Pacing and opponents: the regulation of exercise intensity during competition

M.J. Konings

A thesis submitted for the degree of Doctor of Philosophy

School of Sport, Rehabilitation and Exercise Sciences

University of Essex

Year of award: 2018

ABSTRACT

The goal-directed regulation of the exercise intensity over an exercise bout has been shown to be an essential determinant for performance. During their competition, exercisers are required continuously to make decisions about how and when they are going to invest their limited available energy resources. The regulation of the exercise intensity is an intriguing area of sport science research, and a complex one as demonstrated by the multitude of different theories regarding pacing that are around attempting to explain how this is done. Previous research revealed optimal pacing strategies in time trial exercise and the importance of feedback regarding the internal bodily state. The present thesis adds onto this knowledge by highlighting the external world around the exerciser and its effect on pacing. This has been done by focusing on arguably the most important external variable in competitions: the opponent. It has been shown how opponents could invite exercisers to adjust their pacing behaviour in real-life competitions and in controlled laboratory situations. Moreover, it has been illustrated that even the same opponent could evoke different pacing responses and alter the information-seeking behaviour, depending on the competitive situation that is presented towards the exerciser. It has been demonstrated how an accumulation of preceding race efforts could impact the pacing and performance of elite athletes during their competition. Finally, the reciprocal interaction in pacing decision-making between the effect of an opponent and the internal state of the exerciser was demonstrated, providing novel insights into the regulatory mechanism of exercise regulation. The present findings of this thesis emphasizes the importance of what is happening around the exerciser for the outcome of the decision-making process involved in pacing, and highlight the necessity to incorporate human-environment interactions into models that attempt to explain the regulation of exercise intensity.

De Kansloze Vlucht [in Dutch]

Het mooie van een wielerwedstrijd is dat de sterkste lang niet altijd wint.

De winnaar is niet degene die het beste is gebleken na een steriele vergelijking van lichamelijke kwaliteiten, maar degene die als eerste over de streep komt na een onbegrijpelijke mengeling van goede benen, tactiek, geluk, timing, toeval, openstaande rekeningen, de weersomstandigheden, de acties en reacties van andere renners en nog honderdduizend andere factoren.

Doe een marathon honderd keer over en dezelfde hardloper wint negenennegentig keer; doe een wielerklassieker honderd keer over en de wedstrijd loopt honderd keer anders.

- Thijs Zonneveld, Algemeen Dagblad, 24-03-2014

The Desperate Flight

The beauty of a cycling race is that the strongest one is not always the one who wins.

The winner is not the one who appeared to be the best after a sterile comparison of physical capacities, but the one who firstly crosses the finish line after an inconceivable mixture of strong legs, tactics, luck, timing, coincidence, outstanding debts, weather conditions, actions and reactions of other riders and hundred thousand more factors.

Organise a marathon hundred times and the same runner will win ninety-nine times; Organise a cycling classic hundred times and the race will develop differently hundred times

- Thijs Zonneveld (Dutch columnist), Algemeen Dagblad, 24-03-2014

ACKNOWLEDGEMENTS

This thesis in front of you right now is a culmination of three years of intensive research, dedication and hard work and would not have been possible without the help of the following people that I would like to thank for their contribution and support.

Dr. Florentina Hettinga, our journey started when I was still a Master student back in The Netherlands, interested in pacing and tactics, and has led to the implementation of a new theoretical framework on exercise regulation. Your guidance and support allowed me to develop myself as an academic and as a person, of which I am incredibly grateful. I thoroughly enjoyed our cooperation, the countless coffee breaks and all academic and less academic discussions and conversations.

I am fortunate to have completed this process in the company of some great colleagues. Patrick Schoenmakers, Manhal Boya, Di Fu, Jason Moran thank you for company at coffee breaks, Friday drinks and conferences. I am wishing you all the best in your future careers and I sincerely hope to work with you in the near future.

The experiments in this thesis would not have been realised without all the enthusiastic cyclists around Essex, who were willing to dedicate their spare time to our research. Your efforts made this thesis possible. The successful completion of these experiments would also not have been possible without the help during the data collection of the undergraduate students Jordan Parkinson, Marissa Al, Romy de Jong, Andrew Walker, Matthew Sadler and Alice Klooster. Moreover, I would like to show my appreciation to all co-authors involved in the published versions of the studies within this thesis for they help in this process.

The past couple years have not only been a highlight in academic perspective, but also in a personal way, in which I have been lucky enough to have met my amazing girlfriend Patty van der Poel. Thank you for all your love and care. You motivate me, and I am truly appreciative of all your advice and inspiration. On the same note, I would express my gratitude to my friends for their encouragement, support, and distraction from work whenever I needed it.

Finally, I wish to extend a special thanks to my Mum and Dad, Sabine and Rinaldo. You have been invaluable, and I could not have completed this thesis without you. I am indebted to your understanding and unconditional support to allow me to pursue my aspirations, throughout all my years and locations of study. I endeavour to continue to make you proud.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abbreviations

bpm	Beats per minute
CI	Confidence interval
CO	Rest (control) condition of 26 minutes sitting down (Chapter 9)
CV	Coefficient of variation
DJ	Drop jump protocol of 80 drop jumps in 26 minutes 20 seconds (Chapter 9)
FA	10 minutes of 67% PPO cycling protocol prior to time trial (Chapter 9)
FAM	Familiarisation trial
ICC	Intra-class correlations coefficients
IT	Interpolated doublet-twitch
km	Kilometre
m	Meter
mA	Milliampere
ms	Millisecond
µs	Microsecond
MVC	Maximal voluntary contraction force
N	Newton
NO	Time trial riding alone (Chapter 4, 6, 8 and 9)
NF	Non-fatiguing protocol condition prior to time trial (Chapter 9)
OP	Time trial against a virtual opponent (8 and 9)
OP-DEP	Time trial against a virtual opponent with no further restrictions (Chapter 6)
OP-FASTSLOW	Time trial against a 3% faster starting, 1% slower finishing virtual opponent compared to FAM (Chapter 4)
OP-IND	Time trial against a virtual opponent with the restriction overtaking is only allowed once (Chapter 6)
OP-SLOWFAST	Time trial against a 1% slower starting, 3% faster finishing virtual opponent compared to FAM (Chapter 4)
PO	Power output
PPO	Peak power output
PT	Potentiated doublet-twitch force
RPE	Rate of perceived exertion
rpm	Revolutions per minute
SD	Standard deviation
sec	Seconds
TT	Time trial
VA	Voluntary activation
W	Wattage

PART I – INTRODUCTION

CHAPTER 1

Introduction

1.1 Pacing and human-environment interactions

Exercisers are required to decide continuously about how and when to invest their limited energy resources over time in all non-reflex exercise situations to achieve the completion of one or multiple tasks (Edwards and Polman, 2013). This goal-directed regulation of the exercise intensity over an exercise bout is also known as 'pacing' (Abbiss and Laursen, 2008). Although pacing is not exclusive to sports and race performances, an athlete's pacing strategy is widely recognised as an essential determinant for performance (Edwards and Polman, 2013). In this sense, previous research suggests that exercisers are in general well capable to choose an appropriate pacing strategy in time trial exercise most of the time (Hettinga *et al.*, 2011; Hettinga *et al.*, 2012).

Based on the duration of an event, different pacing strategies appear to be optimal in time trial exercise. When the duration of an event is less than 30 seconds, an all-out strategy is advised in order to be able to use all available energy resources before the finish line is reached (Abbiss and Laursen, 2008). In contrast, an even pacing strategy is advised when the duration is over two minutes, thereby minimising the energy losses related to accelerating and decelerating plus preventing a too early onset of fatigue (Hettinga *et al.*, 2006; Abbiss and Laursen, 2008). Finally, modelling studies revealed a positive pacing strategy (i.e. starting fast with a consequently decreasing power output throughout the race) would lead to optimal performance in middle-distance events lasting about 1-2 minutes (Hettinga *et al.*, 2011; Hettinga *et al.*, 2012). Nevertheless, the regulatory mechanisms behind the decision-making process involved in pacing are still strongly debated and not yet well understood. In this perspective, the necessity to incorporate human-environment interactions into the regulation of exercise intensity has been emphasised by several different research groups in recent years

(Smits *et al.,* 2014; Renfree *et al.,* 2014a; Hettinga *et al.,* 2017; Micklewright *et al.,* 2017; Venhorst *et al.,* 2017).

To incorporate human-environment interactions into the regulation of exercise intensity, an important question that needs to be considered first is how individuals perceive the external world. In this sense, two different theories of (visual) perception-action coupling can be distinguished: a constructivist approach and an ecological approach. The constructivist approach towards perception advocates an indirect coupling between perception and action (Gregory, 1974). Perception is determined via the construction of an internal representation of reality in our mind based on previous experiences and stored information (Gregory, 1974). However, the constructivist approach faces several limitations. For example, it cannot explain how newborns could ever perceive, having no previous experiences. In addition, the constructivist approach has been criticised for underestimating the richness of the available sensory information (Lombardo, 1987; Gibson, 1979).

In contrast, the ecological approach argues a direct rather than indirect perception-action coupling (Gibson, 1966; Gibson, 1972). Instead of creating an internal representation of reality in our mind, individuals perceive direct action possibilities in their environment, so-called affordances (Gibson, 1966; Gibson, 1972). For example, in many occasions a chair could be perceived as an object to sit. However, in specific circumstances the same chair could be perceived as something to stand on in order to get something on top of the closet. In addition, one does not per se have to understand “what” something is, in order to decide “how” to use it (Gibson, 1966; Gibson, 1972). For example, even if one has never seen a chair before, one could still perceive the action possibility to sit on it. In a sport setting many of these perceptual affordances are likely to be present and could potentially affect the regulation of the exercise intensity (Smits *et al.,* 2014). In this respect, an ecological approach towards exercise regulation has recently been advocated as a possibly way to incorporate human-environment interactions onto pacing regulation (Smits *et al.,* 2014).

1.2 Research aim and thesis structure

In Figure 1.1 a schematic overview of the structure of this thesis can be found. In this thesis it is attempted to explore the effects of human-environment interactions on the decision-making process involved in pacing. This has been done by focussing on arguably the most important external factor present in competitive sports: the opponent. That is, knowing that most sport events involve direct competition with other competitors, interaction with the competing athletes seems to be a crucial environmental factor that needs to be incorporated in our models explaining pacing and performance (Hettinga *et al.,* 2017).

In this respect, three different variables can effectively be altered when exploring the regulation of exercise intensity during competition: the opponent, the exerciser, and the situation in which the opponent is present towards the exerciser. The effect of each of these three components (i.e. opponent, competitive situation, exerciser) on exercise regulation will be explored separately via a combination of observational and experimental studies in this thesis.

Observational studies involving large datasets would ensure a high ecological validity and could help us move forward in understanding the pacing decisions of exercisers during real-life competitions. In the observational studies of this thesis, elite short track speed skating races are used in order to explore the regulation of exercise intensity in a real-life competitive situation. It was a deliberate decision to choose this

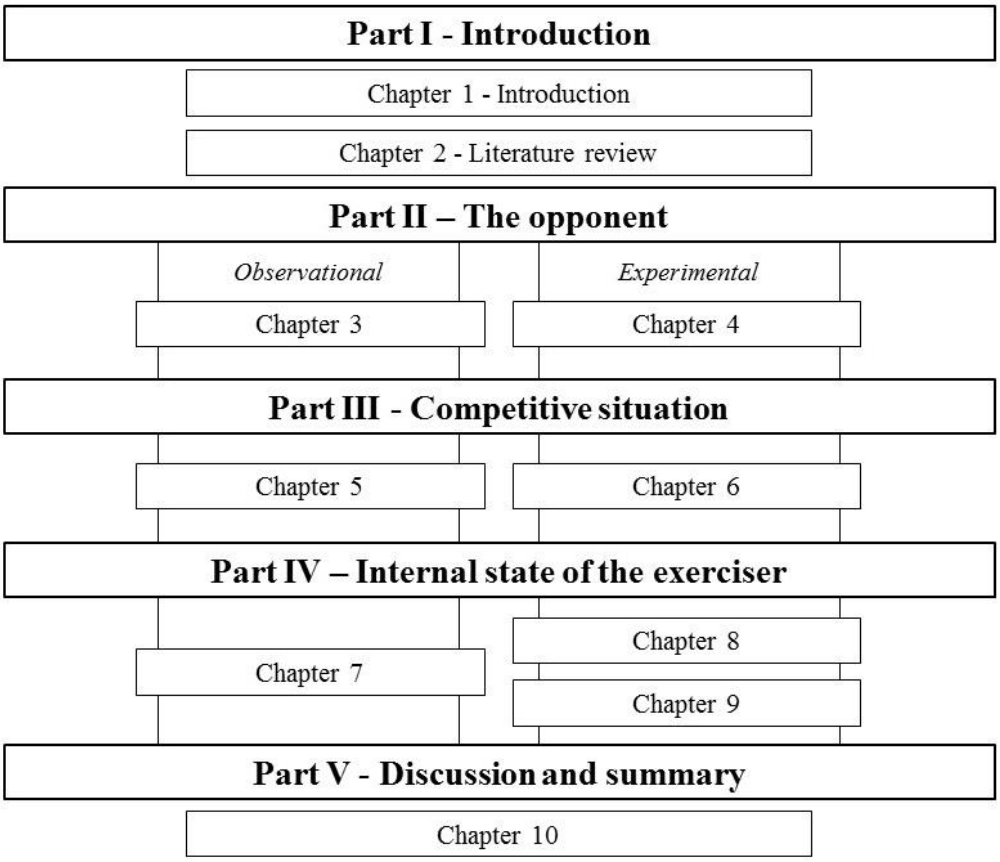

Figure 1.1 Schematic overview of the thesis structure. First of all, the existing literature regarding the regulation of exercise intensity during competition is critically reviewed. Hereafter the effect of an opponent, the competitive situation and the internal state of the exerciser on exercise regulation during competition are each separately examined via a combination of observational and experimental studies. Finally, in the last chapter will be discussed how exercise intensity is regulated during competition based onto the outcomes of the studies in this thesis, the existing literature, and the present theories regarding the regulation of the exercise intensity.

particular sport. The rules and set-up of a short track speed skating competition provide a relatively well-controlled experimental situation. Competitions always take place on a 111.12 m track in an indoor oval ice rink, the rules and distances of the individual disciplines are consistent per event, and accuracy of the collected data is demanded by the event organisation (i.e. the International Skating Union). Moreover, due to the 111.12 m track, data sampling frequency is relatively high for this type of observational analysis.

The experimental studies in the present thesis are designed based on the outcomes of the literature review and the findings of the observational studies. They are used to gain information regarding the underlying mechanisms via manipulations in well-controlled conditions, in which the situation of a time trial against a competing opponent while monitoring pacing behaviour provides interesting novel possibilities to explore how exercisers regulate their exercise intensity in relatively controlled and simplified conditions. Furthermore, the experimental studies provide the opportunity to explore the impact of additional variables such as gaze behaviour and neuromuscular function in this thesis.

1.2.1 Introduction and literature review

In Chapter 2, the present models attempting to explain the regulation of exercise intensity are critically reviewed, and an overview of the existing literature is presented in regard to the effect of competitors on pacing behaviour. Thereafter, it is discussed how human-environment interactions in general, and the opponent in particular, could be incorporated as a determinant in exercise regulation based on the presented pacing models and literature. The regulation of exercise intensity during competition will be further explored in the following chapters via the examination and manipulation of the behaviour of an opponent, the competitive environment presented towards the exerciser, and the internal state of the exerciser using a combination of observational and experimental studies.

1.2.2 The opponent

Chapters 3 and 4 are focussed on the question of how the behaviour of another competitor impacts on pacing regulation. Variability analyses of pacing behaviour between and within short track speed skating races were used in Chapter 3 to explore to what extent the skaters adjust their pacing behaviour based on their other competitors in a real-life competitive situation. In Chapter 4 the effect of the pacing behaviour of an opponent on pacing regulation is further elaborated via an experimental study in which the pacing profile of a virtual opponent was manipulated. This experimental design provided the possibility to examine the effect of the behaviour of a competitor on exercise regulation in a situation in which adjusting pacing behaviour to the other competitor would provide no beneficial or detrimental opportunities in terms of energy saving.

1.2.3 The competitive situation

Chapters 5 and 6 focussed on the competitive situation presented towards the exerciser and its effect on pacing regulation. In this perspective, Chapter 5 examined the influence of different competitive variables within a sport on the decision-making process involved in pacing, such as stage of competition, the number of competitors or possibility of time fastest qualification. In contrast, Chapter 6 explored via a manipulation of the interdependency between competitors a potential underlying mechanism for differences in chosen pacing behaviour between sports. In addition, information-seeking behaviour during competitive time trials was examined in this chapter.

1.2.4 The internal state of the exerciser

Chapters 7, 8 and 9 focussed on the exerciser and interaction of fatigue manipulation, perceived level of exertion and neuromuscular function in combination with the presence of competitors. Using the competition structure of short track speed skating events, Chapter 7 examined the effect of an increased number of high-intensity race efforts on pacing regulation during a head-to-head competition. Chapter 8 explored how the performance improvement in the presence of a virtual opponent is established, while Chapter 9 examined the impact of different fatigue manipulations during competitive and non-competitive self-paced exercise bouts.

1.2.5 Summary and discussion

In the last chapter of this thesis, the novel insights onto the regulation of exercise intensity during competition are summarised for the three identified components (opponent, competitive situation, exerciser), and possible practical applications of these findings are suggested. Finally, how exercise intensity is regulated during competition is discussed based on the generated outcomes from the different studies in this thesis, the existing literature, and the present theories regarding the regulation of exercise intensity.

