Physiological responses to “all-out” and even-paced cycling intervals

Emma K. Zadow

2012

This thesis is submitted as partial fulfilment of the requirements for the degree of Bachelor of Sports Science (Honours) at Murdoch University, Perth, Western Australia.
I declare that this thesis is my own account of my research and contains, as its main content, work which has not previously been submitted for a degree at any tertiary education institution.

(Miss Emma K. Zadow)
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Author: Miss Emma K. Zadow

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ABSTRACT

Background: Endurance cyclists typically devote ~20% of their training regimens to performing low-volume high-intensity interval training which is associated with large physiological and performance benefits. The relationship between intensity and duration is important during high-intensity interval training as both can profoundly influence metabolic energy expenditure, fatigue development and subsequent adaptations. Purpose: Within the literature, most interval training is delivered using either an "all-out" or even-paced approach; however, to the author’s knowledge no study has yet compared the metabolic stress, perceived exertion and fatigue resulting from such intervals. Therefore, this study compared the physiological and perceptual responses to matched mechanical work interval bouts using “all-out” and two different even-paced methodologies (i.e. computer- and athlete-controlled). Methods: In a randomised design, 15 male trained cyclists (age: 39 ± 8 years, body mass: 79.4 ± 8.2kg, VO₂max: 59.8 ± 6.5 ml·kg⁻¹·min⁻¹, peak power: 436 ± 27 W) performed one incremental maximal exercise test, one familiarisation session and three experimental high-intensity interval sessions implementing one of three pacing strategies; (i) “all-out”, (ii) computer-controlled and (iii) athlete-controlled. All experimental sessions were work- matched and consisted of three 3-minute intervals with three minutes of recovery. A 4 km time trial was completed twenty minutes following each experimental interval session to assess measured levels of latent fatigue. Oxygen consumption, heart rate and perceived exertion, pain and effort were recorded throughout the high-intensity interval sessions with average power output and heart rate measured throughout
the 4 km time trial. **Results:** Overall greater (p<0.001) oxygen consumption was observed in the “all-out” condition (54.1 ± 6.6 ml.kg\(^{-1}\).min\(^{-1}\)) compared with the computer- (51.5 ± 5.7 ml.kg\(^{-1}\).min\(^{-1}\)) and athlete-controlled conditions (53.0 ± 5.8 ml.kg\(^{-1}\).min\(^{-1}\)). Furthermore, the time spent at 85% VO\(_{2\text{max}}\) was greater (p<0.001) during the “all-out” trial when compared with computer- and athlete-controlled trials. Sessional perceived exertion was greater in the “all-out” trial when compared with the computer- (p<0.001) and athlete-controlled (p<0.05) conditions. Average power output measured during the 4 km time trial was lower (p<0.001) after the “all-out” session compared with both even-pacing strategies. **Conclusion:** Our findings indicate irrespective of work completed, greater physiological stress was observed within an “all-out” interval training approach when compared with both athlete- and computer- controlled conditions, resulting in greater latent fatigue as measured by 4 km time trial performance. The selections of pacing strategies are likely to play a key role in interval training and should be acknowledged throughout exercise prescription.
DEFINITION OF TERMS

For consistency of interpretation the preceding words are defined:

**Active recovery:** Low-intensity exercise completed between interval repetitions.

**“All-Out”:** A maximal acceleration produced over a set period of time with a higher power output at the beginning of an exercise/interval session.

**Athlete-controlled:** Pacing selection internally controlled via the manipulation of gear ratio and cadence to achieve a nominated power output.

**Computer-Controlled:** Pacing selection with a fixed power output externally controlled for a predetermined period of time.

**High-Intensity interval training:** Physical exercise that is characterized by brief, intermittent bursts of vigorous activity, interspersed by periods of rest/low-intensity exercise.

**Interval training:** Repeated bouts of vigorous exercise interspersed with recovery periods.
ABBREVIATIONS

Selected abbreviations used throughout the text

ANOVA: analysis of variance
AO: “all-out”
CT: continuous training
dw: dry weight
HIT: High-intensity interval training
HR\text{max}: maximum heart rate
km: kilometer
min: minute
PGC-1\alpha: peroxisome-proliferator activated receptor \gamma co-activator
PPO: peak power output
REP: repetitions
s: second
TT: time trial
Ve BTPS: expired ventilation body temperature and pressure saturation
VT\textsubscript{1}: ventilatory threshold one
W: watt
wk: week

AC: athlete-controlled
CC: computer-controlled
D: day
EVA: exposure variation analysis
HR: heart rate
kJ: kilojoule
m: meter
mmol/L: millimoles per litre
P\text{max}: power associated with maximal aerobic capacity
PTS: peak treadmill speed
RPE: rating of perceived exertion
T\text{max}: time associated with maximal aerobic capacity
VAS: visual analogue scale
VO\textsubscript{2max}: maximal aerobic capacity
VT\textsubscript{2}: ventilatory threshold two
W:R: work to rest ratio
CHAPTER ONE: INTRODUCTION

1.1. BACKGROUND TO THE STUDY

Cycling performance is largely influenced by one’s maximal aerobic capacity (VO$_{2\text{max}}$), metabolic thresholds (i.e. lactate or ventilation thresholds) and economy of motion $^{[1-5]}$. In an attempt to improve endurance exercise performance, cyclists have historically spent approximately 80% of their training time performing prolonged (>1-2 hour) low to moderate training $^{[6]}$, which can significantly enhance oxygen delivery, oxygen utilisation and exercise performance $^{[1, 2, 7, 8]}$. The use of high-intensity interval training (i.e. physical exercise that is characterized by brief, intermittent bursts of vigorous activity, interspersed by periods of rest/low-intensity exercise) has been shown to induce similar improvements in maximal aerobic capacity, metabolic thresholds, cardiovascular dynamics, and maintenance of acid-base balance with a delayed onset of fatigue $^{[2-5, 7, 9-13]}$. Furthermore, high-intensity interval training has been shown to result in superior increases in cycling performance when compared with traditional low-intensity continuous training $^{[13, 14]}$ as it more likely reflects the true stochastic nature of racing. As high-intensity interval training can provide significant metabolic, aerobic and performance improvements to cyclists, significantly reducing the necessary training time, $^{[7, 15, 16]}$ this technique is now a common training practice in this population $^{[4, 6, 11, 17]}$.

The accumulation of long periods of time cycling at high-intensities has been proposed to be the catalyst responsible for the training adaptations observed after high-intensity interval training $^{[4, 5, 15, 16, 18-20]}$. Indeed, as work bouts are interspersed with active or passive periods of rest, athletes are able to capitalise on the time
spent at higher workloads \cite{10} resulting in significant vascular shear and metabolic stress which in turn promotes favourable physiological adaptations which underpin performance improvements \cite{2, 19, 21-24}. Although the benefits of high-intensity interval training are well documented \cite{11, 13, 15, 17}, conjecture exists with regards to optimal volume of intensity and/or duration in which to prescribe interval sessions \cite{2, 3, 5, 15, 25, 26}. Cycling intensity and duration are inversely related and both significantly influence the demands on particular metabolic pathways \cite{27-29}, the maximal intensity achievable \cite{21, 30} and as a consequence, the adaptations from training \cite{2, 3, 7, 15, 25}. Within the literature, a multitude of interval programs exist with evidence supporting the use of both short (i.e. <1 min at >120% VO\textsubscript{2max}) \cite{2, 21, 31, 32} and longer (>2 mins at 85-90% VO\textsubscript{2max}) \cite{13, 14, 16} duration intervals in order to induce aerobic metabolic (see Table 2) and performance adaptations (Table 3).

The distribution of work throughout an interval or interval session (i.e. pacing or pacing selection) is also likely to have a significant influence on the maximal power output achievable, energy systems utilised and as a consequence, the adaptations from interval training. For instance, faster oxygen uptake (i.e. VO\textsubscript{2} on-kinetics), greater utilisation of aerobic metabolism \cite{32-34} and greater average power output during a single 5 minute cycling performance trial has been observed when using an “all-out” effort (a maximal acceleration produced over a set period of time with a higher power output at the beginning of an exercise/interval session), compared with a slower start or even-paced strategies \cite{33-35}. Such an “all-out” pacing selection also results in a period of time during which athletes cycle at extremely high exercise intensities which are likely to induce significant vascular shear and metabolic stress \cite{4, 7, 36} and increased anaerobic energy demand \cite{24, 37, 38}.
This type of interval, although usually very short (i.e. <1 min), has been shown to provide significant aerobic adaptations and performance benefits \[2, 19, 33-35\]. To date, no studies have examined the influence of this pacing strategy in longer duration intervals.

