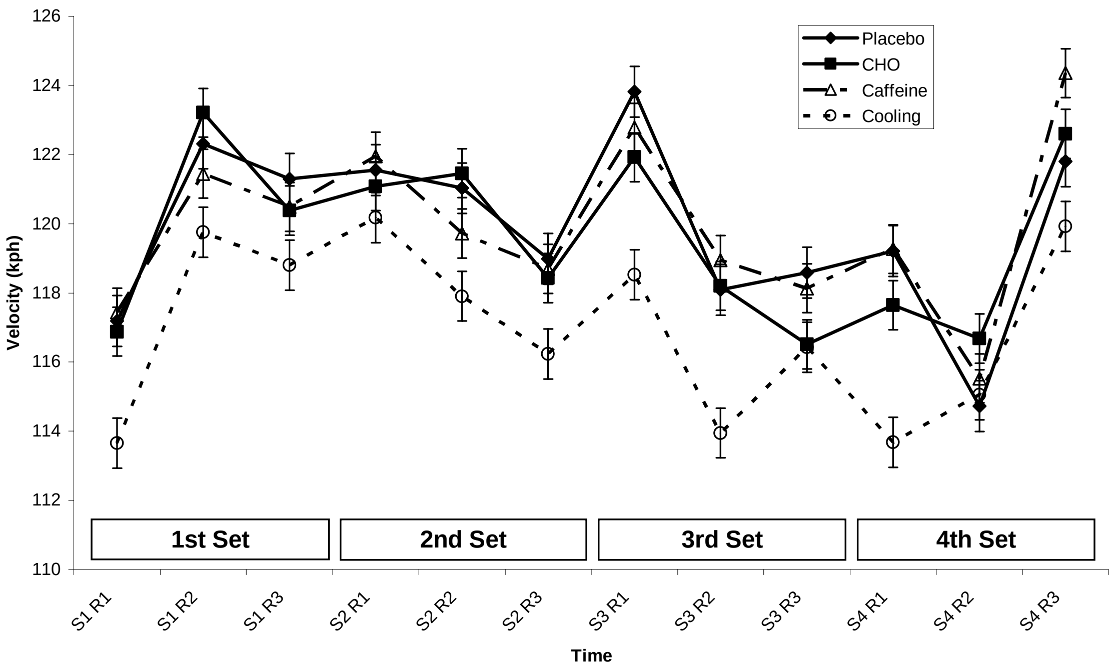

Figure 4.23. Groundstroke velocity over the duration of the simulated match. The analysis includes only forehand strokes. Values presented are mean ± *SE*.

Groundstroke accuracy, illustrated in Figure 4.24, decreased over time (p = 0.004), but was not significantly affected by any other variable. A tendency was evident for participants undertaking the CHO condition to be slightly less accurate (CHO: 35 ± 5%) than other conditions (PLA: 36 ± 5%, CAF: 36 ± 4%, cooling: 36 ± 5%). This observation was reflected by effect sizes of accuracy averaged over the course of each trial (ES = 0.26, 0.30, 0.19; PLA, CAF and cooling conditions, respectively). A number of other moderate and small effects were noted between conditions, however fluctuations in performance again made interpretation difficult. Additional effects can be sourced in

Appendix X. The inter-trial reliability for accuracy of groundstrokes, measured over the duration of the simulated match, was 8.26%.

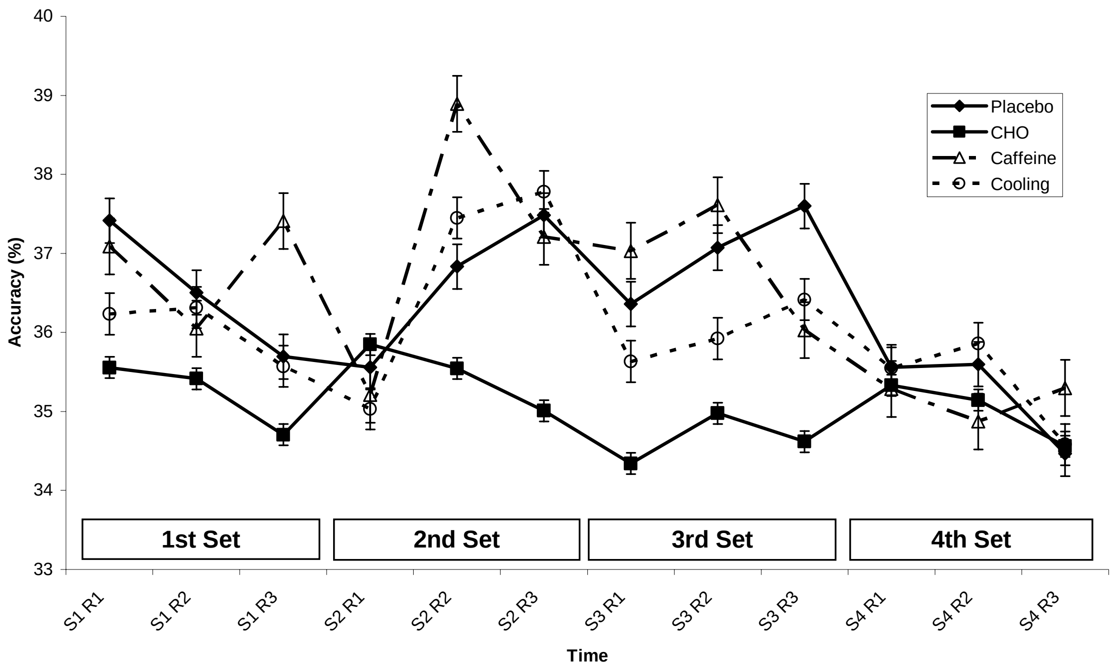

Figure 4.24. Groundstroke accuracy over the duration of the simulated match. Values presented are mean + *SE*.

Process Measures

Serve kinematics: phase temporal analyses.

Participants were filmed as they performed the serve velocity and accuracy test. The footage was used to conduct the temporal analysis of the serve. High-speed footage of the entire serve sequence (i.e., from preparation to follow through) was divided into five phases and the length of each phase, or the temporal component, was determined by counting the number of frames per phase. The number of frames was then converted to time (ms). Herein, the analysis focuses on individual phases. However, the reliability measure of temporal phases of the serve (8.29%) was obtained by averaging the reliability of each phase of the serve over the duration of the experimental protocol.

Phase 1 – preparation to ball release.

Interaction effects were identified, condition by time (p = 0.035) and temperature by time (p = 0.026), but no main effects were revealed for the preparatory phase of the service action. No consistent trends could be identified between conditions. This response is evident in Figure 4.25 and affirmed by the return of only trivial effect sizes of average phase time from commencement of the simulated match to completion. Additional effect sizes relative to specific measurements throughout the simulated match can be sourced in Appendixes Y – BB.

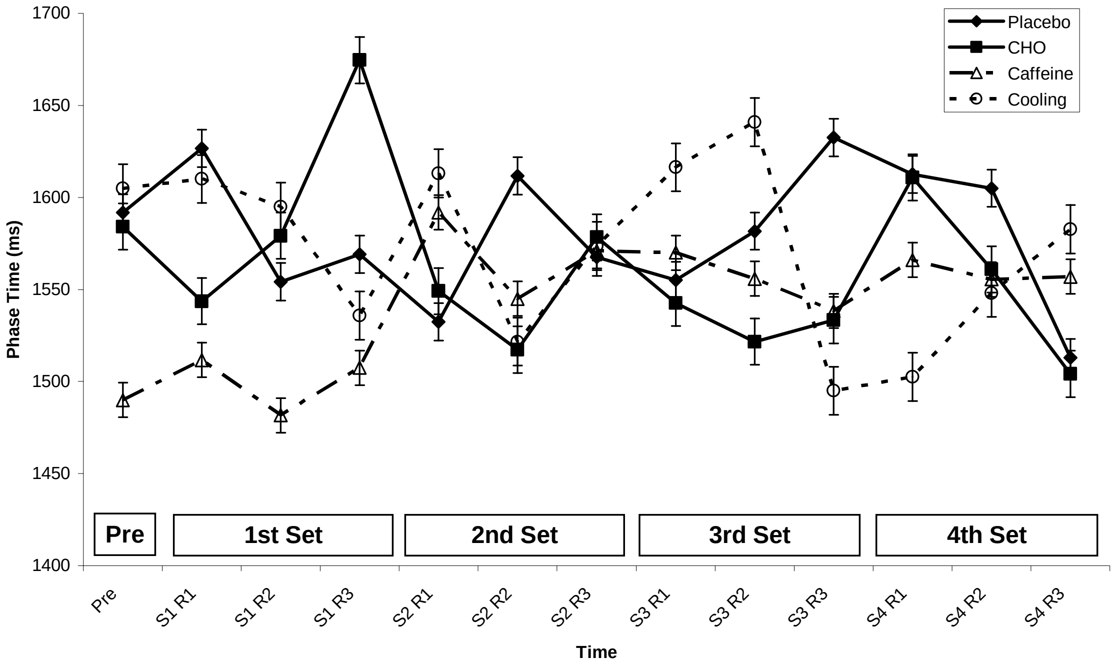

Figure 4.25. Temporal analysis of the initial phase of the service action (preparation to ball release) over the duration of the simulated match. Values presented are mean ± *SE*.

Phase 2 – ball release to maximum height of the ball toss.

No main effects or interactions were revealed in the temporal analysis of the second phase of the serve. Examination of effect sizes of average phase time from commencement of the simulated match to completion supported this statistical notion (*ES* < 0.20), however at individual collection points CAF appeared to induce a faster sequential action as depicted in Figure 4.26. A number of small effect sizes were noted for the CAF condition in comparison to other conditions, these can be sourced in Appendixes Y – BB.

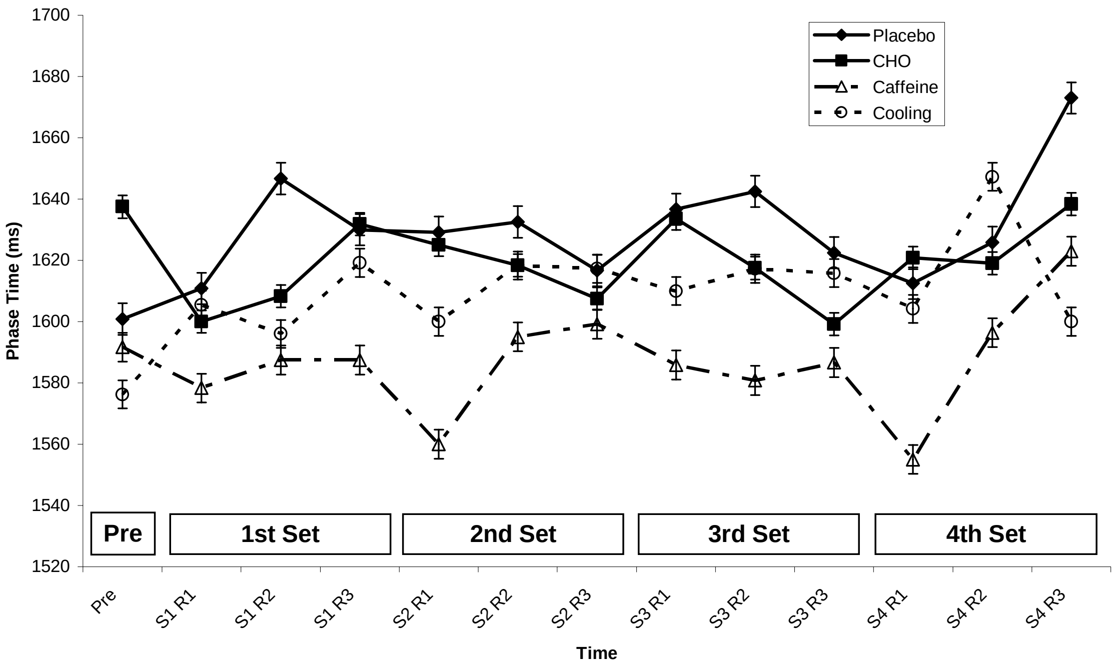

Figure 4.26. Temporal analysis of the second phase of the service action (ball release to maximum height of the ball toss) over the duration of the simulated match. Values presented are mean ± *SE*.

Phase 3 – maximum height of ball toss to racquet-ball impact.