CHAPTER 2

The regulation of exercise intensity during competition, a critical review of literature

Abstract

An athlete's pacing strategy is widely recognised as an essential determinant for performance. In this respect, most of the present pacing models seem to be focused on the regulation of exercise intensity during time trial exercise at maximal effort, and concepts such as teleoanticipation and exercise templates. As a result, although human-environment interactions have been emphasised as a crucial determinant for pacing behaviour, how they affect pacing behaviour is not yet well understood. The present literature review attempted to critically revise the existing literature regarding the effect of a competitor on pacing behaviour and performance. PubMed, CINAHL, and Web of Science were searched for studies about pacing in sports and (interpersonal) competition between January 2000 to December 2016 using the following combination of terms: 1. Sports [MeSH] AND 2. Pacing (OR Pacing strategy OR Pacing behaviour OR Race analysis OR Performance OR Competition OR competitors OR opponents), leading to 65 included papers. Especially in the most recent years, the number of observational pacing studies (N=51) has increased exponentially. Yet most of these studies do not go beyond simply describing the used pacing strategies. In addition, most experimental studies (N=14) that examined the influence of a competitor have mainly focussed on the performance effects of presenting an opponent rather than on the resulting changes in pacing. Nevertheless, the present literature review supports the idea that an opponent could invite an athlete to adjust pacing behaviour and affect performance, and should be incorporated in any model that attempts to explain exercise regulation.

2.1 The regulation of exercise intensity

Pacing has been defined as the goal-directed regulation of the exercise intensity over an exercise bout (Edwards and Polman, 2013), and is widely recognised as an essential determinant for performance (Abbiss and Laursen, 2008). However, the regulatory mechanisms behind the decision-making process involved in pacing are still strongly debated. For a long time the predominant theory has in the exercise physiology has been that performance is limited by metabolic changes in the exercising muscles, so called peripheral fatigue (Hill *et al.,* 1924). Based on the work of Hill and colleagues in the 1920s it was argued that exercise termination would happen when a catastrophic failure of homoeostasis in the exercising muscles occurred as a result of lactic acid accumulation and/or myocardial ischaemia (Hill *et al.,* 1924). However, in the late 1990s, the Hill model was questioned more and more, mainly because it did not allow a role for the brain in the regulation of exercise and the protection of homeostasis. For example, the Hill model could not explain why people tended to finish with an end spurt during a time trial (Noakes, 2000).

As an alternative, Ulmer (1996) proposed that exercise is regulated centrally based on the process of teleoanticipation, where efferent commands try to link the demands of the task with the (expected) metabolic and biomechanical costs. To coordinate afferent and efferent signals and prevent the exercise intensity to exceed exercise limits, a central programmer was proposed that would act as an input/output black box. Noakes and colleagues expanded on this new approach in which the brain has a dominant control position and introduced the Central Governor model (CGM) (Noakes and St Clair Gibson, 2004; Noakes *et al.,* 2005; Lambert *et al.,* 2005; Tucker, 2009; Noakes, 2011; Noakes, 2000). According to the CGM, homeostasis is protected under all conditions and behaviour will be changed when internal homeostasis is threatened (Tucker *et al.,* 2006). In this respect, exhaustion is perceived as a relative rather than an absolute event, and fatigue as a symptom and not a physical state. That is, a subconscious governor located in the brain regulates the exercise intensity by projecting the sensation of fatigue to the conscious brain based on the skeletal muscle mass that is recruited during exercise (Noakes and St Clair Gibson, 2004). This implies that pacing decisions would be the outcome of the interplay between the sensation of fatigue and the expected remaining demands of the exercise bout (Noakes *et al.*, 2005; Tucker, 2009). An updated version in 2009 added the RPE template to the CGM, proposing pacing is regulated in an anticipatory manner in which the momentary RPE is compared to the expected RPE at that point in the race (Tucker, 2009). Finally, the same South African research group introduced recently the Integrative Governor Model (St Clair Gibson *et al.*, 2017). In this most recent model it is suggested that competition between homeostatic drives is central to exercise regulation and is based on governing principles, using complex algorithms and dynamic negative feedback activity (St Clair Gibson *et al.*, 2017).

Although the introduction of a central brain component in the regulation of the exercise intensity did led to many novel insights, several scientists have questioned the existence of a subconscious (dominant) control region in the brain regulating whole-body homeostasis and pacing. Moreover, the CGM seems biased towards internal information, thereby underrating the influence of external information on pacing decisions (Venhorst *et al.,* 2017). Finally, based on the fact that catastrophic failures of homeostasis can and do occur (Esteve-Lanao *et al.,* 2008), it can be argued that the central governor could at least be overridden (Smits *et al.,* 2014). Therefore, alternative mechanisms have been proposed. For example, a peripheral governor has been suggested (MacIntosh and Shahi, 2011). Marcora (2008) introduced a psychobiological model, where the decision to terminate exercise is made by the conscious brain without the need to include an additional subconscious governor. Exercise will be terminated when the effort required by the exercise is equal to the maximum effort the athlete is willing to exert, or when the athlete believes they have exerted a true maximal effort (Marcora, 2010; Marcora, 2008). Edwards and Polman (2013) proposed to consider the brain as a complex system of neural communications, in which pacing is regulated by consciousness. They argued that low levels of physical effort are regulated by the conscious brain, but possibly do not require conscious attention. In contrast, the accumulation of negative triggers caused by high-intensity exercise will lead to the conscious awareness to control the exercise regulation (Edwards and Polman, 2013).

In this respect, the conscious-subconscious dichotomy has been predominant in the debate of how pace is regulated during exercise. Yet it can be questioned whether this discussion is still helping us moving forward in our understanding of the regulatory mechanisms involved in pacing (Micklewright *et al.,* 2017). Alternatively, Micklewright *et al.,* (2017) proposed to approach the mechanisms involved in the decision-making process of pacing as being intuitive or deliberative (Tversky and Kahneman, 1974; Kahneman, 2011). Intuitive thinking is fast, requires little cognitive effort, and facilitates parallel functions. In contrast, deliberative thinking is slow, demands much cognitive effort, and is sequential (Tversky and Kahneman, 1974; Kahneman, 2011). In broader sense, we could then make the distinction between a pre-planned strategy and in-race adaptations. Concepts as teleoanticipation and template formation are crucial for this pre-planned strategy and could be perceived as a mainly deliberative process (Micklewright *et al.,* 2017). In contrast, in-race adaptations in pacing behaviour are likely more intuitive responses driven by human-environment interactions (Micklewright *et al.,* 2017).

Finally, two recent reviews attempted to incorporate decision-making theories into the regulation of exercise intensity, arguing pacing can be seen the behavioural outcome of an underlying continuous decision-making process. Renfree *et al*. (2014a) proposed a heuristic decision-making model. In this sense, heuristics could be considered as ‘rules of thumb’ or ‘gut instincts’, and require relatively low cognitive processing demands (Renfree *et al.,* 2014a). This heuristic decision-making strategy ignores some available information to make decisions more quickly and/or accurately than can be achieved through more complex methods (Renfree *et al.,* 2014a). In contrast, Smits *et al*. (2014) argued an ecological-psychological approach towards pacing, in which perception and action are intrinsically linked. According to the ecological-psychology, individuals perceive direct action possibilities in their environment, so-called affordances, that can invite the exerciser for action (Gibson, 1966; Gibson, 1972). A continuous and simultaneous interaction between environmental stimuli and an individual’s action capabilities would occur in a natural environment, in which action selection and specification should be seen as the same dynamic process rather than distinct serial stages (Smith and Pepping, 2010). The interactions between external stimuli and internal bodily state would lead to the specification of potential actions, and the competition between these potential actions while exposed to an array of biasing influences, such as significant changes in homeostasis and fatigue or the motivation to outperform one another (Smits *et al.*, 2014).

The variety of models and theories as mentioned above attempting to explain the regulation of exercise intensity highlight the complexity of pacing. Despite the differences between the presented models, some factors appeared to be shared by nearly all of them. For example, the importance of sensations of fatigue and the perceived level of exertion and/or effort, knowledge about the endpoint and the expected remaining distance/duration, and a willingness to tolerate discomfort in anticipation of future rewards. In Section 2.3, we will further discuss how human-environment interactions in general, and the opponent in particular, could be incorporated as determinant in exercise regulation based on the presented pacing models. However, first an overview of the existing literature regarding the regulation of exercise intensity during competition will be presented.

2.2 The role of interpersonal competition in pacing research

As a first step in exploring the influence of an opponent on pacing regulation the existing literature has been critically revised. PubMed, CINAHL, and Web of Science were searched for studies about pacing in sports and (interpersonal) competition between January 2000 to December 2016 using the following combination of terms: 1. Sports [MeSH] AND 2. Pacing (OR Pacing strategy OR Pacing behaviour OR Race analysis OR Performance OR Competition OR competitors OR opponents). The initial search resulted in 640 papers. After reading the body of these remaining articles, 513 papers were excluded because studies did not describe pacing. Lastly, 62 papers were excluded whereas the design of the study could not be perceived as a competitive situation, leading to 65 included papers (see Table 2.1). A distinction will be made between observational and experimental studies. The observational studies will be examined to provide insight into the pacing decisions of exercisers during real-life competitions, while the experimental studies will be used to gain information regarding the underlying mechanisms via manipulations in well-controlled conditions.

Table 2.1 Overview of the articles about pacing behaviour and competition included in this review.

Study	Sport	Distance	Study type	Type of Comp	Proficiency	No. of subjects
Wiersma et al., 2017	Long track speed skating	1500 m	Obs	TT	Talent	104
Stone et al., 2017	Cycling	4000 m	Exp	H-H	Trained	10
Losnegard et al., 2016	Cross-country skiing	10 km 15 km	Obs Obs	TT TT	Elite Elite	14 22
Deaner & Lowen, 2016	Cross-country running	5000 m	Obs	H-H	Trained	3948
Van Biesen et al., 2016	Track running	400 m 1500 m	Obs Obs	H-H H-H	Elite Elite	47 28
Hanley, 2016	Road running	42.1 km	Obs	H-H	Elite	1222
Renfree et al., 2016	Road running	100 km	Obs	H-H	Elite	196
Jones et al. 2016b	Cycling	16.1 km	Exp	H-H	Trained	17
Lipińska et al., 2016a	Swimming	800 m	Obs	H-H	Elite	20
Lipińska et al., 2016b	Swimming	1500 m	Obs	H-H	Elite	24
Edwards et al. 2016	Rowing	6800 m	Obs	H-H	Elite	228
Taylor et al., 2016	Swimming	400 m	Obs	H-H	Elite	1176
Noorbergen et al., 2016	Short track speed skating	500 m 1000 m	Obs Obs	H-H H-H	Elite Elite	1056 844
Konings et al., 2016	Short track speed skating	1500 m	Obs	H-H	Elite	510
Heidenfelder et al., 2016	Road cycling	4860 km	Obs	H-H	Trained	?
Carlsson et al., 2016	Skiing	90 km	Obs	H-H	Trained	2400
Nikolaidis & Knechtle, 2016	Swimming	100 m 200 m 400 m 800 m	Obs Obs Obs Obs	H-H H-H H-H H-H	Elite Elite Elite Elite	1602 1228 772 880
Kerhervé et al., 2016	Road running	173 km	Obs	H-H	Trained	10
Tan et al., 2016	Road running	101 km 161 km	Obs Obs	H-H H-H	Trained Trained	120 47
Bossi et al., 2016	Road running	24 hours	Obs	TT	Trained	501

Jones et al. 2016a	Cycling	16.1 km	Exp	H-H	Trained	20
Shei et al. 2016	Cycling	4000 m	Exp	H-H	Trained	14
Wright, 2016	Para-cycling	500 m 1000 m	Obs Obs	TT	Elite Elite	47 21
Williams et al., 2015a	Cycling	16.1 km	Exp	H-H	Trained	12
Williams et al., 2015b	Cycling	16.1 km	Exp	H-H	Trained	15
Tomazini et al., 2015	Running	3000 m	Exp	H-H	Recreational	9
Kerhervé et al., 2015	Road running	106 km	Obs	H-H	Trained	15
Hanley, 2015	Road running	21.1 km	Obs	H-H	Elite	838
Knechtle et al., 2015	Road running	100 km	Obs	H-H	Trained	1000
Mytton et al., 2015	Swimming Track running	400 m 1500 m	Obs Obs	H-H H-H	Elite Elite	48 60
Deaner et al., 2015	Road running	42.1 km	Obs	H-H	Amateur	91929
Moffatt et al., 2014	Track cycling	1000 m	Obs	H-H	Elite	462
Renfree et al., 2014b	Track running	800 m 1500 m	Obs Obs	H-H H-H	Elite Elite	109 136
Esteve-Lanao et al., 2014	Cross country running	12 km	Obs	H-H	Elite	768
Hanley, 2014	Cross-country running	12 km	Obs	H-H	Elite	1273
Hoffman, 2014	Road running	161 km	Obs	H-H	Elite	24
Santos-Lozano et al., 2014	Road running	42.1 km	Exp	H-H	All	190228
Lambrick et al., 2013	Track running	800 m	Exp	TT	Novices	13
Dwyer et al., 2013	Track cycling	Elimina-tion	Obs	H-H	Elite	91
Hanley, 2013	Race walking	20 km 50 km	Obs Obs	H-H H-H	Elite Elite	439 232
Renfree & St Clair Gibson, 2013	Road running	42.1 km	Obs	H-H	Elite	60
Bath et al., 2012	Track running	5 km	Exp	H-H	Trained	11

Thiel et al., 2012	Track running	800 m	Obs	H-H	Elite	16
		1500 m	Obs	H-H	Elite	24
		5 km	Obs	H-H	Elite	29
		10 km	Obs	H-H	Elite	64
Stone et al. 2012	Cycling	4000 m	Exp	H-H	Trained	9
Corbett et al., 2012	Cycling	2000 m	Exp	H-H	Amateur	14
Mauger et al., 2012	Swimming	400 m	Obs	H-H	Sub-elite	264
Hettinga et al., 2012	Cycling	1500 m	Obs	TT	Trained	6
Hanley et al., 2011	Road running	5 km	Obs	H-H	Sub-elite	20
Muehlbauer & Melges, 2011	Rowing	2000 m	Obs	H-H	Elite	1682
Le Meur et al., 2011	Triathlon (running)	9.68 km	Obs	H-H	Elite	12
Saraslanidis et al., 2011	Track running	400 m	Obs	H-H	Amateur	8
Smith & Hopkins, 2011	Rowing	2000 m	Obs	H-H	Elite	4234
Hettinga et al., 2011	Long track speed skating	1500 m	Obs	TT	Sub-elite	7
Brown et al., 2010	Rowing	2000 m	Obs	TT	Sub-elite	507
Muehlbauer et al., 2010c	Long track speed skating	1000 m	Obs	TT	Elite	65
Muehlbauer et al., 2010b	Long track speed skating	1500 m	Obs	TT	Elite	114
Muehlbauer et al., 2010a	Long track speed skating	3 km	Obs	TT	Elite	144
		5 km	Obs	TT	Elite	226
		10 km	Obs	TT	Elite	82
Peveler & Green, 2010	Cycling	20 km	Exp	TT	Trained	8
Hanon & Gajer, 2009	Track running	400 m	Obs	H-H	Elite	10
					Sub-elite	10
					Trained	10
Corbett, 2009	Track cycling	1 km	Obs	TT	Elite	42
		3 km	Obs	TT	Elite	68
		4 km	Obs	TT	Elite	68
Hulleman et al., 2007	Cycling	1500 m	Exp	TT	Trained	7
Tucker et al., 2006	Track running	800 m	Obs	H-H	Elite	26
		5 km	Obs	H-H	Elite	32
		10 km	Obs	H-H	Elite	34
Garland, 2005	Rowing	2000 m	Obs	H-H	Elite	1782

Lambert et al. 2004	Road running	100 km	Obs	H-H	Elite	67
Jones & Whipp, 2002	Track running	800 m 5 km	Obs Obs	H-H H-H	Elite Elite	2 2

H-H = Head-to-head competitions; TT = time trial competitions; Exp = experimental; Obs = observational.

2.2.1 Observational studies

The observational studies (N=51) comprise a broad range of sports, involving different rules and regulations to determine performance. In this respect, two main types of competitions can be distinguished: time trial competitions and head-to-head competitions. Time trial competitions are completed without being in a direct face-to-face competition with all other opponents, in which the eventual winner of the event is the athlete with the fastest completion time. In contrast, head-to-head competitions all athletes start at the same time and the winner of the competition is the one who passes the finish line first, leading to an increased emphasis on athlete-environment interactions.

2.2.1.1 Time trial competitions

Due to the structure of time trial sports such as long track speed skating or time trial cycling wherein the winner of the event is the athlete with the fastest completion time, the main aim of each athlete is to complete the given distance as fast as possible. As one can achieve this goal in normal conditions regardless of the behaviour of the other competitors, the interaction with the other competitors seems to be minimised. Indeed, time trial sport athletes showed comparable pacing behaviour as predicted in modelling studies (Foster *et al.,* 2004; Muehlbauer *et al.,* 2010a, 2010b, 2010c; De Koning *et al.*, 1992; van Ingen Schenau and Cavanagh, 1990; Corbett, 2009; Hettinga *et al.*, 2011; Hettinga *et al.,* 2012; Wright, 2016). Moreover, the differences that had been reported appeared to be related more to internal rather than external factors. For example, elite long track speed skaters started relatively slow during 1500 m long track speed skating competitions compared to the predicted optimal pacing strategies in modelling studies (Hettinga *et al.,* 2011; Muehlbauer *et al.,* 2010b). However, an imposed fast start did not improve skating performance, probably due to the relatively high penalty of a declined technique related to fatigue in speed skating (Hettinga *et al.,* 2011; Stoter *et al.,* 2016). Finally, in a longitudinal study, elite long track speed skaters distinguished themselves from non-elite skaters by doing so already from an earlier age (13-15 years old) and even more clearly later on in their adolescence in 1500 m competitive races (Wiersma *et al.,* 2017).