Longer duration intervals (> 2 min) are commonly associated with a more evenly distributed pace \[2, 15, 26\], resulting in a comparatively lower energy contribution from anaerobic metabolism \[2, 7\]. As such, an even-pacing strategy during longer intervals may lower fatigue development \[13, 39\], allowing participants to maximise aerobic stress whilst maintaining relatively high average power outputs during repeated intervals \[4, 5, 15, 16, 18-20\]. Notably, the intensity during such even-paced intervals can be either controlled by the athlete (athlete-controlled) or externally controlled by an ergometer. Interestingly, the physiological and perceptual responses of such trials are not well understood. Indeed, we are aware of only one study that has observed the physiological and perceptual responses during a rowing ergometer session whereby intensity was athlete-controlled and constantly-enforced \[40\] with results indicating enforced constant pacing posing significantly greater physiological challenges to homeostasis than the matched intensity athlete-controlled trials. To date, no study has yet compared even-pacing (computer- and athlete-controlled) with an “all-out” pacing selection during high-intensity interval training.

1.2. PURPOSE STATEMENT/ SIGNIFICANCE OF RESEARCH

Interval training can represent a large portion of a cyclist’s overall training program and has been shown to effectively increase cycling performance through
beneficial physiological adaptations [6]. Of the various studies examining the efficacy of high-intensity interval training a variety of different pacing strategies have been used, including “all-out” [19, 34] and computer- or athlete controlled even-paced intervals [41]. Interestingly, the physiological and perceptual responses to such intervals have not yet been described and thus it is unclear if such strategies may result in different adaptations. For this reason, this study will examine differences in physiological responses and subsequent performance between “all-out” and even-paced interval training in trained cyclists. Findings from this study will improve our understanding of the physiological responses to high-intensity exercise, and provide athletes, coaches, sports scientists and clinicians with information on the influence pacing has on the response to high-intensity aerobic interval training. This information will assist in prescribing the most optimal pacing selection when performing high-intensity interval training.

1.3 RESEARCH QUESTIONS

The following questions are proposed:

1. Is there a difference in the mean physiological responses (heart rate, oxygen consumption) observed during individual efforts and the overall session of a 3 x 3 minute “all-out”, athlete- and computer-controlled cycling interval session when matched for total mechanical work?
2. Will a difference be observed in ratings of perceived exertion (RPE), quadricep pain and effort measured immediately following each individual interval during an “all-out”, athlete- and computer-controlled interval session (3 x 3 minute effort)?
3. Will a difference be observed in sessional RPE between “all-out”, athlete- and computer-controlled interval sessions?

4. Will a greater difference in latent fatigue exist in subsequent performances (measured by: time trial performance and power distribution) following the completion of the “all-out” intervals when compared with the athlete- and computer-controlled cycling intervals?

1.4. HYPOTHESES

The following hypotheses are proposed:

1. No large differences in the mean physiological responses (heart rate, oxygen consumption) will be observed during the individual efforts and the overall session of 3 x 3 minute “all-out”, athlete- and computer-controlled efforts, when matched for total work.

2. Immediately following each interval, greater RPE, quadricep pain and effort will be observed in the “all-out” compared with the athlete- and computer-controlled interval sessions.

3. Sessional RPE will be greater following “all-out”, compared with athlete- and computer-controlled interval sessions.

4. An increase in latent fatigue measured by a decrease in time trial performance and an increase in the variability of power distribution will be observed following the “all-out” interval session when compared with athlete- and computer-controlled interval sessions.

1.5. LIMITATIONS

The researcher acknowledges this research has limitations as follows:
1. All participants were asked to give full effort during the “all-out” interval and testing sessions; however, this cannot be guaranteed.

2. All experimental interval sessions were completed in a laboratory on a cycling ergometer and not the athlete’s own bicycle; thus, our data may lack a degree of ecological validity.

1.6. DELIMITATIONS

1. The information relating to this study is suitable for the selected group and may not be representative of other populations (e.g. elite athletes, unhealthy or clinical populations).
CHAPTER TWO: CRITICAL REVIEW OF THE LITERATURE

2.1. OVERVIEW

The sport of cycling is extremely physical \[^{42}\]; thus, individuals competing in this sport must possess high levels of aerobic fitness and endurance \[^{39}\]. To improve overall endurance exercise performance, cyclists have traditionally devoted large portions of their training regimens to prolonged low to moderate-intensity exercise at \(\sim 60\% - 70\% \text{ of VO}_2\text{max} \[^{1, 2, 6-8}\]. Many athletes (i.e. cyclists) replace a considerable portion of continuous exercise sessions with brief and repeated sessions of low volume high-intensity interval training (i.e. vigorous bouts of physical exercise followed by low-intensity active or passive recovery periods or complete rest \[^{30}\]). Indeed, Seiler \[^{6}\] examined training volumes across various endurance sports, noting approximately 20% of training regimens consist of training at high-intensity, approximately 2-3 sessions per week \[^{6}\]. This method of training is time efficient and induces similar adaptations (reported Table 2) when compared with traditional training. Despite the widespread use and popularity of high-intensity training in sport, recent review articles \[^{2, 3, 5, 15, 25, 26}\] have highlighted the conjecture pertaining to the most optimal intensity and duration prescription.

Within cycling, interval training is commonly completed at intensities below maximum oxygen uptake (i.e. 70-90% VO\(_2\)max) for extended durations (> 60 s) \[^{13,14,18,39}\]. These interval types have been demonstrated to provide benefits to athletes and have been suggested as the preferred method of interval delivery \[^{43}\]. Conversely, intervals performed at higher intensities (> 100% VO\(_2\)max) for shorter durations (< 60 s) can provide similar physiological (see Table 2) and performance
benefits (see Table 3) to traditional endurance training for cyclists and other endurance sport athletes \cite{2, 15, 21, 22}, yet, require only a fraction of the time commitment.

In addition to the duration and intensity, the distribution of work throughout an interval or interval training session (i.e. pacing or pacing selection) is likely to have significant influences on maximal power output achievable, energy systems utilised and as a consequence, the adaptations gained from interval training \cite{44}. Previous research examining low volume high-intensity interval training \cite{2, 4, 7, 9, 11, 13, 18} identified two commonly incorporated pacing techniques regularly employed in interval training programs; these consist of “all-out” efforts (a maximal acceleration produced over a set period of time with a higher power output at the beginning of an exercise/interval session), and even-pacing efforts (maintaining a pre-determined power output) however, these interval strategies are yet to be compared to find the optimal method for interval delivery.

With approximately 20\% of well-trained cyclists’ training programs consisting of high-intensity interval training \cite{6}, there is a continued need to identify the most optimal protocol for interval intensity and duration delivery. It is important not only to select the most appropriate interval, but to also consider the distribution of work within interval training. This literature review will therefore highlight the physiological and performance adaptations consistent with short and long duration interval training and draw attention to the influence of selected pacing strategies (i.e. “all-out” and even-pacing) during such intervals.
2.2. **PHYSICAL DEMANDS OF CYCLING**

Road cyclists must be able to perform in a multitude of conditions including flat land, high mountain passes and individual time trials \[42\]. For this reason, it is not uncommon for cyclists to ride up to 200 km per day (1000 km per week), for prolonged periods of time (four to six hours), at intensities representative of 60-90% of aerobic maximum \[39\]. In order for an individual to be competitive at this level, Hawley et al. \[39\] suggests the minimum physiological requirements include; 1) a high maximal aerobic capacity (\(\text{VO}_{2\text{max}} > 70 \text{ml.kg}^{-1}.\text{min}^{-1}\)), 2) the ability to maintain a high percentage of \(\text{VO}_{2\text{max}}\) for sustained periods, 3) high power output/ speeds at lactate threshold, 4) the ability to withstand high absolute power outputs or speeds whilst resisting the onset of muscular fatigue, 5) an efficient, economic technique and 6) the ability to utilise fat as fuel during exercise at high work rates. It has been suggested that a high training volume is necessary to achieve the above requirements \[16, 38, 45-47\].

**Table 1.** Training characteristics of professional road cyclists during the year.

Reproduced from Lucia et al. \[42\]

<table>
<thead>
<tr>
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<th>Rest (fall)</th>
<th>Pre-competition (winter)</th>
<th>Competition (spring-summer)</th>
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<tr>
<td><strong>Average weekly training (km)</strong></td>
<td>~270</td>
<td>~700</td>
<td>~800</td>
</tr>
<tr>
<td><strong>Exercise intensity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low; &lt;65% (\text{VO}_{2\text{max}})</td>
<td>~88%</td>
<td>~78%</td>
<td>~77%</td>
</tr>
<tr>
<td>Moderate; 65-90% (\text{VO}_{2\text{max}})</td>
<td>~11%</td>
<td>~17%</td>
<td>~15%</td>
</tr>
<tr>
<td>High; 90% (\text{VO}_{2\text{max}})</td>
<td>~1%</td>
<td>~5%</td>
<td>~8%</td>
</tr>
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</table>
2.3. CYCLE TRAINING: THE 80:20 SPLIT

In a 2010 review of training intensity and duration distribution in endurance athletes and sports, Seiler[^6] identified three zones of intensity frequently used by coaches and sports scientists to optimise training. The highest volume of training frequency (accounting for ~80% of endurance athletes regimens) occurs at a low-moderate intensity of ~60-75% of VO$_{2\text{max}}$ or under the first ventilatory threshold (VT$_1$), threshold training completed between 2 to 4 mmol/L blood lactate, whilst the remaining 20% consists of intensities completed at > 85% VO$_{2\text{max}}$[^6]. Even with only 20% of a cyclist’s overall training program aimed at high-intensity interval training, this can account for approximately 7 000 km per year. This volume alone should indicate the need for a well designed and implemented high-intensity interval training program within this population.