The third phase of the serve kinematic sequence (racquet-arm acceleration phase) was significantly affected by time ($p = 0.002$) and the interaction of condition by time ($p <$

0.01). Identification of where the significance lies relative to the condition by time interaction was not discernable from the post-hoc analysis conducted. The method of post-hoc analysis reduced the degrees of freedom of the statistical analysis which intuitively reduced the statistical power of the analysis. Illustrated in Figure 4.27, the length of the phase increased over the duration of the protocol. Additionally, the CAF condition appeared to marginally mitigate the effects of time however this tendency was not substantiated by effect sizes of average phase time from commencement of the simulated match to completion (*ES* < 0.15). Small effect sizes, sporadic in origin, were revealed at a number of times over the duration of the protocol, these can be sourced in Appendixes Y – BB.

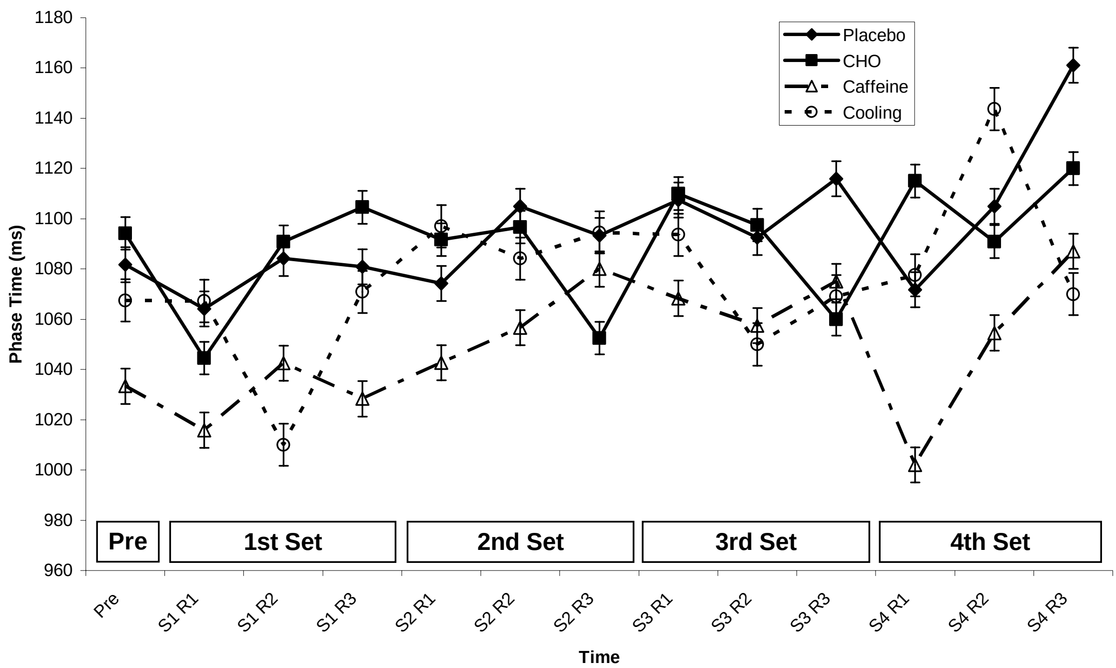

Figure 4.27. Temporal analysis of the third phase of the service action (maximum height of the ball toss to racquet-ball impact) over the duration of the simulated match. Values presented are mean ± *SE*.

Phase 4 – racquet-ball impact to follow through.

Interaction effects were identified, condition by time ($p = 0.03$) and condition by relative humidity ($p = 0.016$), but no main effects were revealed for the follow through phase of the service action. No consistent trends were identified between conditions. This response is evident in Figure 4.28 and affirmed by the return of only trivial effect sizes of average phase time from commencement of the simulated match to completion ($ES < 0.09$). Additional effect sizes relative to specific measurements throughout the simulated match can be sourced in Appendixes Y – BB.

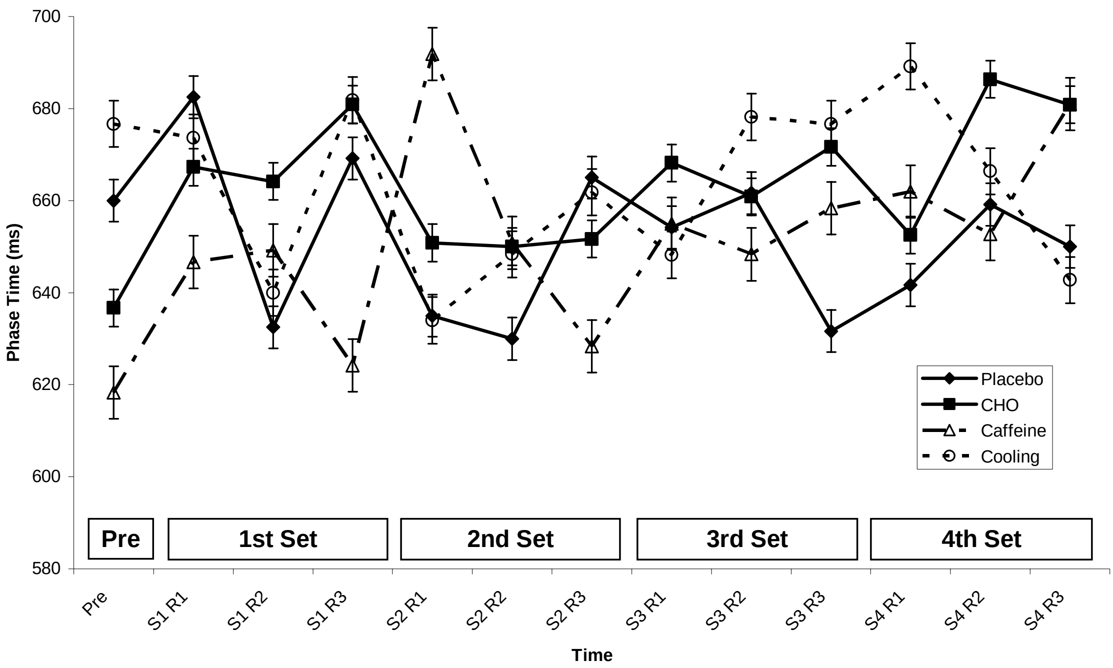

Figure 4.28. Temporal analysis of the fourth phase of the service action (racquet-ball impact to follow through) over the duration of the simulated match. Values presented are mean ± *SE*.

Phase 5 – entire serve sequence (preparation to follow through).

No main effects or interactions were revealed in the temporal analysis of the entire serve sequence. Examination of effect sizes of average phase time from commencement of the simulated match to completion supported this statistical notion (*ES* < 0.20). However, at individual collection points CAF appeared to induce a faster sequential action as depicted in Figure 4.29 and evidenced by the pre-match analysis (CAF: 4709 ± 624 ms; PLA: 4934 ± 666 ms; CHO 4953 ± 559 ms; cooling: 5076 ± 532 ms; ES = 0.35, 0.41, 0.63, for all listed conditions compared against CAF, respectively). A number of other small effect sizes were noted, largely for the CAF condition in comparison to other conditions, these can be sourced in Appendixes Y – BB.

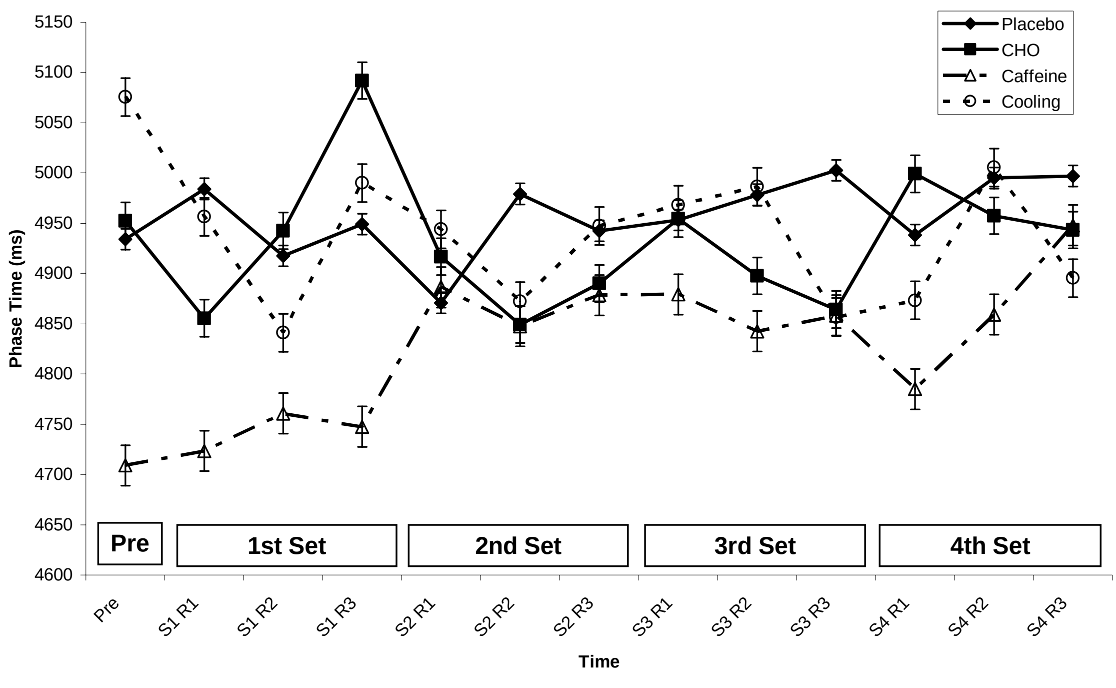

Figure 4.29. Temporal analysis of the entire service action (preparation to follow through) over the duration of the simulated match. Values presented are mean ± *SE*.

Perceptual skill.

Perceptual skill (accuracy) was measured via a computer-based return of serve test. As described in the methodology, participants viewed either the whole service action, including ball flight, or partial serve footage that was occluded at the point of racquet-ball contact. A separate statistical analysis was therefore conducted for occluded and non-occluded trials. In the context of motor-control literature testing protocol reliability is rarely reported and thus reliability was not recorded for this performance parameter.

Non-occluded trials.

When participants viewed the entire serve sequence including ball flight, neither condition, time, nor any other variable or interaction was revealed to significantly influence perceptual accuracy. As illustrated in Figure 4.30, there were no obvious condition-induced performance enhancements; however, when perceptual accuracy was averaged over the duration of the protocol, the cooling condition (84 $\pm$ 19%) returned a slightly higher accuracy (ES = 0.21) than the CHO condition (80 $\pm$ 20%). Fluctuations in performance resulted in various moderate and small effect sizes at individual data collection points; these can be sourced from Appendix CC.

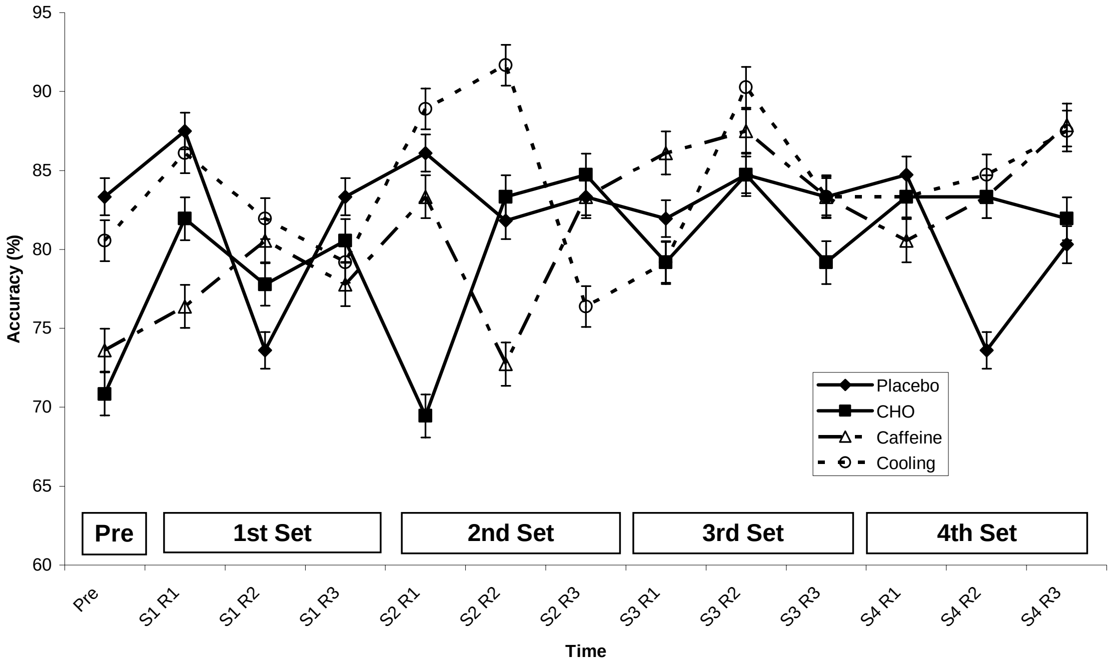

Figure 4.30. Return of serve anticipation accuracy measured using non-occluded footage, over the duration of the simulated match. Values presented are mean ± *SE*.