2.2.1.2 Head-to-head competitions

In head-to-head competitions, successful performance does not necessarily demand optimal (pacing) performance, as completion time is irrelevant as long as you finish before the other competitors. This could lead to races in which individuals perform clearly beneath their best possible performance due to tactical considerations (Thiel *et al.*, 2012; Hettinga *et al.,* 2017; Renfree *et al.,* 2014b). To emphasise the importance of tactical decision-making: it was even shown that one could lose an Olympic gold medal despite a higher average velocity due to adverse tactical positioning wide on the bend (Jones and Whipp, 2002).

The interdependency between the competitors seems to play an important mediating role in the extent to which pacing behaviour is altered based on the behaviour of their competitors. Indeed, when individuals are competing in separate lanes, such as swimming (Mauger *et al.,* 2012; Skorski *et al.,* 2014; Mytton *et al.,* 2015; Lipińska *et al.,* 2016a, 2016b; Taylor *et al.,* 2016; Nikolaidis and Knechtle, 2017), 400 m track running (Saraslanidis *et al.,* 2011; Hanon and Gajer, 2009), and rowing (Brown *et al.*, 2010; Muehlbauer and Melges, 2011; Smith and Hopkins, 2011; Garland, 2005), the adopted pacing behaviour is similar to the pacing strategies as predicted in modelling studies (Hettinga *et al.*, 2011; Hettinga *et al.*, 2012) and used in time trial competitions of similar duration. The only study reporting a clear deviation from the theoretically optimal pacing strategy in a discipline using separate lanes in their competition focused on intellectual impaired 400 m and 1500 m runners (Van Biesen *et al.*, 2016), emphasising the importance of the cognitive skills required for optimal pacing regulation. In contrast, when directly competing in the same lane such as in track cycling (Moffatt *et al.*, 2014), long-distance running (Hanley, 2015; Renfree and St Clair Gibson, 2013) and short track speed skating (Konings *et al.*, 2016; Noorbergen *et al.*, 2016), spontaneous group synchronization of movements seems to occur and pacing behaviour is adjusted drastically by the athletes (Codrons *et al.*, 2014; Renfree *et al.*, 2015). In addition, these adjustments become even more extreme during important events such as the Olympic games and World Championships (Renfree and St Clair Gibson, 2013; Thiel *et al.*, 2012). Only when an all-out strategy could be adopted from the beginning of the race, all athletes adopted a comparable pacing strategy compared to time trial sports and modelling studies (Noorbergen *et al.*, 2016; Hanon and Gajer, 2009).

Although head-to-head competitions with no separate lanes seems to evoke the response to interact with the other competitors, the way in which the competitors respond and interact varies greatly per discipline. Sport disciplines with a relatively high beneficial effect of drafting behind your opponent (e.g. short track speed skating, cycling), are characterised by a slow, tactical development of the race (Moffatt *et al.*, 2014; Konings *et al.*, 2016; Noorbergen *et al.*, 2016). That is, a strategy that will assist in saving energy for the final acceleration at the end of a race. A remarkable exception in this perspective is the pacing profile during the elimination discipline in track cycling as a relatively fast start is adopted in these competitions (Dwyer *et al.,* 2013). This might be explained by the unique character of the discipline in which every two laps the last ranked competitor is eliminated out of the race. In addition, at the end of the race with a lower number of competitors variability in lap speed increases significantly (Dwyer *et al.,* 2013). In contrast, sport disciplines where the beneficial effect of drafting is much less predominant such as race walking or middle-distance and long-distance running, are characterised by adopting a fast initial pace that cannot be sustained until the end of the race by most of the (sub-)elite runners (Tucker *et al.*, 2006; Hanley *et al.,* 2011; Hanley, 2013; Hanley, 2014; Deaner *et al.,* 2015; Thiel *et al.*, 2012; Renfree and St Clair Gibson, 2013; Hanley, 2016). In fact, even in ultra-running events winners distinguish themselves by preventing a significant slowdown in the second half of the race compared to their less successful counterparts (Lambert *et al.*, 2004; Hoffman, 2014; Renfree *et al.,* 2016; Bossi *et al.,* 2017; Tan *et al.,* 2016). Interestingly, the slowdown in speed seems to be higher for men compared to women (Deaner *et al.*, 2015; Carlsson *et al.*, 2016; Deaner and Lowen, 2016). In this respect, initial pace has been associated recently with an individual's perception of risk (Micklewright *et al.*, 2015), and might indicate an important mediating role of competition in risk perception. Finally, it has been highlighted in several studies that the appropriate strategy in competition is obviously related to other external aspects such as terrain (Knechtle *et al.,* 2015; Kerhervé *et al.,* 2015; Kerhervé *et al.,* 2016; Heidenfelder *et al.*, 2016; Hoffman, 2014), temperature (Tan *et al.,* 2016; Heidenfelder *et al.,* 2016), and humidity (Tan *et al.,* 2016) rather than solely the other competitors.

2.2.2 Experimental studies

The experimental studies (N=14) that examined the influence of a competitor have mainly focussed on the performance effects rather than the changes in pacing. In addition, most of these studies were set-up to examine the effect of deception rather than the effect of an opponent. However, it appeared that the presence of the virtual avatar rather than the deception itself facilitated changes in performance and perceptual responses (Jones *et al.,* 2016b). Indeed, being aware of the deception did not alter the performance effect of an opponent compared to the deceived conditions (Shei *et al.,* 2016; Jones *et al.,* 2016b).

In general an improved performance during competitive trials compared to individual or non-competitive trials has been found (Bath *et al.,* 2012; Corbett *et al.,* 2012; Hulleman *et al.,* 2007; Williams *et al.,* 2015a, 2015b; Lambrick *et al.,* 2013; Stone *et al.,* 2012; Jones *et al.,* 2016a, 2016b; Shei *et al.,* 2016; Tomazini *et al.,* 2015; Wilmore 1968). The performance improvement related to the presence of an opponent appears to remain quite stable, regardless of the level of performance of the opponent (Williams *et al.,* 2015a; Stone *et al.,* 2017). Yet a different level of performance of the opponent appeared to evoke different psychological responses (Williams *et al.,* 2015a). On top of this, the improvement in performance only seems to occur acutely when the opponent is present, as performance declines back to baseline levels in subsequent time trials riding alone (Jones *et al.,* 2016a).

The improvement in 16.1-km cycling performance achieved when riding against a virtual avatar has been suggested to be related to a greater external distraction, deterring perceived exertion (Williams *et al.,* 2015b). In addition, the improvements during a 2-km head-to-head competition (Corbett *et al.,* 2012) and a 4-km time trial including a deceiving avatar (Stone *et al.,* 2017) were achieved by a greater anaerobic energy contribution while aerobic contribution remained the same. Interestingly, the prospect of a monetary incentive ($100) when the participant outperformed his best performance so far with more than 1 second did not improve 1500 m cycling performance (Hulleman *et al.,* 2007). However, as the prior time trials in this particular study were already designed in order to provoke competitive behaviour, the monetary reward might not have been sufficient to improve performance even more. Moreover, the "competitor" (i.e. best previous performance so far) was not visible during the trial.

The presence of a second runner did not improve 5-km running performance when the distance between the athlete and second runner was maintained at approximately 10 meter during the whole time trial (Bath *et al.,* 2012). However, as the constant gap between athlete and opponent made it impossible for the athlete to take the lead (running behind) or gain distance (running ahead) over the second runner, motivation may not have been increased or even reduced, resulting in no change in running performance (Bath *et al.,* 2012). The perception of approaching or getting further behind your opponent might even be a crucial variable (Meerhoff *et al.,* 2014). However, starting one minute behind (chasing) or in front (being chased) of an opponent did not affect performance significantly, although the differences in performance times may still represent meaningful differences in competitive settings (Peveler and Green, 2010). Although most pacing studies used, up until now, mainly experienced athletes, pacing behaviour of inexperienced exercisers in a competitive environment has been studied once before (Lambrick *et al.,* 2013). Running performance decreased for inexperienced children (9-11 years old) during a competitive 800 meter as they started significantly slower compared to individually completed trials (Lambrick *et al.,* 2013).

2.3 Synthesis

A better understanding of how athletes respond to their opponents could assist coaches and athletes to optimally prepare themselves for the tactical decision-making involved in athletic competitions (Smits *et al.,* 2014; Renfree *et al.,* 2014a). Especially in the last years the number of observational pacing studies increased exponentially, likely related to the technological developments and improved accessibility of online data regarding sport competitions. These observational studies have described over a broad range of sports the used pacing strategies of exercisers in a competitive setting. Unfortunately, most of these papers do not go beyond simply describing the used pacing strategies in a particular sport. Partly this remark is obviously inherent to the design of observational studies, ensuring a high ecological validity yet difficult to incorporate a manipulation of or to control for any of the variable(s) of interest. Nevertheless, the opportunities that are present to examine athlete-environment interactions and pacing using observational data, have not yet been fully elucidated. For example, pacing behaviour could be significantly affected by tactical considerations. Athletes may decide to alter their pacing behaviour based on drafting possibilities, expectations or actions of the opponents affecting winning chances, rather than adopting the theoretically optimal pacing strategy (Konings *et al.,* 2016). Observational studies involving large datasets could help us forward in providing appropriate indicators or methods to assess tactics more objectively. Notable examples have been Hanley (2015, 2016), in which pacing decisions in (half) marathon races have been related to packing or herd behaviour. In addition, in rowing (Edwards *et al.,* 2016), track cycling (Moffatt *et al.,* 2014) and short track speed skating (Konings *et al.,* 2016; Noorbergen *et al.,* 2016) first attempts have been made to incorporate tactical positioning when exploring pacing behaviour.

Most of the included experimental studies used a virtual opponent in order to examine something else (i.e. the effect of deception). In addition, their primary focus appeared to be on the performance effects of presenting an opponent rather than the changes in pacing. Regardless, the situation of a time trial against a virtual opponent while monitoring pacing behaviour provided several novel insights into how exercisers regulate their exercise intensity during competition. In this respect, the performance enhancement related to the presence of a virtual opponent is an intriguing and consistent finding (Williams *et al.,* 2015a, 2015b; Tomazini *et al.,* 2015; Corbett *et al.*, 2012; Wilmore, 1968). In addition, a virtual opponent has been shown to alter psychological responses (Williams *et al.,* 2015b), and the performance improvement when riding against a virtual opponent appeared to be related to a greater anaerobic contribution (Corbett *et al.,* 2012; Stone *et al.,* 2017). Nevertheless, it is not yet fully understood how exercisers are able to establish this performance improvement in the presence of a virtual competitor.

Already in the 1980s researchers attempted to explain how athletes regulated their exercise intensity during competition (Van Ingen Schenau, 1980; Van Ingen Schenau, 1982; Van Ingen Schenau *et al.*, 1983; Van Ingen Schenau and De Groot, 1983; van Ingen Schenau and Cavanagh, 1990; Van Ingen Schenau *et al.*, 1990). Modelling studies revealed optimal pacing strategies related to the duration of an event based on aerodynamics and power losses (Hettinga *et al.,* 2012; Hettinga *et al.*, 2011; De Koning, Foster, Lucía, *et al.,* 2011; De Koning *et al.,* 2005; Foster *et al.,* 2003; De Koning *et al.,* 1999; De Koning *et al.,* 1992; van Ingen Schenau and Cavanagh, 1990; Van Ingen Schenau *et al.,* 1990). Findings that have been confirmed in experimental and observational studies focusing on time trial exercise, bringing us forward in our understanding of the optimal regulation of the exercise intensity in time trial exercise (Hettinga *et al.,* 2012; Hettinga *et al.,* 2011; De Koning *et al.*, 2005). In this respect, most of the present pacing models seem to be focused on the regulation of exercise intensity during time trial exercise at maximal effort, and concepts such as teleoanticipation and exercise templates. Without underestimating the importance of these concepts and useful novel insights it provided into the regulation of exercise intensity, most real-life competitions are not characterised by time trial exercise (Hettinga *et al.,* 2017). As demonstrated in this review, findings as reported in time trial exercise cannot be 1:1 translated to real-life competitions, in which athletes clearly demonstrate different pacing profiles compared to the theoretical optimal strategies. Tactical components, such as favourable positioning, drafting, competing for the optimal line, and minimising fall risk, affect pacing decisions and draw athletes away from the energetically favourable strategies as would be performed in time trial exercise (Hettinga *et al.,* 2017). These findings supports the idea that athlete-environment interactions indeed need to incorporated in models that attempt to explain the regulation of exercise intensity.

Remarkably, nearly all current theories regarding pacing regulation seem to be rooted in a constructivist approach towards perception and action. As a result, similar limitations as highlighted in Chapter 1 for the constructivist approach towards perception can be applied to concepts as template formation, heuristics or algorithms used for decision-making, as proposed in the several existing theories regarding regulation of the exercise intensity. In this respect, an ecological approach towards exercise regulation seems to be the most appropriate to incorporate human-environment interactions onto pacing regulation (Smits *et al.,* 2014). According to the ecological approach, the outcome of the decision-making process involved in pacing is based on the action possibilities presented towards the exerciser during the competition. This approach indeed seems to ease the incorporation of human-environment interactions into the regulation of exercise intensity. The environment may provide invitation for action to the exerciser, so-called affordance, that will always be there to be perceived (Gibson, 1979), providing the opportunity to incorporate human-environment interactions and tactical decision-making onto the regulation of exercise intensity (Smits *et al.,* 2014; Hettinga *et al.,* 2017).

In relation to the three identified competitive components (the opponent, the exerciser, and the situation in which the opponent is present towards the exerciser), it could then be hypothesised that an opponent may act as an invitation for action, and different behaviour of an opponent should be able to evoke a different behavioural response in terms of pacing. Moreover, different competitive situations would likely evoke different pacing responses as it may lead to a competition of multiple affordances presented towards the exerciser in each particular competitive situation. Finally, as the outcome of the decision-making process involved in pacing is based on a continuous and simultaneous interaction between environmental stimuli and an individual's action capabilities, a change in the exerciser's internal state may likely impact the perceived action capabilities, and thus pacing behaviour, of the exerciser.

2.4 Conclusion

The regulation of the exercise intensity is an essential determinant for optimal performance in competitive sports. Previous research revealed optimal pacing strategies in time trial exercise, the importance of feedback regarding the internal bodily state, and has focused on concepts as teleoanticipation (Ulmer, 1996) and template formation (Foster *et al.,* 2009). The importance of in-race adaptations to this planned pacing strategy in response to whatever is happening in the external world around the exerciser, however, has been highlighted recently (Smits *et al.,* 2014; Micklewright *et al.,* 2017). This critical review of literature attempted to examine the effect of an opponent, a crucial human-environment interaction during competition, on pacing behaviour and performance. The present literature review showed that athletes adopted different pacing profiles during head-to-head competitions compared to the theoretical optimal strategies. However, there does not yet exist experimental evidence showing that this alternation in pace is directly the result of the behaviour of the opponent. In addition, the results suggest that the specific demands, rules and structure of a sport affect the chosen pacing behaviour during the competition. Furthermore, an improved time trial performance when riding against a virtual opponent was found, however, it is not yet clear how this performance improvement is established. Based on the observational and experimental studies, the existing pacing models, and taken into consideration the perception-action coupling theories, it has been hypothesised that an opponent may act as an invitation for action provided by the environment and could affect the regulation of the exercise intensity. The following chapters will attempt to further elucidate how pacing regulation depends on the presence and behaviour of opponents, the competitive environment and internal state of the athlete.

PART II – THE OPPONENT

CHAPTER 3

Athlete and race variability in elite short track speed skating

Citation

Konings, M.J., and Hettinga, F.J. (2017). Objectifying tactics: athlete and race variability in elite short track speed skating. International journal of sports physiology and performance. 1-20. DOI:10.1123/ijspp.2016-0779 [epub ahead of print]

. --

Abstract

The present study explored whether race-to-race variation of an athlete and the variation of competitors within a race could provide insight into how and when athletes modify their pacing decisions in response to other competitors. Lap times of elite 500, 1000 and 1500 m short track speed skating competitions between 2011–2016 (n = 6965 races) were collected. Log-transformed lap and finishing times were analysed with mixed linear models. To determine within-athlete race-to-race variability, Athlete Identity (between-athlete differences) and the residual (within-athlete race-to-race variation) were added as random effects. To determine race variability, Race identity (between-race differences) and the residual (within-race variation) were added as random effects. Separate analyses were performed for each event. Within-athlete race-to-race variability of the finishing times increased with the prolonged distance of the event (500 m: CV = 1.6%; 1000 m: CV = 2.8%; 1500 m: CV = 4.1%), mainly due to higher within-athlete race-to-race variability in the initial phase of 1000 m (3.3-6.9%) and 1500 m competitions (8.7-12.2%). During these early stages, within-race variability is relatively low in 1000 m (1.1-1.4%) and 1500 m (1.3-2.8%) competitions. In conclusion, the present study demonstrated how analyses of athlete and race variability could provide insight into tactical pacing decisions in sports where finishing position is emphasised over time. The high variability of short track skaters is a result of the decision to alter initial pacing behaviour based on the behaviour of other competitors in their race, providing support for the assumption that the behaviour of an opponent is a crucial determinant of exercise regulation during elite competitions

3.1 Introduction

To achieve optimal performance, it is essential for athletes to use their available energetic resources efficiently (Foster *et al.*, 2003). Therefore athletes are required to decide continuously how and when to invest their available energy in a process that is known as pacing (Smits *et al.*, 2014). In this respect, modelling studies have shown to be able to determine which pacing strategy should be adopted to achieve the fastest possible finishing time for an athlete (Hettinga *et al.*, 2011; De Koning, Foster, Lucía, *et al.*, 2011; Hettinga *et al.*, 2012). However, in several middle-distance and endurance sport disciplines, finishing times are irrelevant as long as you finish in front of your opponents (Konings *et al.*, 2016; Hettinga *et al.*, 2017). In these types of sports, athletes may decide to alter their pacing behaviour based on drafting possibilities, expectations or actions of any opponents who affect their winning chances, rather than adopting the theoretical most optimal pacing strategy (Konings *et al.*, 2016; Hettinga *et al.*, 2017). Indeed, athletes appear to display different pacing behaviour in sports such as cross-country running (Hanley, 2014), middle-distance running (Renfree *et al.*, 2014b), rowing (Edwards *et al.*, 2016), track cycling (Moffatt *et al.*, 2014), and short track speed skating (Konings *et al.*, 2016; Noorbergen *et al.*, 2016) in comparison with the theoretical most optimal pacing strategy as shown in Chapter 2. However, although several studies indicate a change in chosen pacing behaviour during head-to-head competitions, experimental evidence showing that this alternation in pace is directly the result of the behaviour of the other competitors does not yet exist.