Interestingly, the minimum 80:20 ratio is consistent amongst cyclists completing lower total volumes of training[^48] and those competing in non-road disciplines (i.e. track cyclists)[^49]. Indeed, analysis of the winter and spring mesocycles training volume in sub elite road cyclists indicate overall increases in duration of low and high intensity training from winter (+18 h) to spring (+16 h); yet, a similar 80:20 ratio within each mesocycles was observed (Figure 1)[^48]. Furthermore, an analysis of the 4 000 m gold medal winning pursuit team in the 2000 Sydney Olympics showed in the 200 days preceding the Olympic Games, low-intensity training was performed on approximately 140 days at 50-60% of VO$_{2\text{max}}$ with cycling completed at near competition intensity on fewer than 20 days with only 6 days of high-intensity training completed in this lead up[^49]. This training
program, while specifically designed as major competition preparation followed the minimum 80:20 ratio models.

Figure 1. Cycling intensity and volume of elite Spanish U23 cyclists training in the period November to June. Data redrawn from Zapico et al. [48]

2.4. PHYSIOLOGICAL, METABOLIC & PERFORMANCE RESPONSES TO HIGH-INTENSITY INTERVAL TRAINING

2.4.1. PHYSIOLOGICAL AND METABOLIC RESPONSES

High-intensity interval training provides a time-efficient method for inducing numerous physiological and metabolic adaptations to facilitate exercise capacity in endurance athletes [2-4, 6, 7, 21]. For instance, recent evidence on the efficacy of this training protocol have led to observations of improved fatigue resistance [13, 15, 39], enhanced lactate [5, 16, 50] and VO\textsubscript{2} kinetics [35, 51, 52] and VO\textsubscript{2max} [3, 5, 19, 29], with rapid changes in the metabolic profile of skeletal muscle and ion buffering capacity [2, 14, 22, 24]. Regardless, the above mentioned changes are not universal throughout all high-intensity interval training protocols; thus, understanding the specific
adaptations (metabolic and physiological) consistent with commonly employed high-intensity training programs is essential. Specifically, the manipulation of the intensity and duration paradox (i.e. inverse relationship between intensity and duration) alters the demands on particular metabolic pathways \[10, 16, 24, 53\], the maximal intensity achievable \[25\] and the adaptations occurring as a result from training \[1, 7, 9, 17\]. Within this literature review, intervals will be categorised as short (1 to 60 s; > 90-100% of VO
\(_{2}\text{max}\)) \[2, 9, 15, 19, 21, 31\] or long duration (> 60 s; ~60-80% of VO
\(_{2}\text{max}\)) \[1, 13, 14, 18, 39, 53\].

Short duration high-intensity interval training programs are increasingly being used to promote both central and peripheral adaptations in athletes and untrained individuals \[3, 17, 31, 54, 55\]. Indeed, Daussin et al. \[52\] observed significantly greater increases in VO
\(_{2}\text{max}\), cardiac output and maximal arteriovenous oxygen extraction after eight weeks of high-intensity interval training using one minute intervals at intensities of 90% of the power associated with VO
\(_{2}\text{max}\) (P
\(_{\text{max}}\)) when compared with continuous work matched training. The increase in VO
\(_{2}\text{max}\) following short high-intensity interval training can partially be explained by the up regulation of cell signalling proteins associated with improved aerobic function and oxidative capacity (e.g. peroxisome-proliferator activated receptor y co-activator; PGC-1α) which have been observed in individuals after repeated 30 seconds supra-maximal efforts \[21, 31\]. Furthermore, this type of high-intensity interval training is associated with reducing glycogen utilisation and lactate accumulation \[7\] both of which can benefit endurance exercise performance \[36\].
In comparison to performing short duration high-intensity training, longer duration intervals can also provide beneficial metabolic and physiological adaptations. This type of high-intensity interval training is associated with increases in VO\(_{2}\)\(_{\text{max}}\) \(^{29, 56}\), oxidative enzyme activity \(^{2, 7, 32}\), electron transport intermediates \(^{2, 7, 52}\), glycogen storage \(^{22, 36}\) and fat oxidation \(^{53}\). For instance, Perry et al. \(^{53}\) observed a 9% increase in VO\(_{2}\)\(_{\text{max}}\) which was consistent with increases in cytochrome c oxidase IV (+18%) and the maximal activities of mitochondrial enzymes citrate synthase (+26%), β-hydroxyacyl-CoA dehydrogenase (+29%), aspartate-amino transferase (+26%) and pyruvate dehydrogenase (+21%) in eight recreationally active participants after six weeks of high-intensity interval training (ten x 4-minute intervals at 90% VO\(_{2}\)\(_{\text{peak}}\)). Similar changes have been observed in highly trained cyclists (VO\(_{2}\)\(_{\text{max}}\) ~ 66 ml.kg\(^{-1}\).min\(^{-1}\)) after completing four weeks of eight x 5-minute intervals at 80% peak power output indicating this type of training can induced beneficial metabolic response across a wide range of fitness profiles \(^{18}\).
### Table 2. Physiological and metabolic benefits of high-intensity training vs. continuous training

<table>
<thead>
<tr>
<th>Author</th>
<th>HIT training protocol type &amp; intensity</th>
<th>Time commitment &amp; training volume</th>
<th>Continuous training protocol &amp; intensity</th>
<th>Time commitment &amp; training volume</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gibala et al. 2006 [2]</td>
<td>4-6 x 30 s “all-out” maximal efforts @ ~250% VO(_{2})peak, with 4 min active recovery</td>
<td>~2.5 h ~630 kJ</td>
<td>90-120 min @ 65% of VO(_{2})peak</td>
<td>~10.5 h ~6500 kJ</td>
<td>Similar ↑ in muscle oxidative capacity; maximal activity of cytochrome c oxidase (COX) and COX subunits II and IV protein content; ↑ muscle buffering capacity &amp; glycogen content in both conditions.</td>
</tr>
<tr>
<td>Burgomaster et al. 2006 [22]</td>
<td>4-6 x 30 s “all-out” maximal efforts @ ~500W with 4.5 mins active recovery</td>
<td>~10 min (~1.5 h including rest) ~225 kJ</td>
<td>40-60 min cycling @ 65% of VO(_{2})peak (~150 W)</td>
<td>~4.5 h ~2250 kJ</td>
<td>Similar ↑ in mitochondrial markers for skeletal muscle, CHO and lipid oxidation and protein content of peroxisome proliferator-activated receptor-ϒ coactivator-1α (PGC1-α) in both conditions. ↓Glycogen utilisation during exercise.</td>
</tr>
<tr>
<td>Berger et al. 2006 [51]</td>
<td>20 x 1 min @ 90% VO(_{2})peak; 1 min recovery period</td>
<td>4 sessions per week; 6 wk duration</td>
<td>30 min @ 60% VO(_{2})peak</td>
<td>3-4 sessions; 30 min duration; 6 wk duration</td>
<td>HIT and continuous training similarly effective in enhancing VO(_{2}) on-kinetic response.</td>
</tr>
<tr>
<td>Helgerud et al. 2007 [29]</td>
<td>G3: 47 x 15 s @ 90-95% HR(<em>{\text{max}}) G4: 4 x 4 min @ 90-95% HR(</em>{\text{max}})</td>
<td>3 d per wk for 8 wk</td>
<td>G1: LSD @ 70% HR(<em>{\text{max}}) for 45 mins G2: Lactate threshold 85% HR(</em>{\text{max}}) for 24.25 mins</td>
<td>3 d per week for 8 wk</td>
<td>↑ VO(<em>{2})max in G3 (5.5%) &amp; G4 (7.2%), ↑ SV by 10% in G3 &amp; G4; no change in VO(</em>{2})max in G1 &amp; G2.</td>
</tr>
<tr>
<td>Daussin et al. 2007 [3]</td>
<td>4 mins at LT with 1 min at 90% P(_{\text{max}})</td>
<td>20 min increased by 5 mins every 2 wk – 35 min during last 2 wk ~4,126 ± 389 kJ</td>
<td>106 ± 10 W or +61% of P(_{\text{max}})</td>
<td>8 wk ~4,177 ± 395 kJ</td>
<td>↑ P(<em>{\text{max}}) In HIT, no difference in power @ LT between 2 methods; ↑ in VO(</em>{2})max &amp; Q(<em>{\text{max}}) after HIT. ↑ AVO(</em>{2}) difference in both protocols</td>
</tr>
<tr>
<td>Daussin et al. 2008 [52]</td>
<td>1 min @ 90% P(<em>{\text{max}}) with 4 mins at 56% P(</em>{\text{max}})</td>
<td>20 min ↑ by 5 min every two wk to 35 min ~4,227 ± 112 kJ</td>
<td>61% P(_{\text{max}})</td>
<td>8 wk ~4,320 ± 115 kJ</td>
<td>HIT associated with faster VO(<em>{2}) kinetics &amp; max CO; VO(</em>{2})max increased after both methods</td>
</tr>
<tr>
<td>Author</td>
<td>HIT training protocol type &amp; intensity</td>
<td>Time commitment &amp; training volume</td>
<td>Continuous Training Protocol &amp; Intensity</td>
<td>Time commitment &amp; training volume</td>
<td>Main findings</td>
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<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>McKay et al. 2009 [32]</td>
<td>8–12 x 1-min intervals @ 120% VO$_{2\max}$</td>
<td>Total exercise time: 80 min 8 sessions over a 19 day period 1,800 kJ</td>
<td>90–120 min @ 65% VO$_{2\max}$</td>
<td>Total exercise time: 825 min 8 sessions over a 19 day period 8,500 kJ</td>
<td>Phase II tVO$<em>{2p}$ ↓ by ~20% after 2 HIT training sessions &amp; ~40% after 8 days of training, similar changes occurred in both groups; ↓ in tVO$</em>{2p}$ (i.e., faster VO$<em>{2p}$ kinetics) occurred in a progressive, linear fashion over 8 training sessions in both HIT and CT groups; ↑ speeding of VO$</em>{2p}$ kinetics.</td>
</tr>
<tr>
<td>Psilander et al. 2010 [31]</td>
<td>7 x 30 s “all-out” maximal efforts with 1 min of active recovery at 50 W</td>
<td>3.5 min 135 ± 5 Kj</td>
<td>3 x 20 min bouts @ 87% of VO$_{2\text{peak}}$</td>
<td>60 min 1095 ± 43 kJ</td>
<td>Similar ↑ in PGC-1α related co-activator (PRC) and peroxisome proliferator-activated receptor δ (PPARδ) in both conditions.</td>
</tr>
<tr>
<td>Stepto et al. 2012 [57]</td>
<td>6 x 5 mins @ 90-100% VO$_{2\text{peak}}$</td>
<td>10 d with 4 sessions</td>
<td>45-90 min @ 75% VO$_{2\text{peak}}$</td>
<td>10 d with 6 sessions</td>
<td>↑ PGC1-α mRNA expression after exercise in both pre- and post-training; COX IV mRNA and COX IV protein expression ↑ by training but COX IV protein expression ↓ by acute exercise pre- and post-training. ↑ mitochondrial gene expression and protein abundance</td>
</tr>
<tr>
<td>Bartlett et al. 2012 [55]</td>
<td>6 x 3 mins @ 90% VO$_{2\max}$ 3 mins active recovery</td>
<td>matched work-running</td>
<td>50 min @ 70% VO$_{2\max}$</td>
<td></td>
<td>Similar activation of molecular signalling pathways associated with regulation of mitochondrial biogenesis in both conditions.</td>
</tr>
</tbody>
</table>