Occluded trials.

There were no significant effects of condition or any other variable on perceptual accuracy when the analysis was conducted on trials of occluded footage only. This was supported by trivial effect sizes ($ES < 0.10$), which were revealed when perceptual accuracy was averaged over the duration of the protocol and compared across conditions. Figure 4.31 illustrates the inconsistency of performance. Effect sizes associated to each of the individual data points can be sourced from Appendix DD.

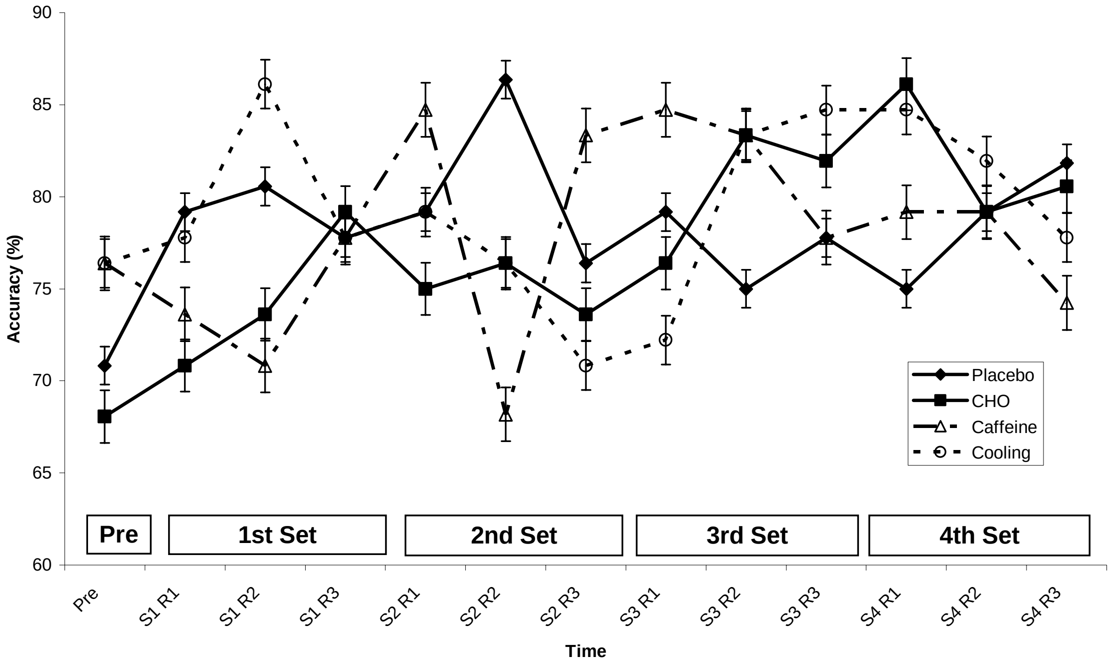

Figure 4.31. Return of serve anticipation accuracy measured using occluded footage, over the duration of the simulated match. Values presented are mean $\pm$ *SE*.

Discussion

The purpose of this investigation was to determine the ergogenic potential of caffeine, carbohydrates and cooling strategies to enhance selected measures of tennis performance. Professional tennis players currently use these strategies during competition, based on anecdotal support, to reduce the severity of adverse physiological response that manifest during matches and tournaments and compromise performance. Specifically, this investigation aimed to counteract hyperthermia, hypoglycaemia, dehydration and central fatigue, which are physiological perturbations previously reported in tennis (Bergeron, 2003; McCarthy et al., 1998; Struder et al., 1995; Therminarias et al., 1994). The selected interventions (carbohydrates supplementation, caffeine supplementation and cooling bath and ice-vest usage) were implemented to target these specific manifestations of fatigue.

Additionally, the experimental strategies were chosen because of their current usage and the ease of application into the strict time constraints of tennis match play. It was envisaged that usage of the experimental interventions would mitigate development of the targeted facets of fatigue. Additionally, strategies would reduce performance deterioration or enhance performance over the duration of a prolonged simulated tennis match, relative to a player following no potentially ergogenic strategy (placebo-control).

To establish if the experimental strategies were capable of alleviating adverse physiological responses and counteracting associated performance decrements firstly required the development of an ecologically valid testing protocol. Based on information gathered from literature on statistical match analyses (O'Donoghue & Liddle, 1998a; O'Donoghue & Ingram, 2001; Richers, 1995) and the initial match and tournament research conducted (see Investigation 1, Chapter 3), a 2 hr 40 min simulated tennis match was constructed. The protocol utilised a ball-machine for standardisation of ball projection, point length and playing intensity. The characteristics of the match (i.e., warm-up duration and allocated rest periods between points, games and sets) complied with rules and regulations of the ITF - the governing international sporting body for tennis.

To confirm the ecological validity of the devised simulated match several physiological markers were monitored throughout. The time profiles of HR, T_C, blood variables and RPE were indicative of a match-like response and compared favourably to results of previous investigations (Bergeron et al., 1991; Ferrauti et al., 2003; Smekal et al., 2001; Therminarias et al., 1994). Subsequent to the 30-min pre-match resting period, and on commencement of the simulated match, both HR and T_C displayed a sharp increase before plateauing at a submaximal level for the protocol duration (approximately 165 bpm and 37.8 °C, respectively). Rating of perceived exertion climbed gradually over the course of the protocol and peaked towards completion at a level reflective of moderate physiological strain (RPE ~15.5 or "Hard"). Blood lactate increased only marginally above resting concentrations throughout the protocol, which again supports previous observations during simulated tennis or match play (Bergeron et al., 1991; Ferrauti, Bergeron, Pluim, & Weber, 2001; Reilly & Palmer, 1994).

The environmental conditions under which the current experimental trials were conducted were only mild relative to those often confronting players during tournaments. Despite this, physiological responses were consistent with previous investigations of simulated match play. It is conceivable that thermally challenging conditions and performing trials outdoors (i.e., exposing participants to radiative heat effects of the sun) would have increased match intensity and physiological strain, leading to more overt performance reductions and more substantial benefits ascribed to the experimental strategies. This position is supported by the demonstrated nominal central fatigue response which is not consistent with previous investigations of CNS stress during prolonged tennis activity (Struder et al., 1995; Struder et al., 1999). Furthermore, the perceptual performance results of this investigation by no means reflect the general findings when non-sport specific cognitive tasks are performed under fatigue (S. Hancock & McNaughton, 1986) or thermally challenging conditions (P. A. Hancock, 1986, 1993).

It is not unreasonable to suggest that repetitive muscle microtrauma is a mechanism which could induce performance deterioration in tennis. The proliferation of CK, as an indirect measure of muscle damage (Armstrong, Warren, & Warren, 1991; Cheung, Hume, & Maxwell, 2003; Evans & Cannon, 1991; Schutte & Lambert, 2001), would support this; however only a mild increase in CK concentration was induced during the simulated tennis protocol. It is conceivable that longer duration matches of higher intensity could potentially elicit a greater response. This suggestion encourages research into the more atypical manifestations of fatigue, acute muscle trauma and central mechanisms, as performance deterioration was evident despite only mild disruption to physiological status. Examination of both central and peripheral responses in a field setting would provide unique insight to the performance and injury implications. Additionally this research may reveal that both conditions perpetuate and intensify over the course of a tournament.

Performance and Physiological Effects of Experimental Strategies

Carbohydrate supplementation.

The time profile of blood glucose over the duration of the simulated match (illustrated in Figure 4.13, page 133) supports the efficacy of CHO ingestion to compliment endogenous blood glucose availability. As previously stated, the prescribed method of supplementation was a commercially available CHO-electrolyte drink, one which is commonly used by current professional tennis players, and is often supplied during tournaments. This common supplementation procedure did not however completely attenuate declining blood glucose concentration towards the end of the protocol. The trend suggests that if the protocol had extended beyond the standardised duration (2 hr 40 min), equivalent to that of an average four set match, the debilitating performance effects of hypoglycaemia could have appeared. Notably, it is not uncommon for Grand Slam tournament matches to be played over 3 to 5 hr, increasing an athlete's predisposition to hypoglycaemia particularly when players also compete in doubles tournaments or lengthy matches on consecutive days. This finding supports the notion of Ferrauti et al. (2003) who reported hypoglycaemia during measurement of diurnal changes in blood glucose concentration in tennis players as they performed successive singles and doubles practice matches on one day, indicative of a regular training day or tournament scenario.

Despite the obvious trend for reduced substrate availability toward the latter stages of the simulated match and the differential blood glucose concentrations between the supplementation and placebo conditions, the intervention did not induce any significant performance enhancement. Pertaining to the effects on functional performance parameters, such as serve and groundstroke velocity and accuracy, CHO supplementation failed to increase functional power or to enhance motor control over that of the placebo trial. Therefore, this investigation does not resolve the contentious debate over the benefits ascribed to tennis performance skills from CHO supplementation (refer to Table 2.2, Chapter 2). In those studies which demonstrated benefits from CHO supplementation, ergogenic properties are generally afforded to groundstroke performance and movement-specific capacities, for example, agility and acceleration (E. R. Burke & Ekblom, 1982; Ferrauti et al., 1997; Vergauwen, Brouns et al., 1998). At present no consistent trends appear relative to tennis or other skill-based sports (Abt, Zhou, & Weatherby, 1998; Ostojic & Mazic, 2002; Zeederberg et al., 1996); however, great support for the procedure is evident in studies on endurance-based sports or exercise (Coggan & Coyle, 1987; Davis et al., 1992; Pitsiladis & Maughan, 1999; Welsh et al., 2002). In the tennis domain, developing a testing procedure which possesses robust reliability, ecological validity and measurement sensitivity are methodological limitations central to attempts to arrive at a consensus as to the benefits conferred by CHO supplementation.

This investigation involved a biomechanical analysis of the first serve, the purpose being to identify the underlying mechanisms for reduced serve and groundstroke proficiency previously reported during prolonged tennis matches or experimental settings (Davey et al., 2002; Dawson et al., 1985; Vergauwen, Spaepen et al., 1998). The serve was broken into five sequential temporal phases, from preparation to follow through. It was hypothesised that physiological perturbations would impair technical aspects of the kinematic process, specifically the timing of individual phases (Elliott et al., 2003). Additionally, heightened blood glucose concentration, a recognised facilitator of neural activity or a suppressant of CNS fatigue (Davis et al., 1992; Davis et al., 1999), would mitigate the fatigue response. The effects of physiological perturbations appeared to occur during the racquet-arm acceleration phases of the motion (phases 2 and 3). The gradual trend for both phases to lengthen over the duration of the protocol is illustrated in Figures 4.26 and 4.27 (see pages 151 and 152, respectively); however, there is no evidence of the proposed stimulatory role of CHO supplementation. This investigation is thought to be the first to adopt a mechanistic approach in an attempt to identify an underlying technical fault to explain reduced functional performance. Regardless of the intervention effects (or lack thereof), the technical analysis of skills integral to the sport and the understanding of the effects of homeostatic disruption on these components is an important step in the development of potential strategies to minimise performance decrements. Furthermore, it is evidence of the holistic approach needed to quantify performance of this multifaceted skill sport, and should be incorporated into future research.