Analysis of the variability in chosen pacing behaviour by athletes might provide a possible way to examine the effect of competitors on the decision-making process involved in pacing. In this respect, the performance of an athlete will always show random variation from competition to competition (Paton and Hopkins, 2006).

Nevertheless, the variation of an athlete from race to race may also offer interesting insights into an individual's race strategy and to what extent athletes modify their pacing behaviour in response to the behaviour of other competitors (Micklewright *et al.,* 2017). That is, an athlete may decide to alter the chosen pacing behaviour based on the other competitors, and as a result within-athlete race-to-race variability might be affected because of tactical considerations.

To objectively capture and understand the importance of the behaviour of the other competitors in a race, differences in variability between- and within a race will be explored in this study, in addition to within-athlete race-to-race variability. Between-race variability can be defined as the variability caused by the differences in mean pace between races. In contrast, within-race variability would be the variability that is a result of differences between athletes within a race. In this sense, a low variability in lap time within a race would indicate all competitors in that particular race are adopting a similar pace. In contrast, in combination with a high within-athlete race-to-race variability, this would strongly suggest athletes are adjusting their pacing behaviour in that lap based on the behaviour of their opponents. By using this new approach, it might become possible to distinguish whether the within-athlete race-to-race variability in pacing behaviour is mainly caused by random race-to-race variation of an individual's pre-determined race strategy or whether athletes are reacting and interacting with their fellow competitors.

The aim of the present study is to examine the within-athlete race-to-race variability in elite short track speed skating competitions. Secondly, the extent of the variability that can be assigned to differences of competitors between- or within a race will be explored. High within-athlete race-to-race variability is hypothesised in the beginning and final race stages. However, a relatively low within-race variability and high between-race variability is expected in the initial race stages, indicating that athletes adjusted their own pacing behaviour in response to other competitors in the early stages of competition.

3.2 Methods

3.2.1 Data acquisition

Finishing and intermediate lap times were gathered for men and women from 500 m (4.5 laps), 1000 m (9 laps) and 1500 m (13.5 laps) Short Track Speed Skating World Cups, the European Championships, World Championships, and the Olympic Games during the seasons 2011/12 until 2015/16. In total, 39 indoor competitions (28 World Cups, 5 European Championships, 5 World Championships, and 1 Olympic Games) were analysed. Each short track competition consisted of qualification stages in which a skater had to qualify for the next stage by finishing in first or second position, and the final race where the goal was to win the event. Lap times were measured using electronic time-measuring systems based on optical detectors that started automatically by the firing of a starting-gun and that recorded automatically the time in which the finish line was reached by each competitor. The International Skating Union (ISU) demands that lap times are recorded with the accuracy of at least a hundredth of a second. Therefore, for every automatic timekeeping system a certificate stating the reliability and accuracy of the system had to be presented to the referee before the competition, ensuring that all systems recorded with the accuracy of at least a hundredth of a second. No written consent was given by participants as all data used are publicly available at the ISU website (http://www.sportresult.com/federations/ISU/ShortTrack/) and no interventions occurred during the data collection. The study was approved by the local ethical committee and in accordance with the Declaration of Helsinki.

Races involving falls, disqualifications and/or missing values were excluded out of the dataset, whereas falls and/or disqualifications could affect the lap times and positioning of the skater. In addition, outliers, defined as performances with a standardised residual >5.0, were excluded from the dataset (Hopkins *et al.*, 2009). A standardised residual >5.0 means that the performance was far slower than normal for the given skater. This resulted for the 500 m in 10483 of the 11675 skating performances (89.8%), for the 1000 m in 9889 of the 11164 skating performances (88.6%), and for the 1500 m in 7890 of the 9148 skating performances (86.2%) that were examined.

3.2.2 Statistical analysis

The mixed linear modelling procedure in SPSS was used for the analyses of each event. Finishing and lap times were log transformed before modelling, because this approach yields variability as a percent of the mean (CV), which is the natural metric for most measures of athletic performance (Hopkins, 2000). Subsequently, within- and between-athlete CV were derived by back transformation into percentages of the residual and subject random effects in the mixed model.

Separate analyses were performed for data from each event. To determine within-athlete race-to-race variability, the fixed effect in the model was Sex and the random effects were Athlete identity (between-athletes differences) and the residual (within-athlete race-to-race variation). To determine within-race variability, the fixed effect in the model was Sex and the random effects were Race identity (between-race differences) and the residual (within-race variation). The dependent variables were the natural log of the lap times and finishing times in an event; As stated above, analysis of this transformed variables yields CV, which are variations in performance expressed as a percent of average performance (Hopkins *et al.,* 1999). Precision of the estimates of CV are shown as 90% confidence limits which represent the limits within which the true value is 90% likely to occur. In addition, separate analyses were performed in regard to the within-athlete race-to-race variability and between-athlete differences for top 10 short track speed skaters. Top 10 skaters were determined based on the World Cup classification per event per season.

Intra-class correlations coefficients (ICC) were used to determine the predictability of finishing times in elite short track speed skating competitions. The within-athlete ICC (reproducibility of finishing times for athletes) was calculated as the sum of the pure between-athlete variance divided by the sum of the pure between-athlete variance and within-athlete variance. To assess the magnitude of the ICCs, thresholds of 0.14, 0.36, 0.54, 0.69, and 0.83 for low, moderate, high, very high, and extremely high were used (Smith and Hopkins, 2011; Spencer *et al.,* 2014).

3.3 Results

Mean ± SD of the lap times and finish times in seconds of the 500, 1000 and 1500 m event can be found in Table 3.1. The CV and 90% confidence intervals for the finishing times of the 500 m, 1000 m and 1500 m events are reported in Table 3.2. Within-athlete race-to-race variability of the finishing times increased with a prolonged distance of the race (500 m: 1.6%; 1000 m: 2.8%; 1500 m: 4.1%). The CV and 90% confidence intervals for all the lap times per event for all athletes can be found in Figure 3.1. Within-athlete race-to-race variability was high in the initial phase of 1000 m (3.3-6.9%), and in particular 1500 m competitions (8.7-12.2%). At the same time,

Table 3.1 Mean ± SD of the lap times and finish times in seconds of the 500, 1000 and 1500 m event

	500 m	**1000 m**	**1500 m**
Lap 1	7.32 ± 0.34	13.68 ± 0.98	9.71 ± 1.02
Lap 2	9.32 ± 0.37	10.40 ± 0.80	13.17 ± 1.67
Lap 3	8.87 ± 0.38	10.04 ± 0.65	12.15 ± 1.48
Lap 4	9.01 ± 0.40	9.81 ± 0.51	11.61 ± 1.27
Lap 5	9.26 ± 0.43	9.65 ± 0.46	11.13 ± 1.09
Lap 6		9.51 ± 0.45	10.67 ± 0.87
Lap 7		9.46 ± 0.48	10.30 ± 0.66
Lap 8		9.53 ± 0.56	10.06 ± 0.57
Lap 9		9.76 ± 0.65	9.87 ± 0.49
Lap 10			9.73 ± 0.47
Lap 11			9.62 ± 0.48
Lap 12			9.62 ± 0.57
Lap 13			9.75 ± 0.69
Lap 14			10.04 ± 0.83
Finish time	43.78 ± 1.78	91.85 ± 4.10	147.43 ± 7.97

within-race variability was relatively low in these beginning stages of 1000 m (1.1-1.4%) and 1500 m (1.3-2.8%) competitions. This would indicate that within a race all skaters are adopting a similar initial pace, but the chosen pace varies greatly between races. The CV and 90% confidence intervals for finish times per event for Top 10 athletes can be found in Table 3.3. The CV and 90% confidence intervals for all the lap

Table 3.2 Within-athlete variability and within-race variability in finishing times expressed as coefficients of variation (CV) and the 90% confidence limits in 500 m, 1000 m and 1500 m competitions.

	Athlete			**Race**		
	Fixed	Random		Fixed	Random	
	Sex	Within-athlete	Between-athlete	Sex	Within-race	Between-race
500m	5.6 (± 0.6)	1.64 (x/÷ 1.01)	3.71 (x/÷ 1.07)	6.0 (± 0.2)	2.11 (x/÷ 1.02)	1.89 (x/÷ 1.03)
1000m	5.2 (± 0.5)	2.80 (x/÷ 1.01)	3.05 (x/÷ 1.07)	5.6 (± 0.3)	1.63 (x/÷ 1.02)	3.24 (x/÷ 1.03)
1500m	5.9 (± 0.5)	4.07 (x/÷ 1.02)	2.38 (x/÷ 1.09)	5.8 (± 0.4)	1.42 (x/÷ 1.02)	4.46 (x/÷ 1.04)

times per event for Top 10 athletes can be found in Figure 3.2. The within-athlete race-to-race variability appeared to be relatively similar for Top 10 skaters compared to all skaters. The between-athlete differences are much smaller between Top 10 skaters compared to all skaters, as you may expect. Sex resulted in a most likely difference in finish time of about 5-6% (± 0.5%) in all events.

ICCs for all laps per event can be found in Table 3.4. The within-athlete predictability for the finish time, expressed as ICC, was extremely high for the 500 m event, high for the 1000 m event, and low for the 1500 m event. During the race within-athlete predictability was high for the first lap of the 500 m event, and very high for the other laps. No to low within-athlete predictability was found for the lap times of the first five laps of the 1000 m event. For the sixth lap and ninth lap of the 1000 m event ICCs were high, while ICCs of the seventh and eight lap were very high. No to low within-athlete predictability was found for the lap times of the first nine laps of the 1500 m event. For the tenth lap a moderate ICC was reported, while high ICCs were found in the final four laps of the 1500 m event.

Table 3.3 Within-athlete variability for Top 10 skaters in finishing times expressed as coefficients of variation (CV) and the 90% confidence limits in 500, 1000 and 1500 m competitions

	Athlete – Top 10		
	Fixed	Random	
	Sex	Within-athlete	Between-athlete
500 m	6.2 ± 0.5	1.37 x/÷ 1.03	0.89 x/÷ 1.20
1000 m	5.9 ± 0.5	2.42 x/÷ 1.03	0.75 x/÷ 1.27
1500 m	6.0 ± 0.8	4.17 x/÷ 1.03	1.30 x/÷ 1.30

Table 3.4 Within-athlete predictability expressed as intra-class correlation coefficients of each event for all skaters

	500 m	1000 m	1500 m
Lap 1	0.65	0.21	0.19
Lap 2	0.73	0.13	0.09
Lap 3	0.79	0.11	0.08
Lap 4	0.78	0.15	0.08
Lap 5	0.69	0.29	0.08
Lap 6	-	0.61	0.08
Lap 7	-	0.76	0.09
Lap 8	-	0.76	0.10
Lap 9	-	0.63	0.16
Lap 10	-	-	0.38
Lap 11	-	-	0.56
Lap 12	-	-	0.66
Lap 13	-	-	0.65
Lap 14	-	-	0.56
Finish time	0.83	0.54	0.26

3.4 Discussion

Our findings showed that the within-athlete race-to-race variability of the finishing times increased with a prolonged distance of the race (500 m: 1.6%; 1000 m: 2.8%; 1500 m: 4.1%). This increase could mainly be attributed to a higher within-athlete race-to-race variability in the initial phase of 1000 m (3.3-6.9%), and in particular 1500 m competitions (8.7-12.2%). At the same time, within-race variability was relatively low in these beginning stages of 1000 m (1.1-1.4%) and 1500 m (1.3-2.8%) competitions. In this respect, the present study provided evidence for the assumption that interactions between competitors are a crucial determinant for the outcome of an individual's pacing decisions. That is, elite short track speed skaters appeared to often decide not to adopt pacing strategies as used in a time trial setting but instead alter their pacing decisions based on the behaviour of other competitors in the initial phase of 1000 m and 1500 m competitions. Moreover, if we only look at the Top 10 skaters, the

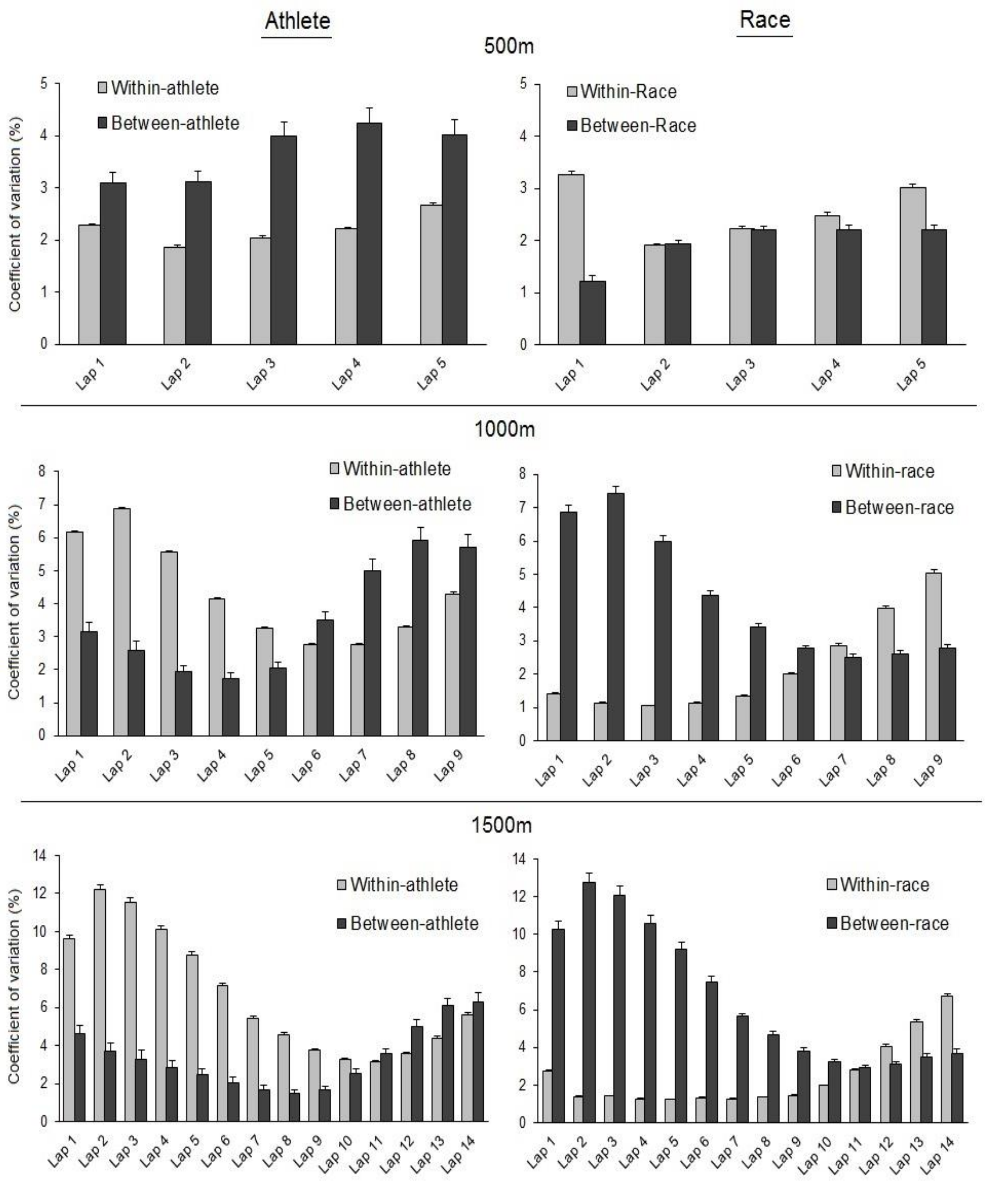

Figure 3.1 Within-athlete race-to-race variability and within-race variability in lap times expressed as coefficients of variation (CV) and the 90% confidence limits in 500 m, 1000 m and 1500 m competitions.