**CHO**: Carbohydrate, **CT**: continuous training, **D**: day, **kJ**: kilojoule, **LSD**: long slow distance, **Q$_{\text{max}}$**: cardiac output, **wk**: week
2.4.2. PERFORMANCE RESPONSES

Increased performance following high-intensity interval training [13-15, 18, 39, 58] is noted as a hallmark of this training modality. Although not an exhaustive list, high-intensity interval training is associated with; enhanced speed [15, 18, 39, 59], time to fatigue [13, 14, 17], and increases in peak power output [13, 14, 39]. The efficacy of this modality is further strengthened by observations indicating as little as four to six interval training sessions can provide performance adaptations in trained and untrained athletes [13, 18, 39]. Indeed, Hawley et al. [39] reported an increased ability to sustain higher absolute and relative work rates with meaningful enhancements in 40 km time trial performance (90-120 seconds/ 1.5-2.0 km h⁻¹) and improved peak power output (15-20 W) after completion of six high-intensity interval training sessions (six to nine x 5 minute durations at 80% of PPO) with only small gains obtained with the completion of a further six sessions. This indicates not all training programs are likely to provide equal benefits to all individuals [15]. As peak power output is highly correlated with VO₂max, it is possible that performances can be improved if training loads and times are manipulated in order to promote optimal adaptations [39].

A multitude of high-intensity interval training programs have been examined within the literature in relation to performance (Table 3). Few studies; however, have provided a direct comparison of different high-intensity interval training methodologies making the determination of the most optimal method complicated. Of note, Stepto et al. [15] examined performance adaptations following 3 weeks of five different high-intensity interval training programs (30 seconds at 175% PP, 60 seconds at 100% PP, 2 minutes at 90% PP, 4 minutes at 85% PP and 8 minutes at
80% PP) and concluded intervals of 30 seconds (175% PP) and 4 minutes (85% PP) provide the greatest enhancement to 40 km time trial performance\textsuperscript{[15]}. These findings give strength to the use of either short duration (< 30 seconds) or long duration (> 3 minutes) high-intensity interval training programs to enhance overall health and performance.

2.5. PACING STRATEGIES DURING INTERVAL TRAINING

Pacing is described as both a conscious or subconscious distribution of power to optimise and regulate physiological changes during an exercise task\textsuperscript{[44, 60]}. The selection of pacing is influenced by the duration and intensity of the work effort\textsuperscript{[44]}, with substrate utilisation further influencing the distribution of pace during exercise\textsuperscript{[18, 28, 61]}. Pacing strategies (explanation of these strategies provided by Abbiss and Laursen\textsuperscript{[62]}) have been observed during endurance based competition\textsuperscript{[27, 28, 44, 63, 64]}. Nevertheless, the distribution of pace during each effort of a high-intensity interval session within the literature is typically either “all-out” or moderately even-paced. An “all-out” pacing selection is characterised by a very short initial period (~5-10 seconds) of maximal power output followed by a sharp reduction to a maintainable power output often followed by a gradual decrease in speed\textsuperscript{[19, 62, 65]}. Conversely, an even-pacing selection involves the athlete performing the entire effort at a constant power output where by intensity is automatically maintained by the ergometer or by the athletes manipulation of cadence and gear selection\textsuperscript{[40]}. Interestingly, both pacing strategies have been shown to provide benefits to aerobic capacity and cycling time trial performance\textsuperscript{[15]}. 

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2.5.1. “ALL-OUT” PACING SELECTION

The application of an “all-out” pacing selection is frequently adopted to produce a supra-maximal interval work effort \(^2\). Due to the explosive nature, intervals using an “all-out” pacing selection are commonly of short durations (< 60 s) as the onset of fatigue is rapid \(^7,21,39,44\) and thus are consistent with the benefits outlined above in regards to short duration intervals (Table 2). Additionally, the use of an “all-out” pacing selection during short duration intervals has shown to be as effective as traditional endurance training (Tables 2 and 3). For example, Gibala et al. \(^2\) observed similar improvements in performances in both a 50 and 750kJ time trial for individuals who completed a training program consisting of 30 second “all-out” intervals compared with individuals completing a traditional endurance training program despite a ~90% lower training volume (~630 vs ~6500kJ) in the “all-out” group. It is important to note, to the author’s knowledge no studies have examined the use of an “all-out” interval pacing selection for efforts extending beyond one minute. Unlike computer-controlled constant pace intervals, long “all-out” intervals do not require any specific external feedback (i.e. external power monitors) to perform the intervals and therefore could be easier to implement for many cyclists.
### Table 3. Performance responses to high-intensity interval training