Another component of tennis performance rarely addressed in literature is perceptual-cognitive skill. This process is of interest as anticipation and decision making have been recognised as capacities that differentiate expert and novice tennis players (Goulet et al., 1989; Rowe & McKenna, 2001; Singer et al., 1996; Williams et al., 2002). This investigation assessed the imposing effects of physiological strain on tennis-specific perceptual skill. The efficacy of experimental strategies in enhancing these capacities and essentially counteracting the effects of physiological stressors were also tested. Similarly, cognitive function has previously been shown to implode with fatigue (S. Hancock & McNaughton, 1986), yet augmented with CHO supplementation (Welsh et al., 2002; Winnick et al., 2005). The findings of this investigation did not identify CHO supplementation or increased blood glucose as a perceptual catalyst. Specifically, there were no significant differences in perceptual accuracy between conditions or across occlusion times, if anything marginal learning effects were displayed.

Failing this investigation to reveal any effects of physiological perturbation or CHO on perceptual function, the above methods provide a means for future investigation to be conducted, using ecologically valid testing protocols. It remains to be discovered if CHO supplementation performs a perceptual facilitatory role in tennis, similar to that observed during other prolonged activities (Winnick et al., 2005). It is possible that the benefit of adequate blood glucose and muscle glycogen concentrations to prolonged skill-based performance is not consistent with that commonly reported in endurance sports, such a cycling and running (Bosch, Dennis, & Noakes, 1993; Coggan & Coyle, 1987). The inconsistent findings of this investigation and those of other skill-based sports (Abt et al., 1998; Ostojic & Mazic, 2002), are evidence that further work is required before carbohydrates are confidently recommended for their performance enhancement capacity. Based on the findings of this investigation, ingestion of CHO is recommended for its physiological properties only; that is, energy provision, increased fluid consumption and fluid retention (Bergeron et al., 2006) and delaying fatigue by counteracting hypoglycaemia (Coyle et al., 1986). Notwithstanding the benefits of these responses alone, further research is required to consolidate its role in tennis performance holistically. Pertaining to serve and groundstroke proficiency, the sensitivity of testing measures needs to be further tightened to ensure that subtle changes in performance associated with the intervention are able to be detected. Also, further attempts should be made to increase the ecological validity of these tests by incorporating a decision making component rather than a pre-programmed instruction to hit the ball at a target.

Caffeine supplementation.

Caffeine supplementation was chosen as an experimental strategy used to overcome the effects of fatigue on tennis performance for a number of reasons. Firstly, there is emerging and existing evidence advocating the use of caffeine to delay fatigue during prolonged endurance events of intermittent or continuous nature (C. A. Bridge & Jones, 2006; Cox et al., 2002; Ferrauti et al., 1997; Spriet et al., 1992). Secondly, the socially accepted psychoactive drug has been removed from the banned substance list of the World Anti-Doping Agency (WADA) and the International Olympic Committee. Thirdly, the supplement has central and molecular stimulatory properties (van Duinen et al., 2005), which some professional tennis players currently use and perceive to enhance performance.

Corresponding to this perception, several performance effects attributed to the caffeine supplement were identified in the current investigation. Figure 4.21 (see page 146) illustrates how serve velocity, for participants in the CAF trial, deviated away from the decreasing trend evident in all other conditions. This observation, along with the alleviation of RPE toward the latter stages of the simulated match (Figure 4.19, page 141) is indicative of a fatigue-reversal and CNS effects conferred by the caffeine supplementation (C. A. Bridge & Jones, 2006; Lorist & Snel, 1997; Smit, Cotton, Hughes, & Rogers, 2004). The ergogenic effects of caffeine were not however observed in groundstroke velocity, nor were any obvious benefits afforded to the accuracy component of both skill tests. This result is somewhat challenging of previous investigations that reported significant improvements in serve and groundstroke quality when tennis players supplemented with caffeine or caffeine + CHO during simulated match play (Ferrauti et al., 1997; Vergauwen, Brouns et al., 1998). However, the research findings are equivocal (Struder et al., 1999) and a number of methodological shortcomings have confounded results. Both Ferrauti et al. (1997) and Struder et al. (1999) chose not to measure velocity of serves or groundstrokes, and hence a speed-accuracy trade-off could not be discounted. As no improvements for stroke accuracy were observed in this or previous investigations, it could be suggested that caffeine has a greater capacity to sustain movement power than movement accuracy. Further work is required to confirm what appears to be a fatigue-resistant capability afforded to caffeine, however the enhancement of serve velocity over the duration of a prolonged match is a significant revelation. Future investigations should again look to strengthen the sensitivity of skill assessments to ensure subtle changes in performance can be detected.

The mechanism behind the increase in serve velocity over the duration of the simulated match observed in the CAF condition appears linked to the stimulatory effects of caffeine on serve kinematics. Although not significant, the racquet-arm acceleration phase of the service action (Phase 2) displayed a trend to be faster as a result of caffeine supplementation. It is suggested that the speeding-up of the throwing action phase transferred to increased angular velocity of the racquet-arm, thus imparting greater force to the ball at the point of racquet-ball impact (Elliott et al., 2003; Fleisig et al., 2003). Ultimately, this underlying kinematic process established an increase in serve speed which occurred despite a trend for reduced perceived exertion (i.e., lower perceived effort but increased force). This finding is common to previous caffeine related research (Birnbaum & Herbst, 2004; C. A. Bridge & Jones, 2006; Cox et al., 2002) and is likely linked to the stimulatory effects on the CNS (Deslandes et al., 2004, 2005).

In the current investigation there was a trend for reduced sensation of fatigue towards the latter stages of the protocol. The effects of caffeine may have been more pronounced had the protocol extended beyond that of the standardised duration. This finding corresponds to that of the CHO condition, which mitigated hypoglycaemia towards the end of the prolonged simulated match. The observed performance enhancement and fatigue resistance was associated with only modest levels of caffeine supplementation (3 $mg.kg^{-1}$) compared to previous investigations (Birnbaum & Herbst, 2004; Spriet et al., 1992). Importantly, no participants reported adverse side-effects from the intervention. Although dietary controls were imposed on participants to mitigate the effects of habitual caffeine drinkers nullifying the response to the supplement, small participant numbers did not permit an analysis of responders versus non-responders. Had this occurred, the effects of the caffeine intervention may have been more extensive and reached statistical significance.

Interventions employed in the current investigation were selected on the basis of their current usage. However a primary purpose was to determine the capacity of the experimental strategies to counteract impending physiological perturbations and the associated effects on cognition. In this instance, despite caffeine being a known stimulator of the CNS (Deslandes et al., 2005), no benefits in terms of anticipatory performance were attributed to its usage. This finding is difficult to interpret as existing literature pertaining to the effects of caffeine on performance of cognitive tasks, on most accounts advocates its stimulatory powers (Deslandes et al., 2005; Lorist & Snel, 1997; Smit et al., 2004). The comparative findings of the current investigation may be linked to type of cognitive assessment task employed. Many previous investigations have used simple measures of cognition, such as reaction time tasks. In the current investigation participants viewed and were required to respond to a tennis-specific return of serve scenario. It is possible that the added information processing linked to the response execution outweighed the benefits typically observed during performance of less complex cognitive skills. The small number of test trials, specifically pre-racquet-ball contact occlusion conditions, able to be completed in the allotted time (change of ends) may have reduced the sensitivity of the test to detect any perceptual skill changes. Alternatively, the simulated match scenarios may not have elicited equivalent central demands to that experienced in real game situations (Royal et al., 2006). Further research is therefore required to establish if caffeine supplementation is beneficial for measures of sport-specific perceptual-cognitive skill. At present, caffeine administration appears to enhance tennis performance by attenuating the sensation of fatigue, but these beneficial characteristics extend only to performance of motor skills.

Pre- and intermittent-cooling.

The purpose of the cooling intervention was to counteract the development of hyperthermia and associated performance deficits. However, temperate environmental conditions, a study limitation, hampered the ability to induce a significant degree of thermal strain. Ambient conditions over the duration of the experimental period averaged only 21.2 ± 0.3 °C and 50.4 ± 0.5% (temperature and relative humidity, respectively). These conditions are well below the ambient and court temperatures that players often experience during outdoor tournaments played in the summer months, such as the Australian Open. Ambient temperature being lower than skin temperature enabled efficient dissipation of heat produced metabolically through convection and evaporation. As a result, core body temperature over the duration of the protocol averaged only ~37.8 °C, well below the threshold (39.5 – 40.0 °C) where an athlete's health and performance is compromised (Hargreaves & Febbraio, 1998).

Despite the environmental conditions essentially precluding the thermoregulatory benefits of the cooling intervention, some pertinent performance outcomes were revealed. In contrast to the expected findings, no performance benefits (due to no thermal-induced challenge) were associated with the cooling strategy. Instead, cooling appeared to elicit a reduction in the initial measures of serve and groundstroke velocity. This can only be attributed to the precooling procedure and lower body temperature prior to the simulated match. The inhibitory effects on groundstroke velocity lasted until completion of the third set, approximately 2 hr post-cooling (illustrated in Figure 4.23, page 148). The reduction in power measures is consistent with other investigations of high intensity exercise following cooling (Mitchell, McFarlin, & Dugas, 2003). Collectively these findings may be explained by insufficient warm-up prior to performance assessment. Inhibition of muscle contractile properties, with reduced muscle and body temperature, is speculated as the mechanism for the performance reduction. This is the basis of the pre-exercise warm-up (Bergh & Ekblom, 1979). The time profiles of core body temperature (Figure 4.11, page 130) and thermal sensation (Figure 4.20, page 142) demonstrated the effectiveness of the cooling protocol to increase a player's heat storage capacity and reduce sensations of heat gain. The performance benefits of these physiological and subjective response to the precise cooling method were realised in a cycling study, conducted in a heat chamber (Quod, 2006; unpublished observations). Significant thermal strain has been reported in tennis (Therminarias et al., 1994), so it is clear that efforts should be made to counteract its manifestation. However, if a match or tournament is to be played under temperate environmental conditions, similar to the current investigation, following the precooling strategy would not be recommended.

The cooling intervention increased thermal range, which affords a greater change in core body temperature before reaching hyperthermic levels. However, the post-match increase in prolactin is a physiological concern associated with the implementation of cooling strategies during tournament tennis. Prolactin concentration is a surrogate peripheral index of central fatigue (Pitsiladis, Strachan, Davidson, & Maughan, 2002) and its peripheral concentration increased markedly above pre-match values for participants undertaking the cooling condition. This finding was supported statistically by condition comparisons of effect magnitudes. The manifestation of central fatigue during the cooling trial is difficult to explain given that RPE, T_C and HR mirrored the response to the placebo and other intervention trials. These findings are again likened to the effects of reduced core temperature on neural conduction and muscle contractile properties. For the same applied effort participants were unable to produce the same stroke power compared to the non-cooling conditions. The compound effects exacerbated central fatigue which may not be the response under warmer environmental conditions and body temperatures. Under these conditions it is postulated that the cooling intervention would afford greater performance benefits through reduced susceptibility to exercise-induced heat strain and dehydration. Future research should be conducted that induces a significant thermal loading and examines the thermoregulatory and performance effects of the current cooling manoeuvre or other alternative methods (Grahn, Cao, & Heller, 2005). Less aggressive cooling strategies or cooling only the torso and lower body may address the potential performance constraints imposed by the current protocol.

Summary

The purpose of this investigation was to examine the effect of several experimental interventions on the occurrence of adverse physiological responses and associated performance impairments that evolve over the duration of prolonged tennis matches or tournaments. The experimental strategies employed (carbohydrate ingestion, caffeine supplementation and cooling) are all very practical, are currently used by professional tennis players and each addresses a specific facet of fatigue. Individually, supplementation with a commercially available CHO drink enhanced blood glucose concentration, which mitigated the development of hypoglycaemia, but in contrast to some previous investigations failed to enhance serve or groundstroke proficiency or perceptual processes. Supplementation with a modest amount of caffeine increased serve velocity and revealed some positive trends to augment a number of the underlying biomechanical phases of the serve. In concert with the increased functional power, there was a trend for participants to perceive a reduction in exertion. This response became more pronounced towards the latter stages of the prolonged simulated match where performance deficits associated with physiological perturbations are most likely to occur. No performance benefits were associated with the cooling strategy, which in contrast appeared to reduce groundstroke velocity. However the environmental conditions under which the experiment was conducted were by no means challenging and at no stage did participants experience thermoregulatory strain, which essentially nullified the ergogenic potential of the cooling protocol.