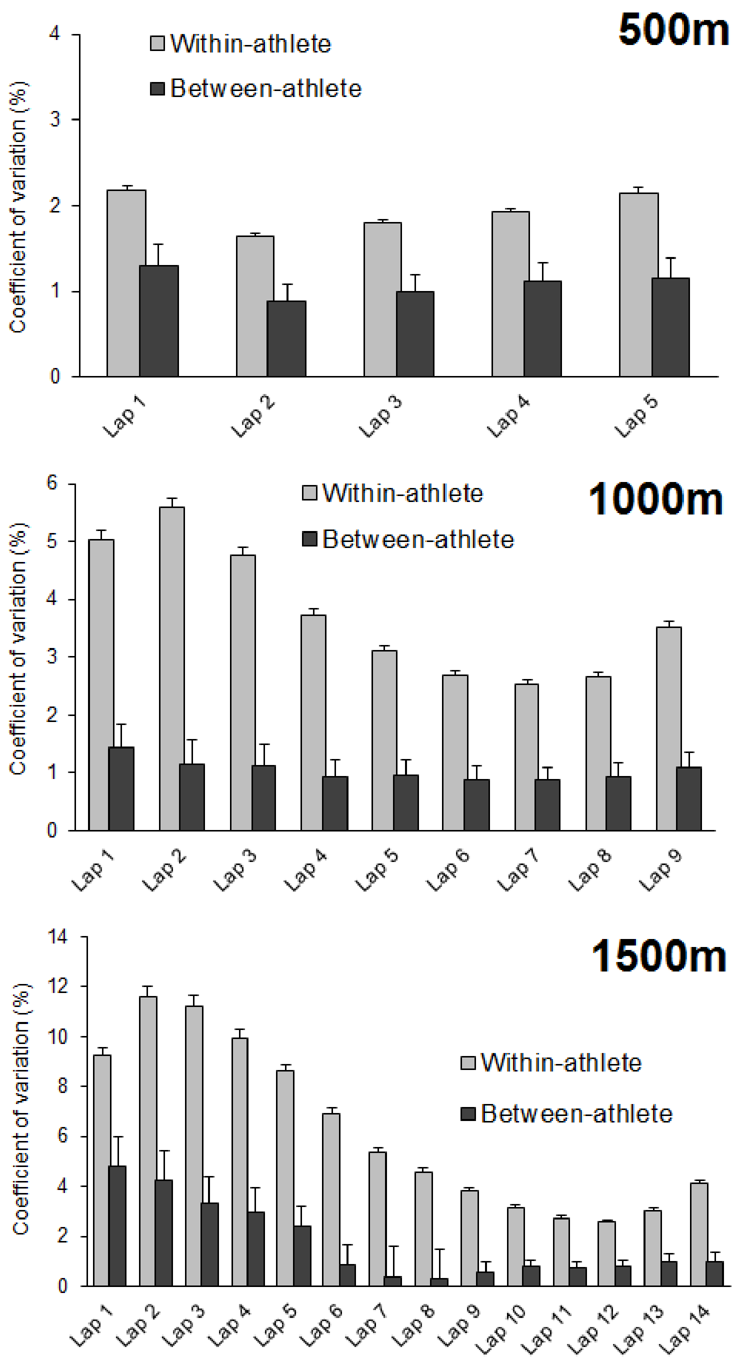

Figure 3.2 Within-athlete race-to-race variability for Top 10 skaters in lap times expressed as coefficients of variation (CV) and the 90% confidence limits in 500 m, 1000 m and 1500 m competitions.

between-athlete differences in lap times are rather low, even in the decisive final segment of the race, emphasising the importance of tactical positioning at the elite level.

To explain the regulation of exercise intensity, anticipatory models have proposed that from the onset of exercise a selected perceived exertion template exists, in which the experienced perceived exertion is continuously compared to the perceived exertion template and exercise intensity is adjusted accordingly (Tucker, 2009). The high variability in chosen initial pacing behaviour as found in this study questions the use of such templates during head-to-head competitions, such as short track speed skating. In fact, the ability to vary the chosen pacing behaviour per race based on whatever is happening around the speed skater, for example in order to benefit from the effect of drafting behind a competitor (Rundell, 1996), seems to be a key element to achieve optimal performance in elite short track speed skating. This does not imply that anticipatory template models are invalid to explain pacing regulation. However, the high variability in pacing behaviour of elite short track speed skaters indicate that the concepts of pre-determined perceived exertion templates used for pacing regulation do not seem to be applicable in head-to-head competitions.

Previous research has made several suggestions to explain why athletes may act differently when an opponent is present. For example, an increased motivation (McCormick *et al.*, 2015), and a shift in attentional focus from internal to external aspects (Williams *et al.*, 2015b) have been mentioned. Moreover, in head-to-head competitions one is required to balance the energetically optimal distribution pace against possible tactical (dis)advantages to perform optimally (Hettinga *et al.*, 2017). As argued in Chapter 2, the behaviour of an opponent may be perceived as an perceptual affordance, inviting for action. The outcomes of present study provide support for this hypothesis, however, it is yet unclear whether this response can be directly linked towards the pacing behaviour of an opponent, or to the beneficial or detrimental opportunities that are related to the behaviour of the other competitors. That is, in addition to the invitation to respond in terms of pacing that an opponent may provide anyway, there are clear advantages for short track speed skaters in altering their pacing behaviour based on their competitors. Short track speed skaters could benefit from the effect of drafting in proximity behind their opponents (Rundell, 1996; Van Ingen Schenau, 1982). When positioning oneself closely behind one of the opponents, the effect of drafting could reduce air frictional losses by 23% (Van Ingen Schenau, 1982). Furthermore, skating in the beginning stages of short track speed skating races at another position than the leading position could provide the opportunity to better oversee your competitors (Renfree *et al.*, 2014b; Moffatt *et al.*, 2014).

During their races, short track speed skaters are required to continuously weigh up these benefits and their ultimate goal to pass the finish line in leading position. Clearly the outcome of this balance differs per event. In the 500 m event, the aim to achieve the first position appeared to be favoured above saving energy in the beginning phase of the race (Noorbergen *et al.*, 2016). In contrast, in the 1000 m and 1500 m events, saving energy in the initial stages to be able to use the remaining energy for the decisive final part of the race appeared to be the commonly used strategy (Konings *et al.*, 2016; Noorbergen *et al.*, 2016). That is, the initial stages of a race in this event are characterised by a relatively low within-race and high between-race variability, while the decisive final part is characterised by a relatively high within-race and low between-race variability.

In comparison with other sports, within-athlete race-to-race variability is relatively high in short track speed skating. For example, within-athlete race-to-race variability of the finishing times was 0.9-1.1% in elite rowers (Smith and Hopkins, 2011) and 0.8-1.3% elite track cyclists (Flyger, 2009; Paton and Hopkins, 2006). Furthermore, the within-athlete race-to-race variability of long track speed skaters (0.3-1.3%; Noordhof *et al.*, 2016) is much lower in comparison with the within-athlete race-to-race variability of short track speed skaters. In addition, the predictability of finishing times is lower in the 1000 m and 1500 m short track events compared to long track speed skating, but similar in the 500 m event. The most likely explanation for these differences is the intrinsic difference in the structure of the competition between long track (individual time trials) and short track speed skating (head-to-head competition). Similarly, the relatively high variability in finishing times between races and the low variability in finishing times of competitors within a race is likely related to this head-to-head competition structure in which completion time is only relevant in relation to other competitors in that particular race.

In this perspective, to provide coaches, athletes and practitioners with a guideline for measuring the effectiveness of an intervention, an improvement equal to 0.3 of the CV in within-athlete race-to-race variability is commonly accepted as the smallest worthwhile enhancement in performance (Malcata and Hopkins, 2014; Hopkins *et al.,* 1999). However, in middle-distance and endurance sport disciplines with a strong interaction of tactical nature between the competitors this particular way of determining the smallest worthwhile enhancements seems to have its limitations. For example, the smallest worthwhile enhancement of the finishing time in the 1500 m short track speed skating event would be 1.80 seconds. This is so large because the variability in finish times is very large, mainly related to tactical decisions in the beginning stages of the race. At first sight, this improvement could be achieved by just adopting a pacing strategy aimed at completing the event as fast as possible. However, in terms of performance quantified using finishing position, this strategy is likely to have a detrimental effect.

Nevertheless, the author would like to recognise and emphasise the importance of a guideline to determine whether an intervention of any kind actually leads to an quantifiable and worthwhile improvement in performance. Yet there might be alternative ways in which it is still possible to determine a smallest worthwhile enhancement. For example, by using the lap with the lowest within-athlete race-to-race variability, in which athletes tend to follow their own strategy and seem not too much influenced by the actions of the opponents. Interestingly, for both the 1000 m as well as the 1500 m, this lap corresponds to the lap in which short track speed skaters in general achieve their fastest lap time. Using this approach, the smallest worthwhile enhancement for the 1000 m would be 0.08 sec in lap 7, and 0.09 sec in lap 11 for the 1500 m.

3.5 Conclusion

The present study provided a novel approach to analyse tactical decision-making in individual middle-distance and endurance sports by using the variation of an athlete from the race to race in combination with the variability in lap times between and within races. As demonstrated in this study, this approach could provide novel insights into the complex process of decision-making that is involved in pacing behaviour and tactical considerations. The relatively high race-to-race variation of the finishing times in elite short track speed skaters during the 1000 m and 1500 m events could be mainly assigned to the high within-athlete race-to-race variability in the initial laps of the race. It appears that this high variability of the skater is a result of the skater's decision to alter initial pacing behaviour based on the behaviour of other competitors in that particular race, emphasising the importance of the behaviour of competitors as a determinant for the outcome of an athlete’s pacing decisions during real-life competitions.

CHAPTER 4

The behaviour of an opponent alters pacing decisions in 4-km cycling time trials

Citation

Konings, M.J., Schoenmakers, P.P.J.M., Walker, A., and Hettinga, F.J. (2016).
The behavior of an opponent alters pacing decisions in 4-km cycling time trials.
Physiology and behavior. 158:1-5

. ---

.

Abstract

The present study aimed to explore how athletes respond to different behaviours of their opponents in laboratory-controlled conditions. Twelve moderately to highly physically active participants with at least two years of cycling experience completed four 4-km time trials on a Velotron cycle ergometer. After a familiarisation time trial (FAM), participants performed three experimental time trials in randomised order with no opponent (NO), a virtual opponent who started slower and finished faster compared to FAM (OP-SLOWFAST), or a virtual opponent who started faster and finished slower compared to FAM (OP-FASTSLOW). Repeated-measures ANOVAs ($p < 0.05$) were used to examine differences in pacing and performance related to power output, velocity, and RPE. OP-SLOWFAST and OP-FASTSLOW were completed faster compared to NO (385.5±27.5, 385.0±28.6, and 390.6±29.3 sec, respectively). An interaction effect for condition x distance ($F = 3.944$, $P < 0.001$) indicated differences in pacing profiles between conditions. Post-hoc analysis revealed that a less aggressive starting strategy was adopted in NO compared to OP-FASTSLOW and OP-SLOWFAST during the initial 1000 m. Moreover, a faster starting opponent evoked higher power outputs by the participants in the initial 750 m compared to a slower starting opponent. In conclusion, the present study is the first to show that the behaviour of an opponent affects pacing-related decisions in laboratory-controlled conditions. Our findings provided experimental evidence for the influence of a competitor on exercise regulation, and emphasise the interaction with competitors as an important determinant for an athlete’s pacing decisions, especially during the initial stages of a race.

4.1 Introduction

Pacing has been defined as the goal-directed regulation of exercise intensity over an exercise bout (Edwards and Polman, 2013), in which athletes need to decide how and when to invest their energy (Smits *et al.*, 2014). Recent theoretical frameworks from both heuristic (Renfree *et al.*, 2014a) and ecological (Smits *et al.*, 2014) perspectives emphasised that pacing is a decision-making process in which interaction with the external world is a crucial determinant for the regulation of the exercise intensity. That is, in addition to internal characteristics such as perceived fatigue, athletes may decide to alter their pacing behaviour based on exteroceptive characteristics (Smits *et al.*, 2014) such as drafting possibilities or expectations or actions of the opponents behaviours affecting winning chances.

Even though some form of interpersonal competition is indispensable in every (elite) sport, research about the exact influence of different opponents on pacing behaviour, tactics, decision-making and performance of athletes is still limited. Previous research has explored the effect of an opponent on pacing and performance, and reported a positive effect of the presence of a direct opponent on performance (Bath *et al.,* 2012; Corbett *et al.,* 2012; Hulleman *et al.,* 2007; Tomazini *et al.,* 2015; Jones *et al.,* 2016a; Williams *et al.,* 2015a, 2015b). In addition, the performance enhancement when an opponent is present appeared to be independent of the performance of the opponent (Williams *et al.,* 2015b). The previous chapter provided support for the assumption that the behaviour of an opponent could invite a behavioural response in terms of pacing in exercisers. However, it is still unclear whether this response can actually be directly linked towards the pacing behaviour of an opponent, or only occurs due to potential benefits that are provided by the presence of other competitors, such as reducing air frictional losses via the effect of drafting. Moreover, it is still unclear if every competitor in time trial setting evokes a similar behavioural response or whether different behaviour of the opponents might alter the decisions of the competing athlete.

By manipulating the pacing strategy of a virtual opponent, the present study explored how exercisers responded to different opponents in a well-controlled, experimental setting. It is hypothesised that exercisers adapt their pacing behaviour and decision-making regarding the regulation of exercise intensity over the race based on the strategy employed by the opponent. It is expected that a faster or slower starting opponent will invite exercisers to adopt a respectively faster or slower starting pacing strategy, mirroring the behaviour of the opponent. This will provide support for the notion that there is an interdependence of perception and action when regulating exercise intensities in competitive situations, which will emphasise the interaction with the environment as a crucial, but often overlooked determinant for an athlete's decisions regarding the regulation of exercise intensity.

4.2 Materials and methods

4.2.1 Participants

Twelve participants with at least two years of cycling experience (age: 25.8±9.5 years; body mass: 74.2±10.8 kg; height: 176.2±6.4 cm) participated in this study. All participants were moderate to highly physically active (two or more moderate to high-intensity training sessions per week), familiar to pacing their exercise, and were able to complete a 4-km cycling time trial within seven minutes. Before participating all participants gave written informed consent and completed a health screening questionnaire (Physical Activity Readiness Questionnaire; Cardinal *et al.,* 1996). The study was approved by the university's local ethical committee in accordance to the Declaration of Helsinki.

4.2.2 Experimental procedures

Participants completed four 4-km cycling time trials. They were allowed to perform a 5-min self-paced warm-up of low to moderate intensity, followed by a 5-min inactive recovery period before starting the time trials. To control for warm-up intensity, participants were asked to exercise at an intensity similar to previous visits. The first time trial was always a familiarisation trial (FAM). Hereafter, participants completed one time trial without opponent (NO) and two time trials with an opponent (OP-FASTSLOW and OP-SLOWFAST) in a random order.

Two opponents (OP-SLOWFAST and OP-FASTSLOW, respectively) were constructed for each participant using different pacing profiles compared to the participant in his FAM in order to explore how athletes respond to different opponents. OP-FASTSLOW adopted a faster pace (+3% compared to FAM) between 250 m-2000 m, followed by a slower pace (-1% compared to FAM) between 2000 m-3750 m. In contrast, OP-SLOWFAST adopted a slower pace (-1% compared to FAM) between 250 m-2000 m, followed by a faster pace (+3% compared to FAM) between 2000 m-3750 m. Both opponents adopted a velocity in the first and last 250 m that was 1% faster compared to the participants' FAM in order to match the start and end spurt of the participants. This was done to increase the participant's perception of the opponent as a realistic competitor of a level of performance within reach of the participant. Based on an expected performance improvement of 1% after FAM (Corbett *et al.*, 2009; Williams *et al.*, 2015b), the pacing profiles of the both opponents were constructed to a finishing time 1% faster compared to FAM. Although the pacing strategies differed between the opponent conditions, the finishing time of the opponent was for both opponent conditions exactly the same. Accuracy of the "constructed opponents" compared to the "calculated opponent" has been determined. If an error of more than 1 sec was found, the trial was repeated until an acceptable error was achieved. The mean error was 0.39 ± 0.18 sec, with a maximal error of 0.76 sec.

Before every time trial, participants were instructed to perform optimally and give maximal effort. No verbal coaching or motivation was given to the participants during any of the trials. In order to simulate real competitive situations, participants were shown a leader board before the start of the virtual opponent trials on which they could compare their ranked previous performances to other (anonymous) participants. A "ghost" rider was added to the first and last positions on the chart, so that also the fastest and slowest rider believed that there was respectively a rider ranked closely ahead or behind them, who would be competitive for him as opponent (Peveler and Green, 2010). In addition, participants were told that their opponent would be of similar level of performance in order to stimulate the participant to perceive the virtual opponent as a realistic and competitive one.

Time trials were completed at the same time of the day (± 2 hours), and the same day of the week to minimise circadian variation (Brisswalter *et al.,* 2007; Fernandes *et al.,* 2014). Participants were asked to maintain normal activity and sleep pattern throughout the testing period. In addition, participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 hours, and from caffeine and food consumption respectively, four and two hours before the start of the test. Participants were informed that the study was examining the influence of external factors on performance during cycling time trials. To prevent any pre-meditated influence on preparation or pre-exercise state, the specific feedback presented for each trial was only revealed immediately before the start of the time trial. All trials were conducted in ambient temperatures between 18-21°C.

4.2.3 Apparatus

Time trials were performed on a cycle ergometer (Velotron Dynafit, Racermate, Seattle, USA) that has been shown to be a reliable and valid tool to measure cycling performance and pacing behaviour (Astorino and Cottrell, 2012; Schoenmakers *et al*. 2015; Hettinga *et al*. 2015). Using the Velotron 3D software, a straight and flat 4-km time trial course with no wind was programmed and projected onto a screen for all trials. During the time trials only relative distance feedback was provided. In the opponent conditions, a virtual opponent was projected. Participant started every trial in the same gear, but were free to change their gear ratio throughout the time trial. Power output, velocity, distance, cadence, and gearing were monitored continuously during each trial (sample frequency = 4 Hz). Rate of perceived exertion (RPE) on a Borg-scale of 6-20 (Borg, 1982) was asked after the warm-up, before the start of the time trial, at three random points during the time trial, and directly after passing the finish line.

4.2.4 Statistical analysis

Mean power output, velocity, cadence, and finish time were calculated in order to examine performance. Differences in performance between conditions were assessed using a repeated-measures ANOVA. During each time trial, RPE was asked at three random moments. Before statistical analyses on RPE were performed, it was calculated whether these moments were, on average, asked at similar points during the race for every condition using a One-Way ANOVA. To assess differences in pacing behaviour between the conditions, average power output, cadence, and split times for each 250 m segment were calculated, and differences were tested using a two-way repeated-measures ANOVA (conditions x distance). Post-hoc tests with Bonferroni correction were performed when significant results were found. All analyses were performed using SPSS 19.0, and significance was accepted at $P < 0.05$. Data are presented as means ± SD.