<table>
<thead>
<tr>
<th>Author</th>
<th>HIT protocol &amp; training intensity</th>
<th>Time commitment &amp; training volume</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acevedo &amp; Goldfarb et al. 1989 [66]</td>
<td>Male distance runners ↑ training intensity to 90-95% HRmax</td>
<td>8 weeks</td>
<td>63 s ↓ in 10-km race times</td>
</tr>
<tr>
<td>Lindsay et al. 1996 [13]</td>
<td>6-8 x 5 min @ 80% PPO</td>
<td>6 sessions over 4 weeks</td>
<td>↑ in 40 km time trial performance (54.4 ± 3.2 vs. 56.4 ± 3.6 min) and time to fatigue at 150% of peak power (72.5 ± 7.6 vs. 60.5 ± 9.3 s)</td>
</tr>
<tr>
<td>Westgarth-Taylor et al. 1997 [14]</td>
<td>6-9 x 5 min @ 80% Wpeak (~85-88% of VO₂peak); 1 min complete rest or recovery at &lt; 100 W</td>
<td>12 sessions over 6 wk</td>
<td>Faster 40 km TT performances in HIT group - ↑ in absolute work rate (291 – 327W) &amp; relative work rate (72.6 – 78.1W), ↑ 40 km time trial speeds from 42.0 to 43.0 km.h⁻¹</td>
</tr>
<tr>
<td>Weston et al. 1997 [18]</td>
<td>8 x 5 min @ 80% PPO; 60 s recovery</td>
<td>6 sessions over 3 weeks</td>
<td>Significant improvements in intense exercise performance (time to fatigue @ 150% PPO) &amp; 40 km time trial performance</td>
</tr>
<tr>
<td>Hawley et al. 1997 [39]</td>
<td>6-9 x 5 min @ 80% PPO; 1 min complete rest or active recovery at &lt;100 W</td>
<td>6-12 sessions over 7 weeks; Total time: 36 to 54 mins</td>
<td>↑ ability to sustain higher absolute &amp; relative work rates, ↑ 40 km time trial speed (1.5-2.0 km.h⁻¹/90-120 seconds) and ↑ peak power output (15-20W)</td>
</tr>
<tr>
<td>Stepto et al. 1999 [15]</td>
<td>5 different types of interval durations &amp; intensities; (12 x 30 s @ 175% PPO; -12 x 1 min @ 100% PPO; -12 x 2 min @ 90% PPO; -8 x 4 min @ 85% PPO; -4 x 8 min @ 80% PPO)</td>
<td>6 sessions over 3 weeks</td>
<td>30 s and 4 min groups = greatest gains in 40 km time trial speed (1-4%)</td>
</tr>
<tr>
<td>Laursen et al. 2005 [17]</td>
<td>G1: 8 x 60% Tmax @ Pmax, 1: 2 work-recovery G2: 8 x 60% Tmax @ Pmax, 65% HRmax G3: 12 x 30 s @ 175%, 4.5 min recovery</td>
<td>8 sessions over 4 weeks</td>
<td>↑ 40 km TT performance in all HIT groups (+4.4 to + 5.8%)</td>
</tr>
<tr>
<td>Burgomaster et al. 2005 [21]</td>
<td>4-7 x 30 s “all-out” efforts @ ~80% VO₂peak; 4 min active recovery</td>
<td>~15 min</td>
<td>↑ cycle endurance capacity from 81-169% in HIT protocol</td>
</tr>
<tr>
<td>Gibala et al 2006 [2]</td>
<td>4-6 x 30 s “all-out” efforts @ ~250% VO₂peak; 4 min active recovery</td>
<td>~2.5 h</td>
<td>↓ time to complete 50kJ and 750kJ cycling time trials after completing HIT; No significant differences between two groups</td>
</tr>
<tr>
<td>Iaia et al. 2009 [58]</td>
<td>8-12 x 30 s sprints; 3 min passive recovery</td>
<td>3-5 sessions over 4 wk; 45 km/wk reduced to 15 km/wk</td>
<td>10 km running performance maintained</td>
</tr>
</tbody>
</table>
2.5.2. **EVEN-PACING SELECTION**

An even distribution of pacing during the work bouts of the high-intensity interval sessions requires energetic resources to be distributed efficiently so a constant set power output is maintained throughout the duration of the repeated work bouts \[^{44}\]. In high-intensity interval training extending beyond one minute, the duration and intensity paradox promotes selection of an even-pacing selection to optimise cycling performance, ensuring completion of the prescribed training session at a high intensity \[^{15}, 27, 62, 67\]. Indeed, several studies \[^{3, 5, 13-16, 22, 39, 53}\] incorporating even-pacing strategies in high-intensity training programs, prescribe intervals at set power output as a percentage of the athletes peak power output or VO\(_{2}\)max. These intervals are normally extended beyond two minutes in duration and thus are consistent with the above mentioned (Table 2) metabolic and performance changes outlined for long duration intervals. Unlike an “all-out” pacing selection (i.e. going as hard as possible), even-pacing can be established via athlete-control (i.e. individual manipulations of movement to maintain intensity) or external-control (intensity set by external device irrespective of individual actions) with reported differences existing between these two methods \[^{40}\]. Lander et al. \[^{40}\] observed lower physiological strain when rowers completed matched 5 000m time trials using both an athlete- and external-controlled pacing selection (intensity matched to athlete-controlled trial). These findings indicate, during constant paced exercise the ability to modify the manner of effort can lower physiological stress; yet, have no influence on performance. To date, this has not been examined in cycling where the advent of electromagnetically and mechanically braked cycling
ergometers can allow individuals to complete even-paced intervals using both self- and computer-controlled methodologies.

2.6. SUMMARY

The high physical demands and large training volumes (> 35,000 km) performed by endurance cyclists has resulted in the need for optimal time efficient training strategies which can provide the greatest physiological and metabolic adaptations aimed at increasing athletic performance. The replacement of continuous exercise sessions with low volume high-intensity interval training has been shown to produce similar, if not greater, physiological and performance adaptations compared with traditional endurance training. These findings have lead coaches and sports scientists to prescribe high-intensity interval training as a significant portion (approximately 20%) of an athlete’s overall training program. Even in the face of overwhelming evidence for the benefits of high-intensity interval training conjecture still exists regarding the most optimal method of delivery. To date, no studies have examined intervals which combine the pacing characteristics of short and long duration efforts. Furthermore, no studies have examined the influence of the possible methods which could be used to produce an even-paced cycling interval consistent with longer duration efforts. With such emphasis placed on this training modality within cycling, it is essential further research is conducted to fill the void and provide additional information to coaches and sports scientists regarding this training modality.
CHAPTER THREE: METHODS

3.1. STUDY DESIGN

A randomised repeated measures design was employed for this study with participants required to complete three different interval protocols (“all-out”, athlete- and computer-controlled). The study was conducted over five separate visits to the Murdoch University Exercise Physiology Laboratory in Perth, Western Australia. Sessions consisted of: 1) maximal exercise test, 2) familiarisation session and 3) three interval experimental sessions with trials differing only in interval protocol. Visits were separated by a minimum of five days and a maximum of ten days with testing completed at similar times of the day for each session. Participants were required to avoid strenuous activity 24 hours prior to the day of testing and on the day of testing itself whilst maintaining a similar diet prior to each session.

3.2. SAMPLING METHODOLOGY

Fifteen trained male cyclists (age: 39 ± 8 years, height: 181.1 ± 4.9cm, body mass: 79.4 ± 8.2kg, VO₂max: 59.8 ± 6.5 ml·kg⁻¹·min⁻¹, peak power: 436 ± 27 W) volunteered to participate in the study. All participants were required to be illness and injury free, cycling at least 200 km per week at the time of the study, have previous experience with high-intensity interval training and have cycled competitively for the previous two years. A written description of the risks and benefits of this study was provided to participants with signed informed consent obtained prior to data collection.
Ethical approval for this study was obtained from the Murdoch University Human Ethics Committee (Appendix 1).

3.3. PROCEDURES

During the initial visit, participants completed a maximal exercise test on an electronically braked cycle ergometer (Velotron; RacerMate, USA). Participants were required to cycle at an initial resistance of 70 W with increases of 35 W·min$^{-1}$ until volitional fatigue. This test was used to determine the participant’s maximal aerobic capacity (VO$_2$max; descriptive purposes) and the recovery intensity (i.e. power output at 50% of aerobic threshold) used during the interval training sessions.

During the second visit, participants were required to complete a full training session consisting of three 3-minute efforts interspersed with three minutes of active recovery (total of 18 minutes of cycling) on the Velotron cycle ergometer. During this session, participants completed one effort of each pacing condition (i.e. “all-out”, computer-, and athlete-controlled). This session was used to familiarise the participants with the equipment and procedures for all three interval conditions. Prior to the start of the interval session, participants completed a 15 minute standardised warm-up (5 minutes at 30%, 40% and 50% of peak power measured during the maximal exercise test). The interval session consisted of an initial five minutes at a power output equal to 50% of the participants aerobic threshold immediately followed by three 3-minute efforts with three minutes of active recovery (50% power at aerobic threshold) between each effort. During the
initial effort ("all-out"), participants were instructed to "go as hard as they can" to try to produce the highest power output possible. Feedback relating to power output was provided to participants to help achieve the best possible effort. The second effort was completed in an athlete-controlled manner with participants attempting to maintain 90% of the mean power calculated from the "all-out" effort through manipulation of gearing and cadence selection. During the third effort (computer-controlled), participants were instructed to pedal against a resistance of 85% of the mean power output during the "all-out" effort. Resistance was controlled, irrespective of gear or cadence, by the internal RacerMate Velotron Coaching Software designed exclusively for the Velotron cycling ergometer. Immediately upon completion of the interval session, participants were given 20 minutes to rest after which participants were required to complete a 4 km cycling time trial. During the time trial, only feedback on distance covered was provided to participants with cyclist asked to complete the 4 km in the shortest time possible.