Based on findings of the current investigation, all strategies appeared to provide some form of physiological advantage, however only caffeine supplementation afforded benefits to skills indicative of tennis performance. These findings are deduced from assessment of highly trained tennis players performing an ecologically valid prolonged simulated match. Caffeine and CHO supplements are therefore recommended as potential ergogenic strategies that could be implemented by players during training and competition, but further research is required to verify their performance enhancing capacity. Players should however trial the strategies during training, before entering competition, and consult a sport scientist for guidelines to the practices. Under conditions specific to this investigation, the cooling manoeuvre would not be recommended as a strategy to be adopted by players during competition. For matches and tournaments played under thermally challenging conditions the strategy may prove beneficial, but further research must be conducted to substantiate these claims.

It is clear that physiological compromise, regardless of its manifestation, is an ensuing response to prolonged tennis match play that detrimentally affects performance. It has also been established that simple and practical strategies exist that have the capacity to counteract fatigue-associated effects. Coaches and athletes should consider the strategies revealed here as viable adjuncts to optimize preparation through provision of an exogenous performance advantage. This investigation measured process facets of performance, perceptual skill and biomechanics, in addition to the commonly used outcome measures. Process measures are fundamental to tennis success, yet have been neglected by previous researchers. Future research should further this work and adopt a holistic approach when attempting to quantify the effects of fatigue or potential ergogenic strategies on tennis performance.

Limitations

During the experimental phase of research and on reflection of the data, several limitations of the study design became apparent. Relative to the aim of trying to induce fatigue similar to that experienced by players during a match, and attempting to mitigate the development of the various facets of fatigue through application of a number of experimental interventions, the following limitations were encountered.

An uncontrollable variable was the environmental conditions. The prolonged experimental protocol was devised to induce fatigue in its various forms, one of which being thermoregulatory strain. It was envisaged that the moderate intensity of the simulated match, would elicit a substantial degree of metabolic heat production, and when linked with challenging environmental conditions would evoke significant thermal strain. However the mild seasonal temperatures and the decision to conduct all trials indoors, to avoid disruption due to inclement weather, precluded the capacity to do so. Shielding participants from the radiative heat of the sun together with the temperate ambient conditions essentially meant that the majority of heat produced metabolically was effectively dissipated, allowing participants to remain normothermic and thus at minimal risk of performance deterioration or exercise induced heat strain. In addition to removing any performance related decrements due to thermal strain, this limitation ultimately nullified the potential for the cooling strategy to attenuate heat stress and ascribe benefits to tennis performance.

This investigation attempted to simulate the demands of a competitive tennis match, and in doing so, measure the various skills indicative of tennis performance. Regarding the assessment of groundstroke proficiency, the selected method of measurement requires standardisation and reliability yet it must possess ecological validity. The current method involved participants being instructed to hit towards a specified target at the opposite end of the court. Although this test produced quantifiable velocity and accuracy scores, it essentially removed all underlying cognitive function or information processing associated with execution of the skill under match conditions. During a match, a player will return various types of strokes according to their position on the court and more importantly, the position of the opponent, rather than the pre-programmed response that is performed here and in other field research attempts. The same can be said for measurement of serve proficiency, where the added pressures of serving for the match, or on the contrary serving to stay in the match, would increase the contextual difficulty of skill execution. Further attempts should be made to fully simulate the demands of match play, however the current research and previous investigations are positive steps towards achieving this.

Mental fatigue is a similar intangible property and its incidence during match play is common, albeit extremely difficult to quantify. Constant information processing for an extended period during competition has a mentally draining effect on the athlete. Players are constantly required to compute factors such as the opponent's strengths and weaknesses, construct points, focus between points, refocus after losing a game or set and deal with crowd interaction. Obviously, the volume of computation required during a simulated match against a ball machine is minimal. Likewise, the ability to tap into the attentional demands of the participant and induce a state of mental tiredness is significantly reduced. This factor may explain the lack of findings relative to the perceptual skill test in the current investigation. As participants were not mentally fatigued reduced perceptual performance was not observed. Future investigations should seek to incorporate mentally draining aspects into performance assessment protocols in order to completely replicate the demands of competition. This methodological issue and the construction of a research-based tournament, is addressed in the final chapter of this thesis (Chapter 5).

Maintaining participant motivation was another factor which may have contributed to the lack of fatigue and performance effects. On four separate occasions participants played a prolonged simulated match against a ball-machine. Attempts were made to fully simulate match conditions and participants were remunerated for their efforts. Regardless, the fact that players were not actually competing, either against an opponent or to receive money or ranking points, affected motivation and this was evidenced in serve and groundstroke velocity. The increase in velocity of both performance measures during the final game of the match is indicative of self-preservation, energy sparing, or a time-on-task effect as has been earlier observed in lengthy experimental protocols (Lorist & Snel, 1997). This suggests that in the current investigation players were able to perform sub-maximally, against instructions, for the majority of the match as a mechanism to offset physiological perturbations which would not be observed under match conditions as it would likely result in loss to the opponent. The ability to function below threshold stands as another obvious constraint of field research. An idealistic world may see the development of a sport science funded tennis tournament where players compete under instruction of the researcher and adhere to any number of experimental strategies. However, as with previous investigators who have trialled experimental strategies during matches and intense training protocols, standardised and controlled intensity for both opponents remains a confounding variable of the methodological approach. Withholding information on the exact duration of the experimental protocol, and simply instructing participants to perform at their highest possible level until they are instructed to stop, is an alternative logical methodology that may overcome the problem of pacing.

The capacity of the current investigation to identify mechanical alterations as the mechanism for deterioration of serve quality with physiological compromise, or enhancement with intervention may have been limited by the method of biomechanical assessment. A complete three-dimensional analysis, in comparison to the one-dimensional temporal analysis applied, would have greatly increased measurement sensitivity and quantification of the skill. However, a project such as that proposed is an enormous task and beyond the scope of this investigation.

Type two errors in the statistical analyses of results cannot be discounted as a potential limitation of the study. We used high performance athletes from an individual sport where most squad sizes are small. Additionally the competitive and travel commitments of tennis players at this level are extremely high, which greatly restricted the ability of many players to participate. The combination of these factors resulted in a limited participant pool. Therefore, it is possible that the lack of change in some performance measures could be a type II error (Drust, Waterhouse, Atkinson, Edwards, & Reilly, 2005). Calculation of effect sizes during the statistical analysis was used to overcome the limitations of a small sample size.

CHAPTER 5

CONCLUSIONS

Abstract

This thesis firstly examined the physiological responses that manifest during professional tournament tennis and the implications of these on actual performance. This knowledge provided a foundation for a second experimental phase that involved the implementation of strategies, into a simulated match play scenario, to mitigate fatigue-induced performance impairments. Adoption of a multifaceted approach to performance assessment, specifically both process and outcome performance skills, was a unique contribution to the extant literature. In particular, the integrated profile between physiology, perceptual skill and stroke kinematics demonstrated the broad nature of the thesis. The value of such an approach is highlighted through the following results. Investigation 1 revealed a qualitative reduction in serve technique during tournament match play. Investigation 2 revealed that the technical impairment could be offset by caffeine supplementation which was found to facilitate serve velocity in the latter stages of a match. Additionally, both caffeine and carbohydrate supplementation counteracted underlying facets of fatigue. The conclusions identified here are reflective of the sequential manner in which the overall conclusions of this thesis were determined. This chapter revisits the experimental pathway and recommendations are made regarding the application of the current findings to future training and match play strategies of elite tennis players. Experimental issues encountered, largely pertaining to the balance between ecological validity and experimental control, are discussed. The descriptive and experimental outcomes of the thesis revealed a number of areas that warrant further investigation, these are presented in the final sections of this chapter.

Introduction

An underlying philosophy throughout this thesis was the integrated and interdisciplinary approach used to understand the interaction between physiology and performance in tennis. Explorations of real tournament conditions and simulated field-based experimental settings were the vehicles used to accomplish this. Central to this philosophy and a logical extension to the current body of tennis science and coaching literature is the combined application of outcome and process measures of performance.

The lack of understanding of tennis physiology obtained directly from professional tournament scenarios is highlighted early in the thesis (Chapter 2) and stands as a significant area for exploration. Not possessing an accurate physiological profile of match play at this level has a number of obvious limitations for future research endeavours. Firstly, identification of the precise factors that limit tennis performance (i.e., central or peripheral mechanisms) remains undetermined and secondly, attempts to examine associated performance implications in a controlled setting are subsequently compromised. Further, this information should be the basis to drive attempts to counteract the prevalence of identified stressors and their performance constraints. The implementation of experimental strategies and training regimens targeting the specific locus of fatigue are suggested examples. Several researchers have conducted investigations along these lines, however the above issues and other methodological oversights have limited the application of the findings (E. R. Burke & Ekblom, 1982; Ferrauti et al., 1997; Magal et al., 2003; Vergauwen, Brouns et al., 1998). At present the most substantial evidence for performance deterioration *in situ* resides largely in the qualitative observations of commentators, coaches and players.

The sequential series of investigation followed in this thesis first described the fundamental physiological and performance parameters of tennis (Chapter 3, Investigation 1) and second utilised this information as a platform for experimentation (Chapter 4, Investigation 2). Specifically, Investigation 1 examined the physiological responses to tournament match play and the implications that these responses impose on performance. Investigation 2 utilised the information gathered in the previous study to devise a simulated match and implement potentially ergogenic strategies directed at the specific manifestations of fatigue. The ergogenic properties of the interventions were quantified using a multifaceted and interdisciplinary approach to performance assessment. This approach is an integral theme throughout the thesis and confers benefits to players, coaches and the various sport science disciplines. Ultimately the findings of the thesis reveal a number of areas for further exploration and these are suggested in subsequent sections. The interdisciplinary approach, although increasing the application of the findings in some ways restricted the depth of exploration of certain performance measures, these and other limitations are discussed in subsequent sections.

The Experimental Series Revisited

Investigation 1: An Integrated Physiological and Performance Profile of Professional Tennis

The first investigation in this thesis (reported in Chapter 3) addressed a fundamental gap in tennis literature by comprehensively describing physiological and performance parameters of professional tournament tennis. Previous exploratory investigations of this upper echelon of tennis have focused largely on notational analyses of match play, specifically, comparisons across different court surfaces (O'Donoghue & Liddle, 1998a, 1998b; O'Donoghue & Ingram, 2001; Richers, 1995), match play intensity and percentage playing time (Smekal et al., 2001) or alternatively injury classifications (Reece, Fricker, & Maguire, 1986). Researchers who have investigated match play scenarios limited the application of their observations by studying simulated match and tournament conditions or working with participants of a sub-professional standard (Christmass et al., 1998; McCarthy et al., 1998; Reilly & Palmer, 1994; Therminarias, Dansou, Chirpaz-Oddou, & Quirion, 1990; Therminarias et al., 1991; Vergauwen, Spaepen et al., 1998; Vodak, Savin, Haskell, & Wood, 1980).

The exploratory study firstly defined the normative morphological and tennis-specific physical capacities of a cohort of athletes that compete at the professional level. The investigation then tracked this group of players through three professional tournaments, part of the 2003/2004 Australian Summer and Autumn International Tennis Circuit. A holistic interactive profile of the notational, physiological and performance characteristics that underlie elite tennis match play was subsequently produced. The notational analysis compared favourably to results of previous investigations (O'Donoghue & Liddle, 1998a, 1998b; O'Donoghue & Ingram, 2001) and the physiological and performance components provided the impetus for further research. Physiological and performance profiles affirmed the anecdotal beliefs of scientists, coaches, players and commentators. Fatigue-associated physiological responses manifest during match play and have the potential to impair performance. Specifically, excessive losses of body fluid and thermal strain stand as the dominant adverse physiological responses to match play. In addition, the link between increases in body temperature and release of pituitary hormones (Low et al., 2005) associated with lethargy, sleepiness and mood (prolactin) also implicates central fatigue as a variable challenging proficient performance. Markers of central fatigue were not addressed in this tournament analysis, however previous research in tennis-specific scenarios (Struder et al., 1995; Struder et al., 1999) provides support for the assertion.