4.3 Results

4.3.1 Performance analysis

Mean (±SD) performance times, power outputs, velocities, and final RPE scores for the four time trial conditions are shown in Table 4.1. Mean finishing times of the virtual opponents were respectively 389.20 ± 29.22 sec (OP-SLOWFAST) and 389.36 ± 29.53 sec (OP-FASTSLOW). A difference in performance times was found between conditions ($p = 0.036$). Post-hoc analysis showed that participants were faster during both OP-SLOWFAST ($F = 3.095$, $p = 0.010$) and OP-FASTSLOW ($F = 4.182$, $p = 0.002$) compared to NO. No difference was found between OP-SLOWFAST and OP-FASTSLOW in performance time ($F = 0.417$, $p = 0.685$). Mean power output (PO) and velocity (V) were higher during both OP-SLOWFAST (PO: $F = 3.274$, $p = 0.007$; V: $F = 3.090$, $p = 0.010$) and OP-FASTSLOW (PO: $F = 3.388$, $p = 0.006$; V: $F = 3.837$, $p = 0.003$) compared to NO, while no difference was found between OP-SLOWFAST and OP-FASTSLOW (PO: $F = 1.047$, $p = 0.317$; V: $F = 0.710$, $p = 0.493$). Finally, participants adopted a higher mean cadence during NO compared to OP-SLOWFAST ($F = 2.433$, $p = 0.033$), but not compared to OP-FASTSLOW ($F = 0.849$, $p = 0.414$).

Table 4.1 Mean ± SD of the completion times, power output, velocity and cadence for each experimental condition.

Condition	Completion Time (sec) [B,C]	Power output (W) [B,C]	Velocity (km/h) [B,C]	Cadence (rpm) [A,B]
FAM	393.08 ± 31.5	279.0 ± 56.3	37.10 ± 2.88	97.1 ± 8.4
NO	390.57 ± 29.3	279.2 ± 51.5	37.30 ± 2.70	101.0 ± 10.8
OP-SLOWFAST	385.53 ± 27.5	288.4 ± 52.2	37.74 ± 2.63	97.6 ± 12.0
OP-FASTSLOW	384.98 ± 28.6	291.6 ± 57.2	37.84 ± 2.84	98.3 ± 13.1

[A] Difference between FAM and NO ($P < 0.05$), [B] Difference between NO and OP-SLOWFAST ($P < 0.05$), [C] Difference between NO and OP-FASTSLOW ($P < 0.05$), [D] Difference between OP-SLOWFAST and OP-FASTSLOW ($P < 0.05$).

No difference in mean cadence was found between OP-SLOWFAST and OP-FASTSLOW (F = 0.317, p = 0.757).

4.3.2 Pacing analysis

Mean power outputs per 250 m section are shown in Figure 4.1. Main effects for condition (F = 3.193, P = 0.036), and distance (F = 13.750, P < 0.001), and an interaction effect for condition x distance (F = 3.944, P < 0.001) were found, indicating differences in pacing profile between conditions. Post-hoc analysis revealed that in the initial 1000 m, a less aggressive starting strategy was adopted in NO compared to FAM, OP-SLOWFAST, and OP-FASTSLOW (see Figure 4.1 and Figure 4.2). Subsequently, higher power outputs in NO were found during the middle part compared to FAM. However, in the OP-SLOWFAST, and OP-FASTSLOW conditions, participants continued at a similar power output compared to NO after respectively 750 and 1000m.

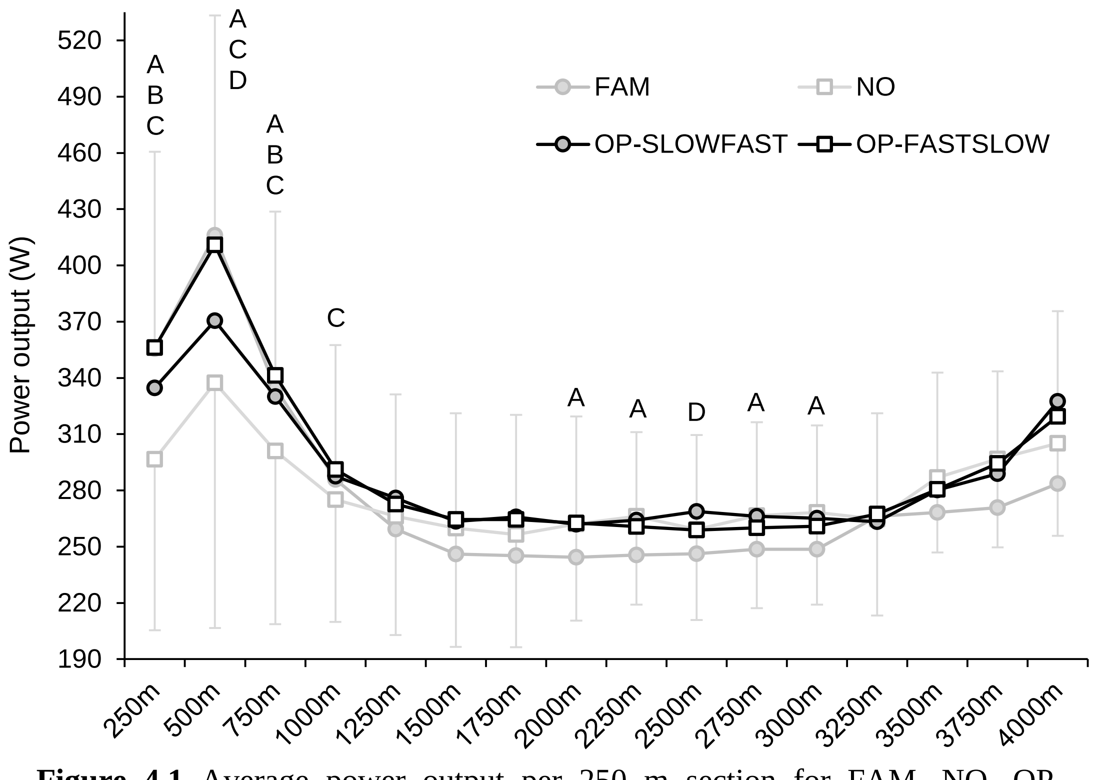

Figure 4.1 Average power output per 250 m section for FAM, NO, OP-SLOWFAST, OP-FASTSLOW.

[A] Difference in power output between FAM and NO (P < 0.05), [B] Difference in power output between NO and OP-SLOWFAST (P < 0.05), [C] Difference in power output between NO and OP-FASTSLOW (P < 0.05), [D] Difference in power output between OP-SLOWFAST and OP-FASTSLOW (P < 0.05).

In addition, power output in the OP-FASTSLOW was higher compared to the OP-SLOWFAST condition during the 250-500 m section, but lower during the 2250-2500 m section.

A significant main effect for distance (F = 10.270, P < 0.001), and an interaction effect for condition x distance (F = 3.120, P < 0.001) were found for cadence, while the main effect for condition was indifferent (F = 1.092, P = 0.332). Post-hoc analysis indicated no differences in cadence during OP-FASTSLOW compared to NO (F = 1.092, P = 0.332) or OP-SLOWFAST (F = 1.092, P = 0.332). In contrast, NO showed a higher cadence compared to OP-SLOWFAST after 1750 m until 3750 m.

No difference was found between conditions for % of time trial completion for the second (F = 0.370, P = 0.695), and third (F = 1.886, P = 0.175) moment when RPE was asked. A difference between conditions for % of time trial completion was found for the first moment when RPE was asked (F = 2.346, P = 0.022). Post-hoc analysis revealed only a significant difference between FAM and NO (F = 2.984, P = 0.003). Mean RPE scores after the warming-up, and before, during and after the time trial per condition were shown in Table 4.2. A main effect for distance (F = 211.195, P < 0.001), and condition (F = 1.980, P = 0.021) were found for RPE, while no condition x distance interaction effect (F = 1.299, P = 0.293) was found. However, post-hoc analysis

Table 4.2 RPE scores (6-20) before, during and after the 4-km time trial (TT)

.	FAM	NO	OP-SLOWFAST	OP-FASTSLOW
Warm-up	10.2 ±2.6	9.3 ± 2.0	8.8 ± 2.3	9.6 ± 3.0
TT start	6.7 ± 1.1	6.4 ± 1.0	6.5 ± 1.2	6.6 ± 1.4
TT 1	14.1 ± 2.2	12.9 ± 2.7	13.5 ± 2.3	13.6 ± 2.2
TT 2	15.6 ± 1.6	15.1 ± 2.3	15.6 ± 1.7	15.8 ± 2.2
TT 3	17.2 ± 1.7	17.0 ± 1.7	16.9 ± 1.4	17.5 ± 1.6
TT finish	18.8 ± 1.1	18.5 ± 1.0	19.1 ± 0.7	19.3 ± 0.8 [A]

[A] Difference between NO and OP-FASTSLOW (P < 0.05).

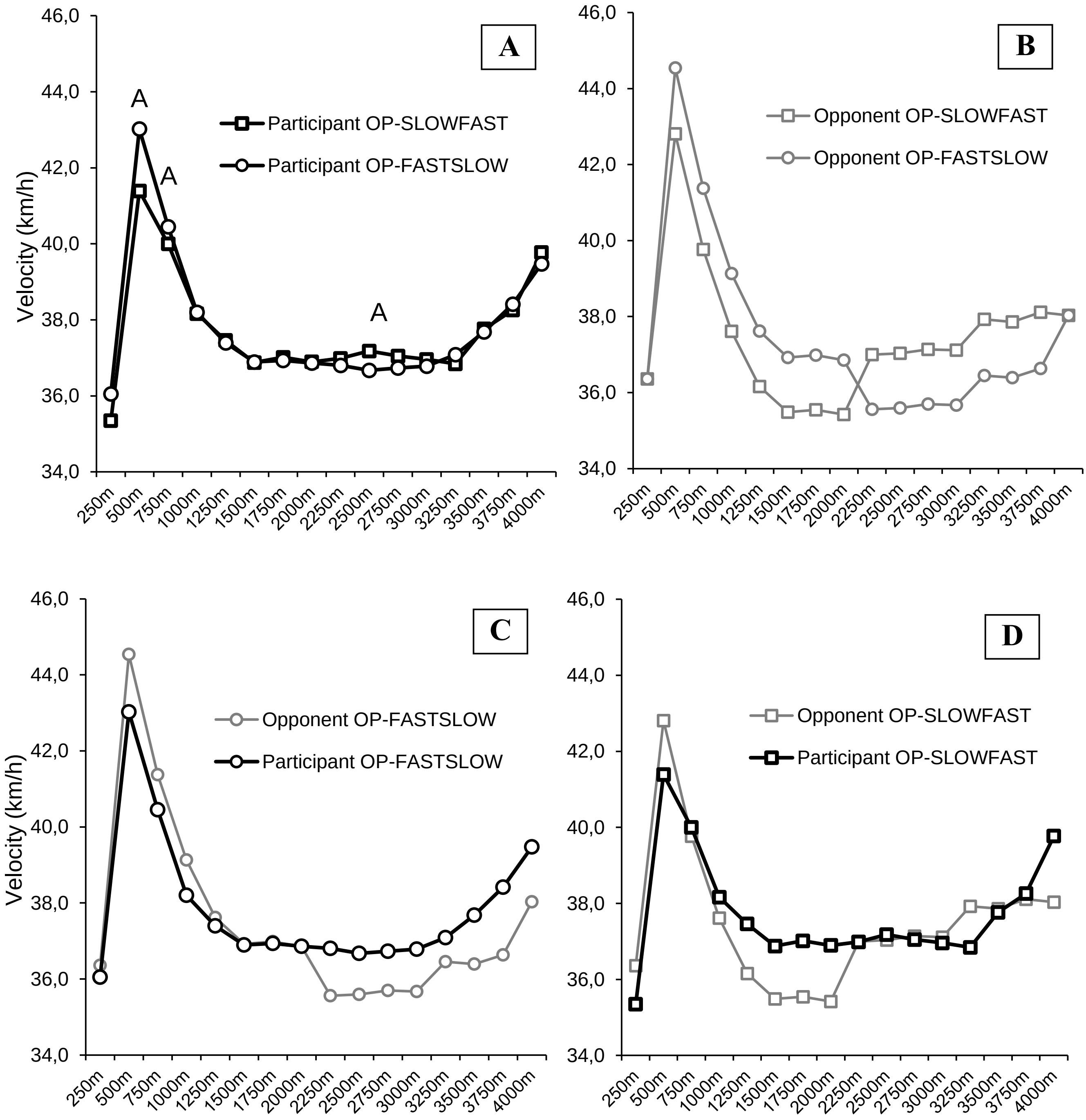

Figure 4.2 Average velocity per 250 m section for OP-SLOWFAST and OP-FASTSLOW and their respective opponents. Panel A: Participants in OP-SLOWFAST and OP-FASTSLOW; Panel B: Virtual opponents in OP-SLOWFAST and OP-FASTSLOW; Panel C: Participant and virtual opponent in OP-FASTSLOW; Panel C: Participant and virtual opponent in OP-SLOW;

[A] Difference in velocity for participant between OP-SLOWFAST and OP-FASTSLOW ($P < 0.05$)

revealed no differences between conditions for the RPE score before or during the time trials. RPE scores at the finish were higher at OP-FASTSLOW (F = 2.462, p = 0.032) but not statistically significant in OP-SLOWFAST (F = 2.206, p = 0.052) compared to NO.

4.4 Discussion

The present study explored whether different pacing strategies of a competing opponent would influence the pacing behaviour of an exerciser. Our main findings indicated that pacing behaviour differed slightly depending on the pacing profile of the virtual opponent. That is, a faster starting opponent evoked a faster start strategy in the competing participant compared to a slower starting opponent. In this respect, the present study adds a crucial determinant for the regulation of exercise intensity onto previous literature that suggested that the exercise intensity was regulated by a predetermined exercise template set in advance of the race, matching the expected physical sensations of effort with the actual physical sensations of effort (Foster *et al*., 2009; Tucker, 2009). The present study expanded on this idea and has shown that this suggested predetermined exercise template can at least be altered by the behaviour of an opponent during the race.

The behaviour of an opponent seems to evoke an intuitive behavioural response in the beginning stages of race that could alter the deliberate decision to adopt a specific pacing profile. This supports the theoretical framework of Smits *et al*., (2014) in which the decision-making processes involved in pacing depend on one's perception of action possibilities in the environment (Smits *et al.*, 2014). In this respect, the present study demonstrated that the behaviour of an opponent appeared to invite athletes to change their behaviour, thereby emphasising the interaction with the environment as an important determinant for the regulation of the exercise intensity. The different actions of the opponents evoked different action responses in the participating cyclists.

The construction of the virtual opponents was a crucial aspect for this study. In order to simulate real competitive situations, the opponents were constructed to be realistic and competitive for the participant. Previous research and pilot measurements indicated a performance improvement of 1% could be expected after the familiarisation trial (Corbett *et al.*, 2009). Therefore, the virtual opponents were constructed in such a way that their finishing time would be 1% faster compared to FAM. Indeed, finishing times in NO were on average 0.7% faster compared to FAM. As a result, the finishing times of the virtual opponents were not different compared to the finishing times of the participants in NO, supporting our aim to construct competitive opponents. With this experimental set-up, an ideal situation has been constructed to investigate how circumstantial factors can affect the regulation of exercise intensity in a sport-specific, well-controlled laboratory condition.

Another crucial element in the construction of the virtual opponents was that to evoke a behavioural response of the athlete, the opponents needed to perform clearly different pacing profiles compared to the self-paced performance of the participant, similar to as could occur in actual competition. Also in this respect, the present study succeeded in constructing realistic and competitive opponents. The pacing profiles of the virtual opponents as used in both opponent conditions were clearly different compared to each other and compared to the pacing strategy of the participants during NO (see Figure 4.2). However, due to the modification in pacing strategy towards a less aggressive start in NO compared to FAM, the relatively slow starting opponent compared to the participant in FAM had on average still a faster initial pace compared to the participant in NO. Similar modifications in pacing strategy in consecutive trials have been found in previous studies, stressing the importance of the inclusion of a familiarisation trial as done in the present study (Corbett *et al.*, 2009; Hulleman *et al.*, 2007). Those studies also indicated that the adopted pacing strategies became relatively stable after the first trial (Corbett *et al.*, 2009; Hulleman *et al.*, 2007).

Moderately trained participants were able to improve 4-km time trial performance against both opponents compared to their individual time trial performance. Previous research has shown that deceptive feedback had no additional acute or residual effect on performance (Jones *et al.*, 2016a). Moreover, the performance enhancement when an opponent is present, appeared to be independent of the performance of the opponent, despite different psychological responses (Williams *et al.*, 2015a). This study adds onto this knowledge by showing that the performance improvement when an opponent is present, is also independent of the pacing profile of the opponent.

The presence of a competitive opponent, independent of its pacing behaviour, seems to enable the participants to use a greater degree of their physiologic capacity that cannot be fully accessed when competing alone (Stone *et al.*, 2012). In fact, previous literature showed a greater anaerobic energy capacity could be achieved during time trials when an opponent was present (Corbett *et al.*, 2012). In addition, the presence of an opponent has been related to a greater external distraction, keeping down perceived exertion when an opponent was present (Williams *et al.*, 2015b). Indeed, differences in RPE were found between the experimental conditions after, but not during the race. One could argue that the improved performance in the opponent conditions compared to NO might be related to the faster VO_2 response associated with a faster start (Bishop *et al.*, 2002; Hettinga *et al.*, 2009). However, in this respect it seems reasonable to expect that the faster starting strategy as used in FAM would also have led to a better performance in FAM compared to NO. However, such an effect has not been found in the present study. Finally, visual perception of the opponent seems crucial for finding performance improvements such as those in the present study. Indeed, participants in previous research involving a non-visible opponent were not able to improve performance, even if a monetary reward was offered (Hulleman *et al.*, 2007). Again, this would suggest that perceptual affordances provided by the environment could influence the maximal effort an athlete is willing to exert, and alter pacing behaviour and performance.