The third testing session required participants to complete the "all-out" interval protocol, consisting of three 3-minute "all-out" efforts with three minutes of active recovery (cycling at 50% of aerobic threshold) between efforts. Prior to the start of the interval session, participants completed a standardised warm-up similar to session two. During the interval efforts, participants were instructed to provide maximal effort at the start and to go as hard as possible for the total three minute duration. Heart rate was recorded at a beat by beat frequency (Polar 810i; Polar;
Finland) with power output recorded at a frequency of 1 Hz via RacerMate Velotron internal software throughout each interval effort. Additionally, expired gas was collected via a Parvo TrueOne metabolic cart (ParvoMedic, USA) from which volume of oxygen consumed and carbon dioxide produced was measured as five second mean values. Immediately following each interval, participants were asked to rate quadricep pain and effort given (0=None, 10= maximal pain) along with perceived exertion (Borg scale; 6 = no exertion, 20 = maximal exertion). Twenty minutes post interval session, participants were required to complete a 4 km cycling time trial with only distance completed provided as feedback. Sessional ratings of perceived exertion were collected twenty minutes following the completion of each experimental training session. The remaining two exercise sessions (computer- and athlete-controlled) were completed in a randomised order and followed identical methodologies to the third testing session with the only difference being in the method of interval delivery. During these sessions, the intensity for each interval was matched to the mean power output achieved during the corresponding interval in the “all-out” interval condition. During the athlete-controlled session, participants were required to match the mean power as close as possible (e.g. ± 3 W) for the entire three minute effort. In order to achieve this goal, a six second ramping protocol was incorporated prior to the onset of each interval, ensuring that at the beginning of interval work efforts, participants were at the required work load. During the computer-controlled session, participants mean power outputs were controlled automatically, ensuring the entire three
minute work bout was spent at their designated power output. To assess the possibility of a training effect during the study, five participants volunteered to complete an additional “all-out” interval session one week after completing all experimental sessions. This session followed identical methodologies to the initial “all-out” interval session.

3.4. DATA PROCESSING

3.4.1 POWER

Power output was collected at a frequency of 1 Hz throughout all interval sessions and 4 km time trials. Mean power output was calculated for the total duration of each interval. Additionally, mean power output was calculated for the initial 30 seconds of each interval. Mean 0.5 km power output was calculated from raw power output data recorded during the 4 km. Exposure variance analysis (EVA) of the raw 4 km time trial power data was used to quantify the time and amplitude domains of the participant’s power output as an expression of the overall time trial time. Individualised power bands were calculated for each participant and condition. Five power bands were calculated from the average power output of each trial (-10%, -5%, 0% (average power), +5%, and +10%) with the total time in each power band further separated by the frequency of occurrence in six predetermined time domains (0-3.75, 3.75-7.5, 7.5-15, 15-30, 30-60, and 60+ seconds) selected based upon previous research in elite female time trialists [68]. To assess the exposure variance analysis matrix, the total standard deviation of the matrix was calculated. A greater standard deviation is associated with
greater monotony of measurement and less-even dispersion of power output.

3.4.2. METABOLIC DATA

Expired gas collected during each interval in the “all-out”, computer- and athlete-controlled conditions was used to calculate mean oxygen consumption during each effort. Furthermore, measures of oxygen consumption were used to determine the time necessary to reach 85% of VO\(_{2\text{max}}\) as measured from the maximal exercise test. From this, the duration of time participants spent at or above 85% VO\(_{2\text{max}}\) was calculated for each interval in each condition.

3.5. STATISTICAL ANALYSIS

Differences in performance (mean power), physiological (oxygen consumption, heart rate) and perceptual (RPE, pain, effort) measures obtained during each interval were analysed using a two-way analysis of variance (2-way ANOVA; Condition x interval) with repeated measures. Similarly, differences in mean 0.5 km power output were analysed using a 2-way ANOVA with repeated measures. Significant main effects or interactions were analysed using a Tukey’s Post Hoc HSD (honestly significant difference) test. Differences in heart rate variability, sessional RPE and the standard deviation from EVA analysis between conditions were analysed using a one-way ANOVA. All statistical analyses were conducted using Statistica statistical analysis software version 7.0 (Statistica; USA) with a p≤0.05 level
of significance. All data has been presented as mean values ± standard deviations unless otherwise specified.
CHAPTER FOUR: RESULTS

4.1 INTERVAL MEASUREMENTS

4.1.1. POWER MEASUREMENTS

Figure 2. Mean (± SD) Peak (A), highest 30 s mean (B) and average power output (C) measured during intervals 1-3 (Int 1–Int 3) in the “all-out” (■), computer- (♦) and athlete-controlled (●) interval conditions. * “all-out” significantly greater compared with both computer- and athlete-controlled conditions. ++ “all-out” and computer-controlled greater when compared with athlete-controlled.
A significant interaction was observed for 30 s mean power output \( F_{(4, 56)} = 14; p<0.001 \) with greater power output observed during intervals one to three in “all-out” compared with the computer- \((p<0.001)\) and athlete-controlled \((p<0.001)\) conditions. In addition, peak power output \( F_{(4, 56)} = 7; p<0.001 \) in the “all-out” condition was greater than both computer- \((p<0.001)\) and athlete-controlled \((p<0.001)\) conditions across all intervals. Furthermore, a significant interaction was observed for average power \( F_{(4, 56)} = 9; p<0.001 \) with higher power output observed during intervals one to three in the “all-out” and computer-controlled conditions when compared with the athlete-controlled condition.
4.1.2. METABOLIC MEASUREMENTS

Figure 3. Mean (± SD) relative VO\(_2\) (A) and time spent at 85% of VO\(_{2\text{max}}\) (B) measured during intervals one to three (Int1–Int3) in the “all-out”, computer- and athlete-controlled interval sessions. * indicates a main effect for condition; ** indicates a main effect for time.

A significant main effect for condition was observed for relative VO\(_2\) (ml.kg\(^{-1}\).min\(^{-1}\)) \([F(2, 28) = 9; p<0.001]\) with the greater measures observed during the “all-out” (54.1 ± 6.6 ml.kg\(^{-1}\).min\(^{-1}\)) and athlete-controlled (53.0 ± 5.8 ml.kg\(^{-1}\).min\(^{-1}\)) conditions compared with computer-controlled (51.5 ± 5.7 ml.kg\(^{-1}\).min\(^{-1}\); P<0.001).
A main effect for condition was observed for the time spent at or greater than 85% of \( \text{VO}_{2\text{max}} \) \( [F(2, 28) = 24; \ p<0.001] \) with longer durations observed in the “all-out” condition (150.7 ± 11.0 s) upon comparison with the computer- (124.1 ± 18.5 s; \ p<0.001) and athlete-controlled (136.2 ± 14.2 s; \ p<0.001) conditions. A significant main effect for time \( [F(2,28) = 4; \ p<0.005] \) was observed for time spent at 85% of \( \text{VO}_{2\text{max}} \) within intervals one (136.8 ± 15.1 s) and two (139.9 ± 14.1 s) when compared with intervals three (134.3 ± 14.5 s; \ p<0.05). A main effect for condition was observed for oxygen consumption \( [F(1,14) = 16; \ p<0.001] \) immediately prior to the first interval in each condition with greater values recorded in the “all-out” (28.7 ± 4.8 ml.kg\(^{-1}\).min\(^{-1}\)) when compared with the athlete- (28.6 ± 3.8 ml.kg\(^{-1}\).min\(^{-1}\)) and the computer-controlled (25.9 ± 2.8 ml.kg\(^{-1}\).min\(^{-1}\)) conditions.
4.1.3. HEART RATE MEASUREMENTS

Table 4. Mean (± SD) heart rate (bpm) measured during each interval in the “all-out” (AO), computer-controlled (CC) and athlete-controlled (AC) conditions.

<table>
<thead>
<tr>
<th></th>
<th>INTERVAL 1</th>
<th>INTERVAL 2 *</th>
<th>INTERVAL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>AO*</td>
<td>165 ± 8</td>
<td>164 ± 10</td>
<td>166± 9</td>
</tr>
<tr>
<td>CC</td>
<td>161 ± 11</td>
<td>155 ± 12</td>
<td>158 ± 10</td>
</tr>
<tr>
<td>AC</td>
<td>160 ± 12</td>
<td>157 ± 12</td>
<td>160 ± 11</td>
</tr>
</tbody>
</table>

* Main effect for condition; “all-out” significantly greater than the computer- and athlete-controlled interval sessions. * Main effect for time; interval 2 less than interval 1 and 3.

Mean heart rate measured during each interval are shown in Table 4. A significant main effect for condition \( F_{(2, 24)} = 18; p<0.001 \) was observed, with greater heart rate measured during the “all-out” compared with the computer-controlled \( (p<0.001) \) and athlete-controlled \( (p<0.001) \) conditions. In addition, a significant main effect for time \( F_{(2, 24)} = 5; p<0.05 \) was observed with greater measures observed during intervals one \( (p<.05) \) and three \( (p<.05) \) compared with interval two.
4.1.4. PERCEPTUAL MEASUREMENTS

Table 5. Mean (± SD) ratings of perceived exertion, quadricep pain and effort measured at completion of each interval in the “all-out” (AO), computer-controlled (CC) and athlete-controlled (AC) conditions.