From a performance perspective the investigation highlighted the constraints of field-based research and the difficulty of quantifying motor performance or skill proficiency *in situ*. Despite these constraints, significant decrements in tennis skills were identified, specifically, modification to serve kinematics over the duration of a match. The qualitative analysis of the serve revealed overt technical inefficiencies with the progression of time and homeostatic disruption. Further, a number of correlations between increasing physiological demand (increasing core body temperature and body mass deficits) and outcome performance markers (first serve velocity, unforced error rate, time between points etc.) were revealed. Although these markers of performance are quite gross and influenced by a number of variables when measured *in situ*, inferences suggest that attempts to maintain homeostasis should afford ergogenic properties. The subsequent experimental phase provided a logical extension to these findings and the work of previous investigators.

Investigation 2: Caffeine, Carbohydrates and Cooling: Are These Strategies Beneficial to Tennis Performance?

The final study within the experimental series (reported in Chapter 4) examined the ergogenic properties of popular strategies used to counteract the fatigue-associated performance deterioration observed and anecdotally reported during prolonged tennis match play. The same cohort of participants was used to examine the effects of caffeine, carbohydrates and cooling on various performance skills. Using the findings of the previous study and information sourced from pertinent literature, a prolonged simulated tennis match was devised and used as the vehicle for experimentation. Physiological and performance responses were compared across interventions and to the placebo-control condition. Trial order was counterbalanced and performed in a single-blinded fashion. A multifaceted approach was applied to assess performance, furthering the work of previous investigators who used a similar methodology but a one-dimensional approach to performance (E. R. Burke & Ekblom, 1982; Ferrauti et al., 1997; Magal et al., 2003; Mitchell et al., 1992; Op 't Eijnde et al., 2001; Struder et al., 1999; Vergauwen, Brouns et al., 1998). Specifically, performance quantification involved measures of both processes (stroke kinematics and perceptual skills) and outcomes (stroke accuracy and velocity).

The results indicated specific performance and physiological benefits associated with each experimental strategy. The CHO condition significantly increased blood glucose concentration over the duration of the simulated match, but did not afford an advantage to any measure of performance. These findings challenge the work of previous investigators who reported enhanced cognitive function and motor skill proficiency in technically oriented sports through CHO ingestion (Ostojic & Mazic, 2002; Vergauwen, Brouns et al., 1998; Winnick et al., 2005), however some refuting evidence exists (Magal et al., 2003; Mitchell et al., 1992; Zeederberg et al., 1996). Future research is needed to substantiate the ergogenic effects of CHO supplementation in tennis.

The effects of caffeine ingestion 30 min prior to commencement of the simulated match were 3-fold. Increased serve velocity was evident during the latter stages of the protocol whereas other conditions demonstrated a fatigue-induced decline. This increased serve velocity, was potentially explained by a temporal analysis of serve kinematics that revealed a trend for caffeine to augment acceleration phases of the service motion. Thirdly, the increasing trend of RPE, in other conditions, appeared to be attenuated with caffeine. The mechanisms behind these findings are the psycho-stimulant effects of caffeine and its actions at the cellular and molecular level as an adenosine antagonist and a catalyst for proliferation of neurotransmitters (Fisone, Borgkvist, & Usiello, 2004; Magkos & Kavouras, 2005; van Duinen et al., 2005). Extensive literature exists on the role of caffeine in cognitive and motor performance enhancement (C. A. Bridge & Jones, 2006; Lorist & Snel, 1997) and while the mechanisms were not directly examined in this thesis, the current research tends to support previous findings. It is postulated, consistent with previous mechanistic researchers, that central stimulatory responses underscore the results (Deslandes et al., 2004, 2005).

The cooling intervention reduced perceptions of heat gain and effectively created a greater thermal range to tolerate excessive heat storage. Unfortunately, excessive heat storage was not induced due to temperate environmental conditions (21.2 $\pm$ 0.3 °C and 50.4 $\pm$ 0.5%) and the intervention appeared to inhibit the producible power of groundstrokes over the duration of the simulated match. This strategy also appeared to be associated with a proliferation of prolactin concentration which is a manifestation of central fatigue. This is not the first investigation to report performance impairment from a pre-exercise cooling manoeuvre (Mitchell et al., 2003). One possible explanation is that reduced muscle temperature and contractile function impaired performance. Altered neuromuscular properties appeared to inhibit the producible intensity during dynamic actions, evidenced here in groundstroke velocity over the duration of the match and the initial assessment of serve velocity. The findings lend support to the benefits of pre-exercise warm-up and negate the need for precooling in temperate conditions. The heightened central fatigue response is interesting as excessive heat gain is more commonly associated with a peripheral efflux of prolactin (M. W. Bridge, Weller, Rayson, & Jones, 2003; Low et al., 2005). This therefore appears to represent either a body temperature dependant response or an increase in central demand resultant of the reduced core temperature and proposed inhibition of muscle contractile properties.

The findings of this investigation support the usage of caffeine by tennis players, however debate still exists relative to the benefits of CHO supplementation and cooling strategies. All strategies appeared to confer some form of physiological advantage (i.e., increased blood glucose, reduced thermal strain, reduced perceived exertion), but only caffeine produced any measurable performance effect (increased serve velocity). Notwithstanding the importance of sustained maximal serve velocity over the duration of a match to the overall outcome of a match, no significant ergogenic properties were realised for other skills that intricately integrate to constitute match performance. Future researchers are encouraged to continue this multifaceted line of performance assessment, in the process addressing methodological limitations, to understand the true effects of these strategies on tennis performance.

Summary and Practical Applications

This experimental series provided a logical extension to the work of previous researchers and attempted to further our understanding of the physiological intricacies of tennis and ultimately enhance tennis performance. An interdisciplinary approach and the inclusion of process and outcome modes of performance assessment are examples of attempts to extend the previous literature and both methods are suggested as integral components of future research. Future research should extend on the themes and issues raised in this investigation whilst continuing to address methodological confounds of field research encountered here and by previous researchers.

From a practical perspective there is currently very little scientific explanation for overt performance deterioration in elite tennis. The conclusions of this thesis assist in removing an element of speculation relative to the underlying physiological mechanisms that evolve during match play and impair performance, for example hyperthermia, dehydration and central fatigue. This knowledge was the foundation to develop and trial strategies that addressed the specific loci of fatigue, namely ingestion of carbohydrates and caffeine or the use of cooling. Previously these strategies were used by players with minimal prescriptive guidelines or understanding of the risks or benefits afforded to the proficiency of tennis skills. Specifically, their prescription was based on inferences from other sports and anecdotal support. These strategies can now be implemented during matches, training or both with evidence-based support for their usage and prior knowledge of their efficacy. In essence, strengthening the empirical knowledge available to scientists, players and coaches regarding when and how to employ caffeine, carbohydrate and cooling strategies in tennis. These interventions may be viewed as fairly fundamental, of low risk and in some cases are already in practice, however trialling such strategies in training, before use in a competition context is recommended. This suggestion is made on the premise that some individuals display reduced responsiveness to caffeine supplementation (i.e., habitual caffeine users). Likewise, lowering core body temperature prior to commencing a match may confer physiological and performance enhancement in thermally challenging conditions.

Limitations

This section discusses the limitations encountered throughout the experimental series and suggests possible means in which they could be addressed in future research.

Investigation 1 produced an integrated profile of the physiological and performance responses to professional tournament tennis. Conducting field research offered a tremendous opportunity to accurately describe *in situ* match characteristics that cannot be completely replicated in a simulated setting. However, many variables such as the environmental conditions, match intensity and duration had the capacity to significantly influence the measured responses with little means of being controlled. Apart from gross performance measures such as games won and error rates, performance quantification is also difficult without interfering with the natural dynamics of the match or having prior knowledge of the players' intentions. Additionally, in Grand Slam tournaments, men's matches are contested over a minimum of 3 sets (maximum of 5 sets). The matches studied in this phase were contested over a maximum of 3 sets and adverse physiological conditions still precipitated. One can only assume a more profound physiological cost and a proportional increase in the task complexity would occur with an increase in match duration alone.

In order to overcome the limitations experienced during Investigation 1, a prolonged simulated tennis match was developed for experimental purposes in Investigation 2. The match was used as a tool to assess the effects of time and physiological perturbations on skills indicative of performance, and the ability of experimental strategies to counteract performance deterioration. Investigations of this nature have been attempted previously (E. R. Burke & Ekblom, 1982; Op 't Eijnde et al., 2001; Struder et al., 1999; Vergauwen, Brouns et al., 1998) however methodological shortfalls, primarily compromised ecological validity of the protocol, limited the findings. Attempting to build on previous efforts, the current protocol was constructed to elicit an intensity and physiological response equivalent to that observed in match conditions. A ball machine was used to ensure reliability, repeatability and to control intensity however this process alone immediately compromised ecological validity. The ball machine removed a significant amount of contextual information and information processing required of the participant in addition to challenging their ability to sustain motivation. Notwithstanding the limitations of the ball machine, the simulated match conditions allowed a comprehensive performance assessment which was not possible under tournament conditions. Construction of an experimental tournament may be a means around this in future investigations and the logistics of this concept are suggested in the future directions sections of this chapter.

Beyond the limits of control in Investigation 2 were the mild environmental conditions in which experimental trials were conducted. This is an obvious methodological limitation as challenging temperature and relative humidity, reflective of the conditions encountered by players during many professional tournaments, would have been likely to induce greater levels of physiological perturbation and performance impairment. Likewise, more intense playing conditions may have ascribed greater ergogenic properties to the interventions. The effects of thermal strain on tennis performance have received little scientific attention. It is therefore suggested that future researchers examine the implications of thermally challenging conditions on skills integral to tennis success.

Perceptual-cognitive skill is an underlying ability of tennis success and accurate discriminator of expert and novice players (Davies & Housner, 2004; Goulet et al., 1989;

Rowe & McKenna, 2001). This investigation did not reveal any effects of physiological perturbations or interventions on perceptual function, however there are several potential explanations. Measurement of perceptual skill was conducted using a tennis-specific return of serve test. This test holds greater ecological validity than numeracy and literacy-based devices previously used to measure perceptual-motor capacity (Blomstrand, Hassmen, & Newsholme, 1991; Deslandes et al., 2005; Gonzalez, 1997; Gopinathan et al., 1988; Welsh et al., 2002; Winnick et al., 2005). The testing scenario was conducted in a field setting which likely attracted greater performance variability, compared to that of a laboratory-based assessment. Trends for learning effects were revealed in the statistical analysis, suggesting the need to spend great time completing familiarisation trials with participants. An alternative explanation for the lack of perceptual skill deficit identified was raised in a simulated water polo testing scenario (Royal et al., 2006). It is suggested that game-like testing protocols do not replicate the central loading (i.e., concentration, information processing) experienced during match play and hence do not impact perceptual performance. Physiological markers confirm the ability to induce homeostatic disruptions, however the limited information processing and decision making demands of a simulated match may not have induced sufficient mental fatigue that is associated with competitive performance. Future researchers should consider these factors when attempting to further the current understanding of game-specific perceptual-motor performance.

Lack of measurement sensitivity has been previously suggested as a limitation of similar investigations seeking to identify significant performance modifications within experimental situations. This may also be the case for the current investigation with measures of serve and groundstroke accuracy possibly being incapable of detecting subtle changes in performance due to physiological compromise or the interventions. However there may also be an alternative explanation. Tests of this nature may inadvertently require players to adjust their stroke intentions in a manner inconsistent with typical match play. Hitting a "winner" in real match scenarios does not demand the ball to be aimed at the perimeter of the court, as were the instructions given to participants here. Despite the explicit instructions, the players' intention may have been to simply get the ball in, therefore reducing the emphasis placed on finite accuracy.

Test sensitivity issues were also central to the biomechanical analysis of the serve. The phase temporal analysis, while an improvement from the qualitative procedure used during Investigation 1, still could be improved. Specifically, a more elaborate three-dimensional analysis would have produced greater quantification of the skill and each of its technical components. Due to time, expertise and expenses associated, a three-dimensional analysis was beyond the scope of this project. Irrespective, the one-dimensional phase temporal analysis identified a number of interesting findings which warrant further exploration.