When racing against an opponent, the cyclists seemed to adapt their initial pace in order to keep up with the pace of their virtual opponent. Interestingly, a change in pace of the opponent halfway the time trial did not have a major effect onto the pacing behaviour of the participants. The tendency to adjust the initial pace to other competitors seems to correspond to pacing strategies as demonstrated during real-life athletic competitions. Elite middle- and long-distance runners tended to adopt a fast starting pace in order to keep up with the leaders (Thiel *et al.*, 2012; Hanley *et al.*, 2011; Renfree and St Clair Gibson, 2013; Deaner *et al.*, 2015; Renfree *et al.*, 2014b). In contrast, athletes adopted a slower initial pace during sports as track cycling and short track speed skating (Moffatt *et al.*, 2014; Konings *et al.*, 2016; De Koning, Foster, Lucía, *et al.*, 2011), most likely due to the aerodynamic benefits of drafting behind your opponents (Rundell, 1996). The present study has shown that even without the presence of any aerodynamic benefit or disadvantages, athletes still are triggered to change their pacing based on the behaviour the opponent. Nevertheless, the role of the specific demands of a sport, such as aerodynamic constraints, needs to be taken into account for optimal decision-making regarding pacing during actual competitions.

4.5 Conclusion

In conclusion, the present study is the first to show that not only presence, but also the behaviour of an opponent affected decisions regarding the regulation of exercise intensity during time trial exercise in laboratory-controlled conditions. Interestingly, both constructed virtual opponent led to an improved performance compared to riding alone, regardless of the pacing strategy of the competitor. These findings emphasise the interaction with competitors as an important determinant of pacing and performance, in which virtual opponents were shown to be able to invite cyclists to alter their pacing behaviour in a setting without the presence of any benefit or disadvantages for doing so.

PART III – THE COMPETITIVE SITUATION

CHAPTER 5

The impact of different competitive environments on pacing and performance

Citation

Konings, M.J., and Hettinga, F.J. (2017). The impact of different competitive environments on pacing and performance. International journal of sport physiology and performance. 1-21. DOI:10.1123/ijspp.2017-0407. [Epub ahead of print]

. ---

Abstract

In real-life competitive situations, athletes are required to continuously make decisions about how and when to invest their available energy resources. This study attempted to identify how different competitive environments invite elite short track speed skaters to modify their pacing behaviour during head-to-head competition. Lap times of elite 500, 1000 and 1500 m short track speed skating competitions between 2010–2016 (n = 34095 races) were collected. Log-transformed lap and finishing times were analysed with mixed linear models. The fixed effects in the model were sex, season, stage of competition, start position, competition importance, event number per tournament, number of competitors per race, altitude, and time qualification. The random effects of the model were athlete identity and the residual (within-athlete race-to-race variation). Separate analyses were performed for each event. Several competitive environments, such as the number of competitors in a race (a higher number of competitors evoked most likely a faster initial pace; CV = 1.9-9.3%), the stage of competition (likely to most likely, a slower initial pace was demonstrated in finals; CV = -1.4-2.0%), the possibility of time qualification (most likely a faster initial pace; CV = 2.6-5.0%) and competition importance (most likely faster races at the Olympics; CV = 1.3-3.5%), altered the pacing decisions of elite skaters in 1000 and 1500 m events. Stage of competition and start position affected 500 m pacing behaviour. As demonstrated in this study, different competitive environments evoked modifications in pacing behaviour, in particular in the initial phase of the race, emphasising the importance of the competitive situation on action selection in exercise regulation.

5.1 Introduction

The regulation of the exercise intensity over an exercise bout, a process known as pacing, is widely recognised as an essential determinant of performance (Edwards and Polman, 2013). In this regulatory mechanism, the sensation of fatigue and a willingness to tolerate discomfort in anticipation of future rewards appears to play a crucial role (Smits *et al.,* 2014). Yet the decision-making process involved in the regulation of exercise intensity has been shown to be rather complex. Several physiological, psychological and biomechanical variables have been revealed to influence on the outcome of pacing decisions (Smits *et al.,* 2014) and performance (Konings *et al.,* 2015). The importance of the interaction between the exerciser and environmental cues has been emphasised, in particular in the context of decision-making and pacing in head-to-head competition (Smits *et al.,* 2014; Hettinga *et al.,* 2017). Perceptual affordances provided by the environment may provoke athletes to respond, thereby evoking in-race adaptations of pacing behaviour (Smits *et al.,* 2014; Hettinga *et al.,* 2017). As shown in observational and experimental studies, an opponent may be such an affordance, inviting exercisers to adjust their pacing behaviour. For example, the presence of a virtual opponent has been revealed to improve time trial performance (Chapter 4; Wilmore, 1968; Williams *et al.,* 2015a, 2015b; Corbett *et al.,* 2012; Tomazini *et al.,* 2015). Moreover, different behaviour of the opponent has been shown to invite different pacing responses (Chapter 3 and 4).

However, apart from the opponents as most obvious affordances in competition, many other external cues will be presented simultaneously to an exerciser in real-life competitive situations. Therefore, it seems likely that the response of an exerciser to an opponent is not only based on the opponent itself, but also on the context in which the opponent is presented to the exerciser. In the present study the effect of different competitive environments on pacing and performance will be explored in short track speed skating competitions, a sport in which it has been shown that the pacing behaviour of a competitor is significantly affected by the pacing behaviour of the other competitors (Chapter 3; Konings *et al.*, 2016; Noorbergen *et al.*, 2016). It is hypothesised that different competitive environments, such as the number of competitors within a race, the stage of competition, and the additional possibility of time fastest qualification, affect the chosen pacing behaviour and performance when competing against others. This would demonstrate the importance of the context in which the opponent is presented to the exerciser in the decision-making process involved in pacing.

5.2 Methods

5.2.1 Participants and data acquisition

Finishing and intermediate lap times were gathered for men and women from 500 m (4.5 laps), 1000 m (9 laps) and 1500 m (13.5 laps) Short Track Speed Skating World Cups, the European Championships and World Championships during the seasons 2010/11 until 2015/16. In total, 47 indoor competitions (thirty-four World Cups, six European Championships, six World Championships, and the Olympic Games) were analysed. Each short track competition consisted of qualification stages in which a skater had to qualify for the next stage by finishing in first or second position, and the final race in which the goal was to win the event. Lap times were recorded for each competitor automatically at the finish line, using electronic time-measuring systems based on optical detectors that started automatically by the firing of a starting-gun. The International Skating Union (ISU) demands that lap times are recorded with the accuracy of at least a hundredth of a second. Therefore, for every automatic timekeeping system that was used, a certificate stating the reliability and accuracy of the system had to be presented to the referee before the competition, ensuring that all systems recorded with the accuracy of at least a hundredth of a second. No written consent was given by participants as all data used are publicly available at the ISU website (http://www.sportresult.com/federations/ISU/ShortTrack/) and no interventions occurred during the data collection. The study was approved by the ethical committee of the University of Essex and in accordance with the Declaration of Helsinki.

In total, 3414 500 m races (14036 skating performances), 3210 1000 m races (13646 skating performances) and 1851 1500 m races (10894 skating performances) were analysed. Whereas falls and/or disqualifications could affect the lap times and positioning of the athlete him/herself as well as those of the other competitors (especially for the lower placed finishers) possibly leading to a misinterpretation of the results, skating performances from races with a disqualification, a fall and/or races with one or more missing values were excluded. In addition, outliers, defined as performances with a standardised residual >5.0, were excluded from the dataset (Hopkins *et al.*, 2009). A standardised residual >5.0 means that the performance was far slower than normal for the given skater. This resulted for the 500 m in 12550 of the 14036 skating performances (89.4%), for the 1000 m in 12143 of the 13646 skating performances (89.0%), and for the 1500 m in 9402 of the 10894 skating performances (86.3%) that were examined.

5.2.2 Statistical analysis

The mixed linear modelling procedure in SPSS was used for the analyses of each event. Finishing and lap times were log transformed before modelling, because this approach yields variability as a percent of the mean (CV), which is the natural metric for most measures of athletic performance (Hopkins, 2000). Subsequently, within- and between-athlete CV were derived by back transformation into percentages of the residual and subject random effects in the mixed model. Separate analyses were performed for data from each event. The fixed effects in the model were Sex (men/women), Season (2010/11 up until 2015/16), Stage of competition (final, semi-final, quarter-final, rep. semi-final, rep. quarterfinal, rep. heats, heats, preliminaries), Start position (inner lane to outer lane), Competition importance (World Cup, European Championships, World Championships, and Olympic Games), Event number per tournament (sometimes an event is performed twice in one Tournament weekend, e.g. 2x 500 m event), Number of competitors per race (varies from two to nine competitors), Altitude (sea-level/high altitude; i.e. >1000 m above sea-level), and the opportunity to qualify for the next stage as one of the time fastest if not qualified via finishing position (Time qualification; no/yes). The random effects of the model were Athlete identity (between-athletes differences) and the residual (within-athlete race-to-race variation). The dependent variables were the natural log of the lap times and finishing times in an event; analysis of these transformed variables yields coefficients of variation (CV), which are variations in performance expressed as a percent of average performance (Hopkins *et al.*, 1999). Precision of the estimates of CV are shown as 95% confidence limits which represent the limits within which the true value is 95% likely to occur. A spreadsheet was used to combine and compare fixed effects and CVs (Hopkins, 2006). The following scale was used for the interpretation of the probability that an effect was substantial or trivial: < 0.5%, most unlikely; 0.5-5%, very unlikely; 5-25%, unlikely; 25-75%, possibly; 75-95%, likely; 95-99.5%, very likely; >99.5, most likely (Hopkins *et al.*, 2009).

5.3 Results

Mean ± SD of the lap times and finish times in seconds of the 500, 1000 and 1500 m event can be found in Table 5.1.

Table 5.1 Mean ± SD of the lap times and finish times in seconds of the 500, 1000 and 1500 m event

	500 m	1000 m	1500 m
Lap 1	7.33 ± 0.35	13.72 ± 0.99	9.73 ± 1.06
Lap 2	9.33 ± 0.38	10.42 ± 0.80	13.16 ± 1.68
Lap 3	8.88 ± 0.39	10.07 ± 0.66	12.14 ± 1.48
Lap 4	9.02 ± 0.41	9.83 ± 0.53	11.60 ± 1.26
Lap 5	9.27 ± 0.44	9.66 ± 0.46	11.10 ± 1.06
Lap 6		9.54 ± 0.46	10.66 ± 0.84
Lap 7		9.49 ± 0.49	10.30 ± 0.65
Lap 8		9.57 ± 0.57	10.06 ± 0.55
Lap 9		9.80 ± 0.66	9.89 ± 0.49
Lap 10			9.75 ± 0.48
Lap 11			9.66 ± 0.51
Lap 12			9.66 ± 0.60
Lap 13			9.80 ± 0.71
Lap 14			10.08 ± 0.84
Finish time	43.82 ± 1.81	92.09 ± 4.18	147.59 ± 7.93

5.3.1 500 m event

Fixed and random effects per lap and for the finish time can be found in Table 5.2 for 500 m races. Men were most likely faster compared to women in all laps. The fixed effect of Season indicated a faster completion of the final three laps (likely to very likely substantial), while differences in the first lap time over the seasons are most likely trivial. Lap times and finishing times were most likely completed faster in finals, semi-finals, and quarterfinals compared to the preliminary stages of the competition. The fixed effects of number of competitors within a race, the competition importance, the possibility of time qualification, and the event number per tournament appeared to be most likely trivial for each lap and for the finishing time. Start position had a most likely substantial effect in the first lap, indicating a more inner start position did lead to faster lap times. A more inner or outer start position did not lead to any likely effect in any other lap time or finish time. Interestingly, races performed at high altitude only led to a likely positive effect compared to sea-level in the final lap.

Table 5.2 Random (x/÷ 95% CI) and fixed effects (± 95% CI) per lap and for the finish time for 500 m short track speed skating races.

	Lap 1	**Lap 2**	**Lap 3**	**Lap 4**	**Lap 5**	**Finish**
Random effects						
Between-athlete	2.1 x/÷1.08	2.0 x/÷1.08	2.6 x/÷1.08	2.7 x/÷1.08	2.7 x/÷1.08	2.5 x/÷1.07
Within-athlete	2.3 x/÷1.01	2.0 x/÷1.01	2.1 x/÷1.01	2.3 x/÷1.01	2.8 x/÷1.01	1.8 x/÷1.01
Fixed effects						
Sex	7.5 ^{MS} ±0.2	6.2 ^{MS} ±0.1	6.3 ^{MS} ±0.2	6.3 ^{MS} ±0.2	6.1 ^{MS} ±0.2	6.4 ^{MS} ±0.1
Season	0.0 ^{MT} ±0.3	1.0 $^{PS/PT}$ ±0.2	1.3 ^{VS} ±0.3	1.2 ^{LS} ±0.3	1.2 ^{LS} ±0.3	1.0 $^{PS/PT}$ ±0.2
Stage of Competition	-0.8 ^{LT} ±0.5	-1.1 $^{PS/PT}$ ±0.4	-1.4 ^{VL} ±0.4	-1.3 ^{LS} ±0.5	-1.2 $^{PS/PT}$ ±0.6	-1.1 ^{LS} ±0.4
Start position	-2.2 ^{MS} ±0.2	0.0 ^{MT} ±0.2	-0.1 ^{MT} ±0.2	-0.1 ^{MT} ±0.3	-0.2 ^{MT} ±0.3	-0.4 ^{MT} ±0.2
No of ST	-0.1 ^{MT} ±0.3	-0.3 ^{MT} ±0.2	-0.1 ^{MT} ±0.2	-0.1 ^{MT} ±0.3	-0.1 ^{MT} ±0.3	-0.1 ^{MT} ±0.2
Altitude	0.1 ^{MT} ±0.2	0.6 ^{MT} ±0.1	0.8 ^{VT} ±0.2	0.9 $^{PS/PT}$ ±0.2	1.2 ^{VS} ±0.2	0.8 ^{MT} ±0.1
Competition importance	0.1 ^{MT} ±0.3	0.5 ^{MT} ±0.4	0.2 ^{MT} ±0.4	0.1 ^{MT} ±0.4	0.0 ^{MT} ±0.5	-0.2 ^{MT} ±0.5
Event No. per tournament	-0.1 ^{MT} ±0.1	-0.1 ^{MT} ±0.1	-0.1 ^{MT} ±0.1	0.1 ^{MT} ±0.1	0.1 ^{MT} ±0.1	0.0 ^{MT} ±0.1
Time qualification	-0.0 ^{MT} ±0.3	-0.1 ^{MT} ±0.2	-0.2 ^{MT} ±0.3	-0.2 ^{MT} ±0.3	-0.1 ^{MT} ±0.4	-0.1 ^{MT} ±0.2

^{MS} most likely substantial; ^{VS} very likely substantial; ^{LS} likely substantial; ^{PS} possibly substantial; ^{PT} possibly trivial; ^{LT} likely trivial; ^{VT} very likely trivial; ^{MT} most likely trivial.

5.3.2 1000 m event

Fixed and random effects per lap and for the finish time can be found in Table 5.3 for 1000 m races. Lap times and finishing times were most likely faster for men compared to women. The fixed effect of Season indicated a change in chosen pacing behaviour over the seasons to a more conservative starting pace and faster final lap times. Except for the first lap, a likely to most likely positive effect on lap times and finish time was found at high altitude compared to sea level. The very likely to most likely substantial fixed effect for the number of competitors within a race in the first four laps, indicates a higher number of competitors leads to a faster initial pace and faster finish time compared to a lower number of competitors within a race. The possibility of time fastest qualification led to a most likely positive effect on lap time in the first three laps and a very likely positive effect on the finish time. The very likely to most likely substantial effect of competition importance in the first four laps, appears to be mainly due to differences in initial pace between the Olympic Games on one hand, and the World cups, European and World championships on the other. Initial pace during the Olympic Games was found to be most likely faster (1.3-6.9%). A more inner or outer start position or whether it was the first or second time the event was organised in a tournament weekend did not led to any likely effect on lap times or finish time. Finals, semi-finals, quarterfinals, and heats were most likely leading to faster lap times in all laps compared to repechage races (1.4-5.9%) and the preliminaries (0.3-5.1%).

5.3.3 1500 m event

Fixed and random effects per lap and for the finish time can be found in Table 5.4 for 1500 m races. Lap times and finishing times were most likely faster for men compared to women. The fixed effect of Season indicated a change in chosen pacing behaviour over the seasons to a more conservative starting pace and faster final lap times. High altitude had a most likely positive effect on the first ten lap times and the finish time compared to sea level performances. The most likely substantial fixed effect for the number of competitors within a race in the first seven laps indicates a higher number of competitors leads to a faster initial pace and faster finish time compared to a lower number of competitors within a race. The possibility of time fastest qualification led to a most likely positive effect on lap time in the first five laps and a most likely positive effect on the finish time. The most likely substantial effect of competition importance in the first six laps, appears to be mainly due to a differences initial pace during the Olympic Games. Initial pace during the Olympic Games was found the be most likely faster (3.2-8.3%) compared to the World cups, European and World championships. Whether it was the first or second time the event was organised in a tournament weekend had a possibly to most likely substantial effect on the first six lap times, indicating a faster initial pace if it was the second time the event was organised in a weekend. The fixed effect of Stage of competition indicated a slower initial pace is adopted the further in the tournament. Finals are slower in the first laps compared to all other stages of competition, while semi-finals and quarterfinals are starting slower compared to all other stages of competition except the finals.

5.4 Discussion

The present study aimed to examine the effect of different competitive environments on pacing and performance in a head-to-head structured competition, such as short track speed skating. Several competitive environments, such as the number of competitors in a race, the stage of competition, the tournament, and the start position appeared to alter the pacing decisions of elite short track speed skaters. These findings demonstrate the importance of the external setting in which an opponent is presented, and highlights several novel external cues that need to be incorporated in understanding the complex decision-making process involved in pacing.