<table>
<thead>
<tr>
<th></th>
<th>INTERVAL ONE</th>
<th>INTERVAL TWO</th>
<th>INTERVAL THREE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RPE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>18.6 ± 1.3*</td>
<td>19.2 ± 0.6*</td>
<td>19.2 ± 1.0*</td>
</tr>
<tr>
<td>CC</td>
<td>16.7 ± 2.3</td>
<td>16.0 ± 2.8</td>
<td>16.3 ± 3.0</td>
</tr>
<tr>
<td>AC</td>
<td>17.1 ± 1.9</td>
<td>16.6 ± 2.0</td>
<td>16.0 ± 2.3</td>
</tr>
<tr>
<td><strong>QUADRICEP PAIN</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO*</td>
<td>6.9 ± 1.4</td>
<td>7.5 ± 1.2</td>
<td>7.7 ± 1.3</td>
</tr>
<tr>
<td>CC</td>
<td>6.2 ± 3.1</td>
<td>6.1 ± 3.0</td>
<td>6.1 ± 2.9</td>
</tr>
<tr>
<td>AC</td>
<td>6.3 ± 2.1</td>
<td>6.3 ± 2.4</td>
<td>6.3 ± 2.4</td>
</tr>
<tr>
<td><strong>EFFORT</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AO</td>
<td>9.3 ± 0.9*</td>
<td>9.4 ± 0.7*</td>
<td>9.6 ± 0.6*</td>
</tr>
<tr>
<td>CC</td>
<td>8.2 ± 1.5</td>
<td>7.8 ± 1.7</td>
<td>7.7 ± 2.0</td>
</tr>
<tr>
<td>AC</td>
<td>8.2 ± 1.3</td>
<td>7.3 ± 1.6</td>
<td>7.3 ± 1.8</td>
</tr>
</tbody>
</table>

* “all-out” significantly greater compared with both computer- and athlete-controlled conditions. + Main effect for condition; “all-out” greater than the computer- and athlete-controlled conditions.

Participant self-reported RPE, quadricep pain, and effort during each interval are shown in Table 6. A significant interaction was observed for RPE \( F_{(4, 56)} = 4, p<0.001 \) with greater perceptions of effort reported immediately after all three intervals in the “all-out” compared with computer- and athlete-controlled conditions. Furthermore, sessional RPE was greater \( F_{(2, 28)} = 11; P<0.001 \) after the “all-out” (18.4±1.1) compared with the computer- (16.1±2.2; \( p<0.001 \)) and athlete-controlled (16.4±1.2; \( p<0.05 \)) conditions. An interaction was observed for effort \( F_{(4, 56)} = 2, p<0.001 \) with greater values reported immediately following all intervals in the “all-out” compared with computer- and athlete-controlled conditions. Self-
reported quadricep pain displayed a main effect for condition \([F_{(2,28)} = 4, p<0.05]\) with greater overall pain observed in the “all-out” (7.4 ± 1.3) compared with the computer-controlled condition (6.2 ± 3.0) only.

4.2. TIME TRIAL MEASUREMENTS

4.2.1. POWER MEASUREMENTS

![Power Output Graph]

**Figure 4.** Mean (± SD) measures of average power achieved in 4 km time trial following the “all-out” (■), computer-(●) and athlete-controlled (●) interval sessions. ** 0.5 km greater than 1.5-3.0 km; # 1.0 km greater than 1.5 to 3.5 km; + 4 km greater than 1.5-3.5 km; * indicates a main effect for condition.

A significant main effect for time was observed in average power output \([F_{(7,98)} = 18; p<0.001]\) with greater power output recorded at 0.5 km, 1.0 km, and 4 km compared with all other time points. Additionally, a main effect for condition was observed \([F_{(2,28)} = 8; p<0.001]\) with less power output measured during the 4 km time trial in the “all-out” (333.0 ± 33.2 W) interval session, when compared with
both the computer- (350.2 ± 41.7 W) and athlete-controlled (354.2 ± 38.6 W) interval conditions.

4.2.2. EVA ANALYSIS

No differences were observed for EVA analysis conducted on 4 km time trial in the “all-out” (7.6 ± 2.4 SD), computer- (6.9 ± 1.9 SD) and athlete-controlled conditions (7.3 ± 2.1 SD).

4.2.3. HEART RATE MEASUREMENTS

No statistical differences were observed in heart rate measurements obtained throughout the 4 km time trials in the “all-out” (164 ± 12 bpm), computer- (161 ± 13 bpm) and athlete-controlled (163 ± 11 bpm) conditions.

4.2.4. ASSESSMENT OF SECOND “ALL-OUT” TRIAL

No statistical differences were observed for measured levels of oxygen consumption between “all-out” trial one and “all-out” trial two during the first (59.4 ± 3.0 ml.kg⁻¹.min⁻¹ vs. 59.0 ± 2.9 ml.kg⁻¹.min⁻¹; respectively), second (59.4 ± 3.0 ml.kg⁻¹.min⁻¹ vs. 60.3 ±3.4 ml.kg⁻¹.min⁻¹; respectively ) or third interval (57.8 ± 4.4 ml.kg⁻¹.min⁻¹ vs. 59.3 ± 3.8 ml.kg⁻¹.min⁻¹; respectively). Furthermore, average power output measured during intervals one, two and three were not different during the first (438.0 ± 35.0 W, 363.3 ± 23.6 W, 356.3 ± 18.0 W; respectively) and second (441.7 ± 50.1 W, 376.4 ± 28.4 W, 377.1 ± 19.9 W; respectively) “all-out” trials. Similar average 4 km time trial power output was measured in the “all-out” trial one (366.2 ± 22.0 W) compared to the “all-out” trial two (360.0 ± 18.6 W).
CHAPTER FIVE: DISCUSSION

The purpose of the current study was to investigate the influence of the selection of pace (“all-out” compared with even-pacing) during high-intensity interval training on physiological, perceptual and subsequent performance responses in trained cyclists. Within high-intensity interval training “all-out” and even-pacing strategies are common and have traditionally been examined using very short (< 30 seconds) [2, 7, 21, 31, 58] or longer (> 1 minute) [3] duration efforts, respectively. The current study examined the influence of various pacing strategies during longer intervals (i.e. 3 minutes) which are consistent with traditional aerobic cycling training programs [15], and to the author’s knowledge has not been a focus of previous research. The main findings from the study were: 1) oxygen consumption was greater during “all-out” and athlete-controlled, when compared with the computer controlled condition, 2) time spent at 85% of VO₂max was significantly greater in the “all-out” condition, when compared with the athlete- and computer-controlled conditions, with greater time spent at 85% VO₂max observed during intervals one and two compared with intervals three, 3) subsequent time trial performance was significantly lower following the “all-out” condition when compared to the computer- and athlete-controlled conditions and 4) participant’s overall ratings of perceived exertion, quadricep pain and ratings of effort were greater in the “all-out” condition compared with both athlete- and computer-controlled conditions.

Despite completing a similar amount of work, overall oxygen consumption during the “all-out” and athlete-controlled intervals were significantly greater than that observed during the computer-controlled condition. The higher oxygen
consumption recorded during the “all-out” condition is likely a result of the supra-maximal sprint effort during the initial stages (e.g. first 30 seconds) of each interval. Such efforts would increase the reliance on anaerobic energy production \[ \text{[19,23,35,40]} \] thus, promoting a large oxygen deficit \[ \text{[60,69,70]} \] and a compensatory increased oxygen consumption throughout the remainder of the effort \[ \text{[70-72]} \]. Furthermore, cycling sprint efforts are associated with a faster rise in oxygen consumption \[ \text{[9,73,74]} \]. Indeed the time to obtain 85% of VO\(_{2\text{max}}\) was faster during the “all-out” efforts resulting in a longer period of time at high oxygen consumption in this condition compared with the athlete- and computer-controlled conditions (Figure 3).

In contrast to the measured differences in oxygen consumption in the “all-out” compared with the athlete- and computer-controlled conditions, we believe differences observed between the athlete- and computer-controlled conditions are not due to physiological phenomena. Instead, during the athlete-controlled efforts to ensure participants maintained the nominated power output for the duration of the entire interval (i.e. three minutes), participants were instructed to increase power output approximately six seconds from the start of each effort. This strategy resulted in greater oxygen consumption measured immediately prior to the start of the effort in the athlete-controlled (28.7 ± 3.8 ml.kg\(^{-1}.\text{min}^{-1}\)) compared with computer-controlled (25.9 ± 2.8 ml.kg\(^{-1}.\text{min}^{-1}\)) condition and ultimately resulted in a greater overall oxygen consumption during this condition.