Future Directions for Tennis Performance and Physiology-Based Research

There are a number of obvious constraints to research conducted during actual tennis tournaments. These were encountered in this experimental series and identified as shortfalls in previous investigations. In order to overcome the constraints of field research future investigators are urged to consider constructing a complete experimental tennis tournament. This approach would enable an abundance of information to be obtained across a number of performance measures and sport science disciplines. Minor match and rule modifications may be in-place to ensure that all physiological and performance components of interest are addressed. For example players and racquets, or both, may be fitted with measurement devices that, while not modifying performance, are not otherwise allowed under the rules of the ITF. Participants could be specifically selected to ensure a homogenous sample and direct application of the findings to the elite tennis population. Statisticians, technological innovators, psychologists and coaches would form part of the research team to measure their respective components of the match or player. Tournament sponsorships, commercial and media support would enable prize money to be offered, an added incentive for players to compete in addition to increasing extrinsic motivation to be victorious.

Irrespective of the research setting, efforts should be made to further advance the methods of performance assessment. Measurement sensitivity issues are a common theme to field tests and one that could be easily rectified through usage of advance technical products, such as Hawk-Eye™. This is a sports tracking device which uses a system of cameras positioned around the court to track ball flight and landing positions relative to court sidelines. It is recognised that these products attract additional expense, however it may be what is required to identify the subtle performance responses under experimentation. Process facets of performance (stroke kinematics and perceptual skills) were quantified in this instance, the results encouraging further exploration. This investigation illustrated a mechanistic link between a fatigue-induced reduction in serve velocity and increased duration of key temporal phases of the service motion that contribute to racquet head velocity. Supplementation with caffeine prior to the match displayed encouraging trends to reverse fatigue-induced temporal slowing. Further investigation is warranted to increase the understanding of this relationship, specifically its mechanisms and those that underscore kinematic capitulation. Researchers could also extend such analyses to other strokes. To increase the sensitivity and quantification of performance measures it is recommended that future investigators employ elaborate performance assessment methods and software, such as a three-dimensional analysis.

The tennis-specific return of serve perceptual skill test reflected the emphasis on ecologically valid testing measures. Not without its limitations, as previously discussed, more elaborate methods of assessment exist that should be incorporated into future investigations. For example, Farrow and Abernethy (2003) described perception-action coupled test settings as a more effective means of examining perceptual skill as it more closely replicates the perceptual-motor constraints typically experienced by players. It is recommended that this field is explored further and that investigators incorporate a movement related or skill execution (coupled) response into the testing apparatus.

The implementation of cooling strategies as part of the pre-, during- and post-match routine of players is a fruitful direction for future research endeavours. The precooling protocol administered in the second experimental phase of this thesis was quite aggressive (whole body immersion), relative to the mild environmental conditions in which simulated matches were conducted. As a result the cooling strategy appeared to induce inhibitory capacities on stroke power which did not dissipate until the latter stages of the match. Perhaps cooling only the lower body (not the predominately active musculature during stroke production – racquet-arm and shoulder) would enhance thermoregulation but not inhibit force. Thermoregulatory aid was not however required due to the temperate environmental settings of the current investigation. It is proposed that when matches are played under hot and humid conditions the reduction in core temperature and thermal sensation would decrease both the susceptibility to exercise-induced heat strain and associated performance implications. Further exploration with this and other topical cooling modalities (Grahn et al., 2005) over a range of environmental conditions will generate accurate prescription guidelines for cooling, and identify what strategy is most suitable and effective. Cooling research should also be extended to other tennis populations. For example, some wheelchair tennis players (spinal lesion classifications) display greatly restricted sweat rate which severely reduces the capacity to dissipate heat. Cooling this athlete population could effectively reduce susceptibility to heat strain and illness, not to mention the potential performance benefits.

Benefits to the tennis community and a wider audience (other sports and therapists) will prevail from applied research into injury prevention. Investigations 1 and 2 both demonstrated a mild pre- versus post-match increase in plasma CK concentration. Proliferation of this blood metabolite is an indirect marker of muscle damage and occurs particularly when the activity or exercise involves eccentric loading (Cheung et al., 2003; Evans & Cannon, 1991). Eccentric contraction of the shoulder musculature is central to tennis stroke production as the agonists and antagonist muscles fire in synchrony to rapidly accelerate and decelerate the racquet arm. This biochemical response is accompanied by a loss of contractile force and the sensation of soreness, despite the magnitude of fibre damage being reduced by conditioning (Armstrong et al., 1991). Given the acute response to a single match or simulated match, as observed in the experimental phases of this thesis, efforts should be made to determine if the response is compounded over the course of a tournament. Therapeutic and prophylactic modalities should also be investigated to reduce the occurrence of injury associated with premature return to match play or inadequate recovery between matches.

The final recommendation for future research that should be pursued pertains to the prevalence of central fatigue in tennis and the implications to performance. It remains undiscovered how tennis performance can deteriorate in comfortable playing conditions where players would be unlikely to display the more common adverse physiological conditions such as cardiorespiratory strain, hyperthermia, hypoglycaemia or dehydration. Early work by Struder et al (1995) demonstrated increases in markers of central fatigue (TRP:BCAA) during 4 hr of tournament style tennis, however no attempt was made to quantify performance. Deterioration of some performance skills, relative to the placebo-control trial in the current investigation, was observed over the duration of the simulated match, with no obvious physiological explanation. The cooling application induced the most profound increase in central fatigue markers which is either a body temperature dependent response or reflective of a central response to the inhibition of muscle contractile properties. These suggestions are largely speculative and it is clear that further exploration of this area is required.

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APPENDIX

Appendix A

Chapter 3 – Investigation 1: The serve kinematic checklist used as a tool by coaches to conduct the qualitative performance analysis.

Serve Kinematic Checklist		
Player		
Serve/File No. 1st / 2nd Court - Deuce / Ad	Yes	No
Swing		
Maintenance of smooth, fluid action (momentum), including racquet speed		
* Intensity of action		
Hip and shoulder rotation (torsion/stretch)		
Sequence of body segments (kinetic chain)		
* If No, please specify:		
Knee flexion and extension		
Tossing Arm		
Height when ball released (consistent/not consistent)		
Consistency in positioning of toss and ball release		
Landing		
Change in distance of landing inside the court after impact		

Appendix B

Chapter 3 – Investigation 1: Comparative environmental conditions measured during men's professional tournament tennis matches played on hard and clay courts. Values represent those of all matches, with participants appearing in the data set on only one occasion (n = 10). Values presented are mean $\pm$ *SD*, maximum and minimum. T_{WB} = Wet bulb temperature.

	Hard court		Clay court	
	mean $\pm$ *SD*	min - max	mean $\pm$ *SD*	min - max
Temperature (°C)	31.4 $\pm$ 6.1	18.2 - 43.1	25.2 $\pm$ 4.3	19.1 - 36.5
Relative humidity (%)	39 $\pm$ 18	12 - 75	32 $\pm$ 7	17 - 43
Wind speed ($m \cdot s^{-1}$)	1.7 $\pm$ 2.1	0.0 - 10.8	1.2 $\pm$ 1.1	0.0 - 5.3
T_{WB} (°C)	21.2 $\pm$ 2.3	15.9 - 26.5	15.7 $\pm$ 2.5	11.7 - 23.7
Court temperature (°C)	40.0 $\pm$ 5.1	31.7 - 51.5	34.1 $\pm$ 4.1	24.6 - 42.7

Appendix C

Chapter 3 – Investigation 1: Comparative physiological responses measured during men's professional tournament tennis matches played on hard and clay courts. Values represent those of all matches, with participants appearing in the data set on only one occasion (*n* = 10). Values presented are mean ± *SD*, maximum and minimum. BGL = Blood glucose; CK = Creatine kinase.

	Hard court		Clay court	
	mean ± *SD*	min - max	mean ± *SD*	min - max
Peak core temperature (°C)	38.90 ± 0.27	38.62 - 39.26	38.68 ± 0.56	37.9 - 39.5
Sweat rate (kg·hr^{-1})	2.25 ± 0.63	1.53 - 3.47	1.52 ± 0.44	0.97 - 2.48
Body mass deficit (%)	-1.17 ± 0.69	-0.17 - -2.44	-0.38 ± 0.63	+0.64 - -1.19
Fluid consumed vs. fluid lost (%)	74 ± 17	34 - 94	87 ± 24	64 - 133
Average heart rate (bpm)	149 ± 15	137 - 173	150 ± 15	130 - 167
Pre-match BGL (mmol·L^{-1})	5.6 ± 0.9	4.5 - 7.1	6.5 ± 1.9	3.8 - 10.4
Post-match BGL (mmol·L^{-1})	7.2 ± 2.0	3.6 - 9.1	9.1 ± 2.5	6.3 - 14.6
Pre-match CK (U·l^{-1})	158	158 -158	361 ± 280	134 - 1135
Post-match CK (U·l^{-1})	470	470 - 470	437 ± 326	161 - 1337
Pre-match creatinine (umol·L^{-1})	66 ± 11	48 - 79	78 ± 6	69 - 89
Post-match creatinine (umol·L^{-1})	86 ± 15	66 - 107	95 ± 9	77 - 113
Pre-match urea (mmol·L^{-1})	5.7 ± 1.7	3.5 - 8.2	6.5 ± 0.6	5.4 - 7.4
Pre-match uric acid (umol·L^{-1})	329 ± 77	176 - 387	332 ± 40	264 - 412
Urine specific gravity	1.023 ± 0.004	1.015 - 1.030	1.020 ± 0.005	1.013 - 1.028

Appendix D

Chapter 3 – Investigation 1: Comparative performance indicators of men's professional tournament tennis matches played on hard and clay courts. Values represent those of all matches, with participants appearing in the data set on only one occasion (*n* = 10). Additionally, values represent those of only the player participating in the investigation. Values presented in parentheses (*N*) represent the number of data from which mean and standard deviation are derived. Values presented are mean ± *SD*.

	Hard court	Clay court
	mean ± *SD*	mean ± *SD*
First serve velocity (kph)	175 ± 12 (*N* = 655)	169 ± 14 (*N* = 655)
Second serve velocity (kph)	137 ± 13 (*N* = 254)	130 ± 13 (*N* = 375)
First serve accuracy (%)	61 ± 24	59 ± 23
Points won on first serve (%)	71 ± 30	72 ± 27
Points won on second serve (%)	61 ± 37	56 ± 37
Unforced Errors (%)	25 ± 14	26 ± 17

Appendix E

Chapter 3 – Investigation 1: Comparative notational analyses of men's professional tournament tennis matches played on hard and clay courts. Values represent those of all matches, with participants appearing in the data set on only one occasion (*n* = 10). Values presented are mean ± *SD*, maximum and minimum.

	Hard court		Clay court	
	mean ± *SD*	min - max	mean ± *SD*	min - max
Match duration (min)	106 ± 33	76 - 171	86 ± 28	61 - 159
Rally duration (s)	6.7 ± 2.3	3.1 - 15.0	8.2 ± 3.4	2.8 - 21.1
Shots per rally	4.6 ± 1.4	2.0 - 8.4	5.1 ± 2.2	2.3 - 13.3
Direction changes per rally	2.6 ± 0.8	1.0 - 5.0	2.9 ± 1.4	1.2 - 8.4
Time between games (s)	61.2 ± 18.8	23.9 - 110.4	51.8 ± 19.9	8.0 - 117.5
Time between points (s)	23.5 ± 5.3	10.9 - 34.4	18.4 ± 3.8	10.2 - 28.8
Time between serves (s)	11.5 ± 3.3	5.2 - 23.4	10.5 ± 2.3	7.6 - 24.4

Appendix F

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, environmental conditions and performance indicators. The correlation matrix was conducted using pooled data from hard and clay court tennis matches. Correlations were conducted using full match data (* represents $p < 0.05$). T_{WB} = Wet bulb temperature.

Physiological variables & environmental conditions	Performance indicators					
	First serve velocity	Second serve velocity	First serve percentage	Points won on the first serve	Points won on the second serve	Unforced errors
Elapsed time	0.555*	-0.033	-0.112	-0.016	0.313	-0.094
Core temperature	0.309	0.041	-0.209	0.101	0.161	-0.032
Body mass deficit	-0.182	-0.177	-0.243	0.213	-0.265	-0.109
Heart rate	0.486*	-0.338	-0.227	0.314	0.176	-0.183
Ambient temperature	0.176	-0.468*	-0.324	0.172	0.271	-0.174
Wind speed	0.077	0.495*	0.033	-0.148	-0.073	0.201
T_{WB}	-0.001	-0.262	0.035	0.110	0.471*	-0.156

Appendix G

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, environmental conditions and serve kinematics. The correlation matrix was conducted using pooled data from hard and clay court tennis matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$). T_{WB} = Wet bulb temperature.