It is hypothesised that in order to provide the appropriate stimuli to induce considerable training adaptations from high-intensity interval training (e.g. increased aerobic capacity and endurance performance (refer to Tables 2 and 3) athletes should maximise the time spent at or above 85% of VO\(_{2\text{max}}\) \[ \text{[15,17,29,75,76]} \].
Furthermore, with high-intensity interval training accounting for 20% of many cyclists' overall training programs [6] the need to provide the most effective training stimuli is paramount else training time could be better spent. Our findings indicated efforts conducted using an “all-out” approach provide the greatest stimuli (i.e. time at 85% VO\(_{2\text{max}}\)) for adaptation (Figures 3) and should be considered by coaches and athletes when prescribing training programs. It should be noted; however, the use of the “all-out” selection of pace resulted in greater heart rates (165 ± 9 bpm) during the efforts compared with the athlete- (159 ± 12 bpm) and computer-controlled (158 ± 11 bpm) conditions indicating greater cardiac stress [77]. Furthermore, in the 4 km time trial lower observed power output in the “all-out” condition indicates a greater degree of fatigue. These findings may be of interest to cyclists since the high stress induced by “all-out” intervals, coupled with insufficient recovery between interval bouts and training sessions, may lead to over-reaching or over-training syndrome [78, 79]. Nevertheless, additional research is warranted to confirm this hypothesis.

Due to the high stress nature of the “all-out” pacing strategy, we suggest this method of interval delivery should be considered during the initial macrocycle of an endurance cyclists training regime, approximately two months prior to competition, during which competition demands are likely to be low and where most traditional interval training occurs [48, 80]. Indeed, Zapico et al. [48] reported a greater portion of high-intensity interval training (8.1 ± 0.2%) in sub23-elite Union Cycliste International during the pre-competition mesocycles when compared to their competition mesocycles (2.4 ± 0.3%). During the remaining in-competition training, our data indicates the use of either an athlete- or computer-controlled
approach to interval training can still provide a stimulus for aerobic adaptations \[\text{[40]},\]
yet, with a lower level of over-all fatigue (Figure 4). Furthermore, in-competition training should be tailored to provide minimal psychological stress to athletes \[\text{[48, 81, 82]}\]. In this study, participants reported lower levels of sessional perceived exertion during the computer-controlled (16.3 ±2.7) and athlete-controlled conditions (16.6 ± 2.1) when compared with the “all-out” condition (19.0 ± 1.0). The lower fatigue (Figure 4) and cognitive stress, consistent with the athlete- and computer-controlled conditions, are likely to increase the compliance to high-intensity interval training during high physiologically demanding periods within a competition macrocycle \[\text{[48, 81, 82]}\].

Within all intervals sessions, the time spent at 85% of VO\textsubscript{2max} was greater during intervals one and two (136.8 ± 15.1 s and 139.9 ± 14.1 s respectively), when compared with interval three (134.3 ± 14.4 s). These results are likely to be representative of a growing level of fatigue throughout the session \[\text{[69]}\]. Compared with the current study, previous high-intensity interval training studies \[\text{[11, 14, 16, 18, 39, 58]}\] have incorporated greater repetitions of work efforts (e.g. four to six efforts per session). Using similar methodologies to our study, it is possible the addition of more intervals could result in a further decrease in oxygen consumption thus reducing cardiovascular stress and decreasing the effectiveness of this training. However, it is currently unclear whether such fatigue is important to cell signalling and thus adaptations following exercise.

During this study, we used exposure variation analysis (EVA) of the 4 km time trial data to quantify variation in power output following our interval conditions as minor variations in power output during a cycling time trial have
previously been used to describe an association between homeostatic control, pacing and fatigue\[^{83, 84}\]. Indeed, it has been suggested increases in the variation of power output during exercise may be associated with increased afferent feedback from the periphery resulting from disturbances to homeostasis\[^{85, 86}\]. For instance, an increase in metabolic disturbances within skeletal muscle cells caused by high exercise intensity will increase activation of group III and IV afferent fibres increasing perceived pain causing a rapid down regulation of exercise intensity\[^{87}\]. Somewhat supporting this hypothesis, Peiffer et al.\[^{83}\] have recently observed a greater variability in power output measured using EVA analysis of a 40 km time trial at 32°C when compared with 17°C, which the authors suggests was due to a higher level of fatigue induced by the heat. Interestingly, in this study no differences were observed between the time trials at 32°C compared with either the 22°C or 27°C conditions\[^{83}\]. In contrast to observed differences in the average 4 km power output in the “all-out” compared with the computer- and athlete-controlled conditions (Figure 4), no differences in EVA were observed between the “all-out” (7.6 ± 2.4), computer- (6.9 ± 1.9) and athlete-controlled (7.3 ± 2.1) conditions. The absence of differences in the EVA matrix may be due to the relatively short duration of the time trial and/or the normothermic environmental conditions. Indeed, we used a time trial one tenth the duration of Peiffer et al.\[^{83}\] and at room temperature (~24°C) which may have resulted in less stress to our participants and ultimately less fatigue\[^{88}\]. Clearly, further research is warranted in order to understand the factors influencing the variability in power output during cycling.
To the author’s knowledge, this study represents the first to assess pacing during high-intensity interval training and thus provide needed information to this field. Nevertheless, we acknowledge there may be limitations with our methodology which could have influenced our findings. Due to our selected methodology and aims within this study, the “all-out” session could not be randomised and was required to be the first condition completed. Therefore, it is possible a training effect may have occurred \(^{[89]}\) which would have influenced the physiological responses during subsequent trials. In an attempt to identify a possible training effect, five participants volunteered to complete a second “all-out” session the week after the final experimental session was completed. No differences were observed between any inter-interval variables or 4 km time trial performance between the first and second “all-out” conditions; thus, we are confident a training effect was not observed during this study. Additionally, during the “all-out” effort it was necessary for participants to provide the greatest level of effort possible. Although we could not mandate all participants provided the necessary level of effort during the “all-out” condition, based on oxygen consumption and heart rate recordings during these efforts, we feel all participants provided the necessary effort for this study.

**CONCLUSION**

Pacing during interval training, while important, has received limited attention within the literature. Our findings indicate, irrespective of work completed, greater physiological stress was associated with an “all-out” interval training approach when compared with athlete- and computer-controlled efforts.
These findings indicate the adaptive response to interval training sessions may differ depending on the pacing selected and individuals are likely to receive greater benefits from an “all-out” selection of pacing. Regardless, greater latent fatigue as evidenced by a larger decrement in 4 km time trial performance following the “all-out” efforts indicate this selection of pacing should be implemented with caution to avoid over-stressing athletes. Whilst all the examined pacing strategies are likely to promote beneficial physiological adaptions, it is important for coaches and athletes to recognise the pros and cons of each method of interval delivery to ensure the most optimal training environment is achieved.

FUTURE DIRECTIONS

Based on the findings from this study, areas have been identified which should be the focus of future research involving pacing and interval training. The higher physiological stress consistent with an “all-out” pacing selection is likely to result in greater physiological adaptions. Future studies are needed to determine if this selection of pacing is superior to other well established interval protocols. Additionally, the use of an “all-out” pacing selection while consistent with shorter efforts (<60 seconds) should be examined in both moderate (e.g. 90 seconds to 2 minutes) and longer (> 3 minutes) durations in order to assess the ecological efficacy of this pacing selection within the field of cycling.
REFERENCES


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Monday, 24 September 2012

Dr Jeremiah Peiffer  
School of Chiropractic and Sports Science  
Murdoch University

Dear Jeremiah,

Project No.  2012/158  
Project Title  Physiological response to ‘all out’ and fixed work cycling intervals

Thank you for addressing the conditions placed on the above application to the Murdoch University Human Research Ethics Committee. On behalf of the Committee, I am pleased to advise the application is now:

APPROVED, with advice

Consent form -

"I understand that all data obtained during this study will be stored for five years during which time my data may be used in retrospective research. The use of this data will be done so in an unidentifiable manner.  "  Could be changed to "I understand that all data obtained during this study will be stored for five years during which time my data may be used in retrospective research. I will not be identified in any future use of this data."

Approval is granted on the understanding that research will be conducted according the standards of the National Statement on Ethical Conduct in Human Research (2007), the Australian Code for the Responsible Conduct of Research (2007) and Murdoch University policies at all times. You must also abide by the Human Research Ethics Committee’s standard conditions of approval (see attached). All reporting forms are available on the Research Ethics web-site.

I wish you every success for your research.

Kind Regards,

Dr. Erdis von Dietze  
Manager of Research Ethics

cc  Dr Chris Abbiss  
Emma Zadow
APPENDIX 2: VISUAL ANALOGUE SCALES

2.1 BORG’S RATING OF PERCEIVED EXERTION

6

7 - Very, very light

8

9 - Very light

10

11 - Fairly light

12

13 - Somewhat hard

14

15 - Hard

16

17 - Very hard

18

19 - Very, very hard

20 - Exhaustion
### 2.2 QUADRICEP PAIN AND EFFORT SCALES

<table>
<thead>
<tr>
<th>QUADRICEP PAIN</th>
<th>EFFORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0- no pain</td>
<td>0- no effort</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
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<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5- moderate pain</td>
<td>5- some effort</td>
</tr>
<tr>
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<td>6</td>
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<tr>
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<td>7</td>
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<td>8</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>10- maximal pain</td>
<td>10- gave my all</td>
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</tbody>
</table>