Physiological variables & environmental conditions	Serve kinematics				
	First serve		Second serve		
	Consistency of arm height at ball release	Consistency of ball toss height & position	Consistency of arm height at ball release	Consistency of ball toss height & position	Consistency of landing position
Elapsed time	0.684**	0.487*	0.492*	-0.169	-0.275
Body mass deficit	-0.309	-0.524*	-0.240	0.436	0.504*
Heart rate	0.672**	0.358	0.422	0.221	0.039
Relative humidity	0.156	0.301	0.130	-0.508*	-0.584*
T_{WB}	0.264	0.653**	0.231	-0.213	-0.276
Wind speed	-0.144	-0.138	-0.170	-0.540*	-0.470
Court temperature	0.565*	0.539*	0.344	-0.241	-0.255

Appendix H

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, notational analyses and environmental conditions. The correlation matrix was conducted using pooled data from hard and clay court tennis matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$). RH = Relative humidity; T_{WB} = Wet bulb temperature.

Physiological variables	Notational analyses and environmental conditions								
	Inter-game time	Inter-point time	Inter-serve time	Shots per rally	Direction changes per rally	Rally duration	RH	T_{WB}	Court temperature
Elapsed time	0.400	0.750**	0.370	0.599**	0.646**	0.537*	0.336	0.558**	0.765**
Core temperature	0.598*	0.538*	-0.465	0.489*	0.512*	0.479	-0.465	0.094	0.331
Body mass deficit	-0.341	-0.636**	-0.688**	-0.497*	-0.684**	-0.347	-0.758**	-0.609**	-0.742**
Heart rate	0.301	0.572*	0.358	0.342	0.344	0.352	-0.460*	0.304	0.312

Appendix I

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, performance indicators, notational analyses and environmental conditions. The correlation matrix was conducted using data from only hard court tennis matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$).

Physiological variables	Performance indicators, notational analyses and environmental conditions							
	First serve velocity	Points won on the second serve	Inter-game time	Inter-point time	Inter-serve time	Unforced errors	Ambient temperature	Court temperature
Elapsed time	0.623**	0.450*	0.304	0.501*	0.277	-0.136	-0.019	0.394
Core temperature	0.169	0.257	0.614*	0.418	-0.645**	0.010	0.072	0.459
Body mass deficit	-0.522*	-0.315	-0.393	-0.419	-0.124	0.059	0.140	-0.590**
Heart rate	-0.626**	0.092	0.121	0.146	-0.073	0.549*	-0.486*	-0.429

Appendix J

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, performance indicators and notational analyses. The correlation matrix was conducted using data from only clay court matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$).

Physiological variables	Performance parameters and notational analyses							
	First serve velocity	Second serve velocity	First serve percentage	Inter-point time	Inter-serve time	Rally duration	Shots per rally	Direction changes per rally
Elapsed time	0.491	-0.679**	0.487*	0.748**	0.345	0.691**	0.733**	0.799**
Core temperature	0.184	-0.383	0.394	0.507*	0.040	0.447	0.456	0.479
Body mass deficit	0.924**	-0.663**	0.637**	0.769**	0.627**	0.850**	0.867**	0.855**
Heart rate	0.731**	-0.652**	0.557*	0.820**	0.621**	0.786**	0.808**	0.842**

Appendix K

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, environmental conditions and serve kinematics. The correlation matrix was conducted using data from only clay court matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$). T_{WB} = Wet bulb temperature.

Physiological variables & environmental conditions	Serve kinematics			
	First serve			
	Consistency of hip & shoulder rotation - separation angle	Consistency of arm height at ball release	Consistency of ball toss height & position	Consistency of landing position
Elapsed time	-0.062	0.428	0.638**	0.783**
Body mass deficit	0.165	0.618*	0.525*	0.751**
Heart rate	0.130	0.559*	0.585*	0.741**
Ambient temperature	-0.548*	-0.439	-0.114	-0.409
Relative humidity	0.256	-0.345	-0.495	-0.782**
T_{WB}	-0.294	-0.398	-0.151	-0.549*

Appendix L

Chapter 3 – Investigation 1: Correlations (*r* values) between physiological responses, environmental conditions and serve kinematics. The correlation matrix was conducted using data from only clay court matches. Correlations were conducted using full match data (* represents $p < 0.05$, ** represents $p < 0.01$).

Physiological variables & environmental conditions	Serve kinematics		
	Second serve		
	Consistency of sequence of body segments - kinetic chain	Consistency of ball toss height & position	Consistency of landing position
Body mass deficit	0.165	0.568*	0.554*
Heart rate	0.130	0.853**	0.578*
Ambient temperature	-0.548*	-0.332	-0.449

Appendix M

Chapter 4 – Investigation 2: The effect size colour classification key used to identify effect magnitudes within the subsequent raw data sheets.

Effect Sizes Key		
	Very Large	> 2.0
	Large	1.2 - 2.0
	Moderate	0.6 - 1.2
	Small	0.2 - 0.6
	Trivial	< 0.2

Appendix DD

Chapter 4 - Investigation 2: Perceptual skill (accuracy) measured from occluded footage over the duration of each trial and condition. Comparative effect magnitudes are presented below.

PLACEBO

Subject	Pre	S1R1	S1R2	S1R3	S2R1	S2R2	S2R3	S3R1	S3R2	S3R3	S4R1	S4R2	S4R3	Average
1	50	50	83	67	50		50	50	83	50	17	33	67	54
2	83	83	100	100	100	83	100	83	83	83	83	100	100	91
3	100	100	83	100	100	100	100	100	100	83	100	100	100	97
4	100	83	67	67	100	100	100	100	100	83	83	100	*	90
5	83	100	100	83	100	83	100	100	83	67	67	100	83	88
6	17	67	33	33	50	83	67	17	0	83	83	50	33	47
7	100	83	100	100	67	100	83	83	100	100	67	83	83	88
8	33	83	67	67	50	67	50	100	67	67	67	83	100	69
9	50	50	67	50	50	67	33	17	17	50	67	67	50	49
10	67	83	83	67	100	100	67	100	67	100	83	67	83	82
11	67	83	100	100	83	67	100	100	100	83	83	83	100	88
12	100	83	83	100	100	100	67	100	100	83	100	83	100	92
Mean	71	79	81	78	79	86	76	79	75	78	75	79	82	78
SD	29	16	20	23	24	15	24	33	34	16	22	21	23	23
2SD	57	32	40	46	47	29	48	65	67	33	44	43	46	46
Max	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Min	17	50	33	33	50	67	33	17	0	50	17	33	33	33

CARBOHYDRATES

Subject	Pre	S1R1	S1R2	S1R3	S2R1	S2R2	S2R3	S3R1	S3R2	S3R3	S4R1	S4R2	S4R3	Average
1	67	67	67	50	67	50	67	50	83	50	83	50	100	65
2	50	33	50	50	50	33	50	67	67	67	83	83	67	58
3	100	83	100	100	67	100	100	83	100	100	100	100	100	95
4	100	83	83	83	83	100	83	100	83	100	83	100	100	91
5	67	100	100	100	100	100	67	100	100	100	100	100	67	92
6	83	83	100	100	100	100	100	100	100	100	100	100	100	97
7	50	67	100	83	67	50	83	100	83	67	83	67	50	73
8	83	50	83	83	50	83	67	83	100	50	83	83	67	74
9	33	50	50	67	83	100	33	33	50	67	50	33	67	55
10	50	67	83	100	100	83	83	83	100	100	83	67	83	83
11	33	67	0	67	50	33	67	33	67	100	83	100	83	60
12	100	100	67	67	83	83	83	83	67	83	100	67	83	82
Mean	68	71	74	79	75	76	74	76	83	82	86	79	81	77
SD	25	20	30	19	19	27	19	25	17	21	14	23	17	21
2SD	50	41	59	38	39	54	39	50	35	41	28	45	34	43
Max	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Min	33	33	0	50	50	33	33	33	50	50	50	33	50	38

CAFFEINE

Subject	Pre	S1R1	S1R2	S1R3	S2R1	S2R2	S2R3	S3R1	S3R2	S3R3	S4R1	S4R2	S4R3	Average
1	83	50	67	50	67	0	50	50	67	50	50	50	50	53
2	83	67	83	100	83	33	83	100	100	100	83	100	100	86
3	100	100	100	100	100	100	100	100	100	100	100	100	100	100
4	100	100	100	83	100	100	100	100	67	83	100	100	83	94
5	100	100	100	100	83	*	100	100	100	100	67	100	100	96
6	67	50	17	50	83	50	67	67	67	33	100	83	50	60
7	17	50	83	83	67	83	67	83	83	67	67	67	50	67
8	83	67	17	33	67	67	83	83	83	83	67	33	50	63
9	67	33	33	50	83	50	50	50	67	67	33	17	67	51
10	67	83	50	83	100	100	100	100	67	67	83	100	67	82
11	67	100	100	100	83	83	100	83	100	83	100	100	100	92
12	83	83	100	100	100	83	100	100	100	100	100	100	*	96
Mean	76	74	71	78	85	68	83	85	83	78	79	79	74	78
SD	23	24	33	25	13	32	20	19	16	22	23	30	23	23
2SD	46	48	67	50	26	64	40	39	32	43	45	61	46	47
Max	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Min	17	33	17	33	67	0	50	50	67	33	33	17	50	36

COOLING

Subject	Pre	S1R1	S1R2	S1R3	S2R1	S2R2	S2R3	S3R1	S3R2	S3R3	S4R1	S4R2	S4R3	Average
1	67	83	83	50	50	83	17	50	67	50	67	83	83	64
2	67	83	100	100	67	100	83	83	100	100	100	83	83	88
3	83	100	83	83	100	67	83	100	67	100	100	100	83	88
4	67	33	100	83	67	83	83	67	100	83	100	83	50	77
5	100	100	100	83	100	67	100	100	100	100	83	67	67	90
6	67	100	100	100	100	100	83	100	100	100	100	100	83	95
7	83	67	67	83	67	83	83	50	67	100	100	83	100	79
8	100	83	67	83	100	83	100	67	100	100	83	100	100	90
9	67	50	83	67	67	67	50	67	67	50	67	33	50	60
10	83	100	100	50	100	67	17	83	100	50	83	67	83	76
11	100	67	67	83	50	83	100	83	100	83	83	100	100	85
12	33	67	83	67	83	33	50	17	33	100	50	83	50	58
Mean	76	78	86	78	79	76	71	72	83	85	85	82	78	79
SD	19	22	14	16	20	18	30	25	22	22	17	19	19	20
2SD	39	43	28	33	41	36	61	50	45	44	33	39	38	41
Max	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Min	33	33	67	50	50	33	17	17	33	50	50	33	50	40

Effect Sizes

Conditions	Pre	S1R1	S1R2	S1R3	S2R1	S2R2	S2R3	S3R1	S3R2	S3R3	S4R1	S4R2	S4R3	Average
Pla v Cho	0.10	0.46	0.28	-0.07	0.19	0.48	0.13	0.10	-0.33	-0.22	-0.62	0.00	0.06	0.05
Pla v Caf	-0.22	0.28	0.36	0.00	-0.30	0.78	-0.31	-0.21	-0.34	0.00	-0.19	0.00	0.33	0.02
Pla v Cool	-0.23	0.07	-0.33	0.00	0.00	0.61	0.205	0.24	-0.30	-0.36	-0.50	-0.14	0.19	-0.04
Cho v Caf	-0.35	-0.13	0.09	0.06	-0.595	0.28	-0.49	-0.37	0.00	0.197	0.38	0.00	0.32	-0.03
Cho v Cool	-0.37	-0.33	-0.57	0.08	-0.21	0.00	0.11	0.17	0.00	-0.13	0.09	-0.13	0.15	-0.09
Caf v Cool	0.00	-0.18	-0.65	0.00	0.33	-0.33	0.50	0.56	0.00	-0.32	-0.28	-0.11	-0.17	-0.06