Different competitive environments appeared to affect mainly the initial phase of a race. In this respect, we have shown in Chapter 3 that in this initial stage elite short

Table 5.3 Random (x/÷ 95% CI) and fixed effects (± 95% CI) per lap and for the finish time for 1000 m short track speed skating races.

	Lap 1	**Lap 2**	**Lap 3**	**Lap 4**	**Lap 5**	**Lap 6**	**Lap 7**	**Lap 8**	**Lap 9**	**Finish**
Random effects										
Between-athlete	1.5 x/÷1.12	1.2 x/÷1.16	1.0 x/÷1.17	0.8 x/÷1.16	0.8 x/÷1.15	1.4 x/÷1.11	2.5 x/÷1.09	3.2 x/÷1.08	3.4 x/÷1.09	1.6 x/÷1.09
Within-athlete	5.4 x/÷1.01	6.2 x/÷1.01	5.0 x/÷1.01	3.8 x/÷1.01	3.1 x/÷1.01	2.8 x/÷1.01	3.1 x/÷1.01	3.8 x/÷1.01	4.8 x/÷1.01	2.6 x/÷1.01
Fixed effects										
Sex	5.0 ±0.3[MS]	5.5 ±0.3[MS]	5.9 ±0.3[MS]	6.4 ±0.2[MS]	6.9 ±0.2[MS]	6.9 ±0.2[MS]	6.9 ±0.2[MS]	6.9 ±0.3[MS]	6.7 ±0.3[MS]	6.4 ±0.2[MS]
Season	-2.1 ±0.6[MS]	-1.2±0.7[PS/PT]	-0.1 ±0.5[MT]	0.5 ±0.4[VT]	0.7 ±0.3[LT]	1.1±0.3[PS/PT]	1.2 ±0.4[LS]	1.4 ±0.5[LS]	1.4 ±0.6[LS]	0.2 ±0.3[MT]
Stage of Competition	-2.0 ±1.2[VS]	-1.6 ±1.4[LS]	-1.8 ±1.1[LS]	-1.7 ±0.9[VS]	-1.7 ±0.7[VS]	-1.4 ±0.6[LS]	-1.4 ±0.7[LS]	-1.4 ±0.9[LS]	-1.3±1.1[PS/PT]	-1.6 ±0.6[VS]
Start position	-0.5±1.3[PS/PT]	0.2 ±1.5[LT]	0.2 ±1.2[LT]	0.2 ±1.0[LT]	0.0 ±0.8[VT]	0.0 ±0.7[VT]	-0.2 ±0.8[VT]	-0.3 ±1.0[VT]	-0.8±1.2[PS/PT]	-0.1 ±0.7[MT]
Number of short trackers	3.8 ±1.1[MS]	3.9 ±1.2[MS]	3.4 ±1.0[MS]	1.9 ±0.7[VS]	0.8 ±0.6[PS/PT]	0.1 ±0.5[MT]	-0.4 ±0.6[VT]	-0.9±0.7[PS/PT]	-0.9±0.9[PS/PT]	1.5 ±0.5[VS]
Altitude	0.2 ±0.3[MT]	1.1 ±0.4[LS]	1.5 ±0.3[MS]	1.7 ±0.2[MS]	2.0 ±0.2[MS]	1.9 ±0.2[MS]	1.7 ±0.2[MS]	1.5 ±0.2[MS]	1.4 ±0.3[VS]	1.4 ±0.2[MS]
Competition importance	1.6 ±1.1[VS]	2.2 ±1.2[MS]	1.9 ±1.0[MS]	1.3 ±0.8[VS]	0.5 ±0.6[MT]	0.3 ±0.6[MT]	0.0 ±0.6[MT]	-0.4 ±0.7[MT]	-0.7 ±0.9[MT]	0.8 ±0.5[LT]
Event No. per tournament	0.5 ±0.3[MT]	0.7 ±0.3[LT]	0.9 ±0.3[LT]	0.8 ±0.2[VT]	0.6 ±0.2[MT]	0.2 ±0.2[MT]	0.0 ±0.2[MT]	-0.1 ±0.2[MT]	-0.1 ±0.3[MT]	0.4 ±0.1[MT]
Time qualification	-2.6 ±1.0[MS]	-2.6 ±1.2[MS]	-2.3 ±1.0[MS]	-1.1±0.8[PS/PT]	-0.7 ±0.6[LT]	-0.3 ±0.6[MT]	-0.4±0.6[MT]	-0.2 ±0.8[MT]	-0.6 ±1.0[VT]	-1.3 ±0.5[VS]

[MS] most likely substantial; [VS] very likely substantial; [LS] likely substantial; [PS] possibly substantial; [PT] possibly trivial; [LT] likely trivial; [VT] very likely trivial; [MT] most likely trivial.

Table 5.4 Random (x/÷ 95% CI) and fixed effects (± 95% CI) per lap and for the finish time for 1500 m short track speed skating races.

	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6	Lap 7	Lap 8
Random effects								
Between-athlete	2.5 x/÷1.12	2.0 x/÷1.18	1.8 x/÷1.20	1.4 x/÷1.22	1.1 x/÷1.25	0.8 x/÷1.30	0.5 x/÷1.37	0.6 x/÷1.27
Within-athlete	8.4 x/÷1.02	10.7 x/÷1.02	10.3 x/÷1.02	9.0 x/÷1.02	7.7 x/÷1.02	6.2 x/÷1.02	4.8 x/÷1.02	4.1 x/÷1.02
Fixed effects								
Sex	4.5 MS ±0.5	6.6 MS ±0.6	7.1 MS ±0.5	7.1 MS ±0.5	7.4 MS ±0.4	6.8 MS ±0.3	6.5 MS ±0.2	6.1 MS ±0.2
Season	-6.5 MS ±1.0	-5.1 MS ±1.2	-3.9 MS ±1.2	-2.6 MS ±1.0	-1.2 PS/PT ±0.9	-0.2 VT ±0.7	0.6 LT ±0.6	1.1 PS/PT ±0.5
Stage of Competition	0.6 PS/PT ±1.5	2.3 LS ±1.8	1.3 PS/PT ±1.7	-0.1 LT ±1.5	-1.4 PS/PT ±1.4	-1.7 LS ±1.0	-1.6 LS ±0.8	-1.4 LS ±0.7
Start position	-1.3 PS/PT ±1.2	0.6 PS/PT ±1.5	0.2 LT ±1.7	0.1 LT ±1.3	0.0 LT ±1.1	0.0 VT ±0.9	-0.1 VT ±0.7	-0.1 MT ±0.6
Number of short trackers	5.0 MS ±1.6	7.9 MS ±2.1	9.3 MS ±2.1	8.3 MS ±1.8	7.0 MS ±1.5	5.9 MS ±1.2	3.9 MS ±0.9	1.7 VS ±0.8
Altitude	3.3 MS ±0.6	4.5 MS ±0.8	4.8 MS ±0.8	4.8 MS ±0.7	4.7 MS ±0.6	3.7 MS ±0.5	2.6 MS ±0.4	2.0 MS ±0.3
Competition importance	3.5 MS ±1.8	3.5 MS ±2.2	3.1 MS ±2.1	2.2 MS ±1.9	2.0 MS ±1.6	2.1 MS ±1.3	0.7 LT ±1.0	0.8 LT ±0.8
Event number per tournament	0.8 LS ±0.4	1.0 PS/PT ±0.6	1.4 LS ±0.5	1.8 MS ±0.5	1.4 VS ±0.4	1.1 PS/PT ±0.3	0.8 VT ±0.3	0.6 MT ±0.2
Time qualification	-3.9 MS ±1.3	-5.0 MS ±1.6	-4.4 MS ±1.6	-3.5 MS ±1.4	-2.6 MS ±1.3	-1.4 LS ±1.0	-0.5 VT ±0.8	-0.5 MT ±0.7

	Lap 9	Lap 10	Lap 11	Lap 12	Lap 13	Lap 14	Finish
Random effects							
Between-athlete	0.7 x/÷1.21	1.4 x/÷1.12	2.7 x/÷1.09	4.0 x/÷1.08	5.0 x/÷1.08	5.2 x/÷1.08	1.4 x/÷1.11
Within-athlete	3.6 x/÷1.02	3.2 x/÷1.02	3.4 x/÷1.02	4.0 x/÷1.02	4.8 x/÷1.02	6.0 x/÷1.02	3.5 x/÷1.02
Fixed effects							
Sex	6.1 [MS] ±0.2	6.3 [MS] ±0.2	6.0 [MS] ±0.3	5.7 [MS] ±0.3	5.5 [MS] ±0.4	4.9 [MS] ±0.5	6.4 [MS] ±0.2
Season	1.4 [VS] ±0.4	1.4 [VS] ±0.4	1.6 [VS] ±0.5	1.6 [VS] ±0.6	1.8 [VS] ±0.7	2.0 [VS] ±0.8	-0.9[PS/PT] ±0.5
Stage of Competition	-1.4 [LS] ±0.6	-1.3 [LS] ±0.6	-1.3 [LS] ±0.6	-1.5 [LS] ±0.7	-1.6 [LS] ±0.8	-1.7 [LS] ±1.0	-0.7 [LT] ±0.6
Start position	-0.1 [MT] ±0.5	-0.2 [MT] ±0.5	-0.2 [MT] ±0.5	-0.3 [VT] ±0.6	-0.4 [LT] ±0.7	-0.7 [LT] ±0.9	-0.1 [MT] ±0.5
Number of short trackers	0.5 [LT] ±0.7	-0.1 [MT] ±0.6	-0.5 [LT] ±0.6	-0.8[PS/PT] ±0.8	-0.8[PS/PT] ±0.9	-0.6 [LT] ±1.1	3.7 [MS] ±0.7
Altitude	2.0 [MS] ±0.3	1.6 [MS] ±0.2	0.8 [VT] ±0.3	0.2 [MT] ±0.3	-0.1 [MT] ±0.4	-0.1 [MT] ±0.5	2.6 [MS] ±0.3
Competition importance	0.8 [LT] ±0.7	0.9 [LT] ±0.7	0.7 [VT] ±0.7	0.4 [MT] ±0.8	0.4 [VT] ±1.0	0.1 [MT] ±1.2	1.6 [MS] ±0.7
Event number per tournament	0.2 [MT] ±0.2	-0.3 [MT] ±0.2	-0.3 [MT] ±0.2	-0.5 [MT] ±0.2	-0.5 [MT] ±0.3	-0.4 [MT] ±0.3	0.5 [MT] ±0.2
Time qualification	-0.2 [MT] ±0.6	-0.3 [MT] ±0.6	0.0 [MT] ±0.6	0.1 [MT] ±0.7	0.0 [MT] ±0.8	-0.2 [MT] ±1.0	-1.8 [MS] ±0.6

[MS] most likely substantial; [VS] very likely substantial; [LS] likely substantial; [PS] possibly substantial; [PT] possibly trivial; [LT] likely trivial; [VT] very likely trivial; [MT] most likely trivial track speed skaters are highly variables between races, however, within a race short track speed skaters appear to adjust their pace to the behaviour of the other contenders. Similarly, Chapter 4 revealed that cyclists seemed to adapt their initial pace in order to keep up with the pace of their virtual opponent. However, the pacing behaviour of the virtual opponents did not alter pacing decisions of cyclists later on in 4-km time trials, despite a significant change in pace of the opponents halfway the time-trial (Chapter 4). A likely explanation for why external cues mainly seem to affect the decision-making of exercisers in the beginning of a race could be the perceived level of fatigue of the exerciser. Variables such as perceived exertion have been shown to be key components in exercise regulation (Smits *et al.,* 2014; Marcora, 2008; Crewe *et al.,* 2008), and will likely accumulate throughout the race. In this perspective, a higher level of fatigue has indeed been shown to alter the attentional focus from external to internal related variables (Brick *et al.,* 2016)

During any point in time during the competition the external world around the exerciser presents multiple invitations for actions to the exerciser, so-called affordances (Withagen *et al.,* 2012; Gibson, 1972). These invitations for action can arise and dissipate over time, and evoke an exerciser's decision to remain on current pace, to slow down or to accelerate (Smits *et al.,* 2014). With the multitude of affordances that are presented to an exerciser continuously and simultaneously, it is up to the athlete to act upon certain affordances, and not on others (Cisek, 2007). In this respect, it seems likely that most of the tested variables in this study affect the action selection process that determines which affordances the athlete acts upon, rather than being affordances themselves.

The outcomes of the present study provide another complication for the template model of exercise regulation: if pacing would be based on matching a predetermined template with the current bodily state, in respect to the remaining distance ahead, this would require the exerciser/governor to have thought of a template or schema for each possible combination of external cues presented around the exerciser before starting to exercise. All of these templates will have to be stored somewhere in the exerciser's memory, leading to a storage problem, a phenomenon that is well-discussed in motor control literature (Schmidt, 1975).

Arguably the clearest example of how competitive environments could impact on pacing behaviour is illustrated by the possibility of time qualification. In some stages of some competitions it was possible to qualify for the next stage not only via finishing position, but also via qualification on the basis of time achieved for the time fastest skaters in that stage of competition whom did not qualify via finishing position in their race. When the possibility to qualify as one of the time fastest in that stage of competition was present, races in that particular stage of competition started most likely faster in the 1000 m and 1500 m event compared to that same stage in other competitions when the possibility of time fastest qualification was not present. This faster initial pace led to very likely (1000 m event) and most likely (1500 m event) faster finishing times when time fastest qualification was possible.

Another environmental factor that appeared to be a crucial factor for the initial pace was the number of competitors competing within a race. That is, the lower the number of competitors within a race the slower the adopted initial pace by the competitors compared to a higher number of competitors. An effect that was especially apparent during the 1000 m and 1500 m competitions. A confounding effect of group size on performance has been reported before (Ingham *et al.,*, 1974; Ringelmann, 1913). Performance of individual members of a group tend to become increasingly less in a cooperative setting as the size of their group increases, and effect well known as the Ringelmann effect (Ingham *et al.,*, 1974; Ringelmann, 1913). To our knowledge, this is the first time a contrary confounding effect is found for group size on decision-making and performance in a competitive situation.

Interestingly, possibly faster finishing times were revealed over the seasons in the 500 m event. The faster finishing times were established mainly by a likely to very likely faster completion of the final three laps rather than by a faster initial lap (most likely trivial effect over the seasons). At the same time, this study once again highlights the importance of the start position for 500 m short track speed skating competitions (Maw *et al.,* 2006; Noorbergen *et al.,* 2016; Muehlbauer and Schindler, 2011). In contrast to the 500 m event, a change in chosen pacing behaviour to a more conservative starting pace and faster final lap times was found over the seasons for the 1000 and 1500 m event. This could be an indication of an increased depth of competition over the years. That is, a similar change to a more conservative initial pace was found in the final stages of the tournament in comparison to the preliminary stages of the tournament during the 1500 m event. For the 500 and 1000 m event, lap times and finishing times were most likely faster in finals, semi-finals, and quarterfinals compared to the preliminary stages of the competition. Remarkably, during the Olympic Games the skaters adopted a faster initial pace compared to World cups, European and World championships, leading to faster finishing times in the 1000 m and 1500 m event. Differences in pacing and performance for competition importance in the 500 m event were found to be most likely trivial.

Noteworthy, yet not surprisingly, sex and altitude affected performance. Men completed their races most likely faster compared to women, while races at high altitude led to most likely faster finishing times compared to races at sea-level for the 1000 and 1500 m event. Interestingly, the difference in finishing time between sea-level and high altitude races was most likely trivial for the 500 m event. In terms of pacing, races at sea-level were most likely slower in the first ten laps of the 1500 m event. For the 1000 m event all laps were likely to most likely faster at high altitude, except for the first lap, while for the 500 m event only the final lap was very likely faster at high altitude.

The possibility to benefit from the effect of drafting behind their opponent is crucial in in short track speed skating competitions, and could reduce air frictional losses up to 23% (Van Ingen Schenau, 1982; Rundell, 1996). Therefore, adjusting your own pacing behaviour based on your competitors could provide a clear advantage in short track speed skating. Whether this has an effect on the influence of the competitive environment on pacing decisions is yet unclear. However, one could expect at least comparable results in sports where aerodynamics play a similar prominent role, such as cycling. In addition, it seems likely that a variable such as time fastest qualification could invite to adjust the chosen pacing behaviour in other sports such as for example running, although more experimental evidence is required to support this hypothesis.

5.5 Conclusion

A multitude of external cues, inviting for action, are presented continuously and simultaneously to an exerciser during a competition. As demonstrated in this study, different competitive environments impacted on pacing behaviour, in particular in the initial phase of the race. In Chapter 3, we demonstrated already that the behaviour of the other contenders in the race could be an important affordance during elite short track speed skating competitions. That is, elite short track speed skaters adjust their pacing response during competition heavily based on the actions and pacing behaviour of the other competitors in their race. However, the adopted pace by the competitors during a race appeared to vary widely between races. The present study revealed that part of this variability per race could be related to the context in which a race is presented. Several competitive environments, such as the number of competitors in a race (a higher number of competitors evoked most likely a faster initial pace), the stage of competition (likely to most likely, a slower initial pace was demonstrated in finals), the possibility of time qualification (most likely a faster initial pace) and competition importance (most likely faster races at the Olympics), altered the pacing decisions of elite skaters in 1000 and 1500 m events. In addition, the stage of competition and start position affected pacing behaviour in the 500 m event. This emphasizes the importance of the competitive environment around the exerciser, especially during head-to-head competition. In this respect, the competitive environment seems to affect pacing regulation via the presentation of affordances (e.g. an opponent) towards the exerciser and due to its influence on the action selection process that determines which affordances the athlete acts upon. Thus, to understand the decision-making involved in pacing both the internal state of the exerciser as well as the external world around the exerciser need to be considered.

CHAPTER 6

Interdependency between athlete and opponent alters pacing and information-seeking behaviour in 4-km cycling time trials

Abstract

This study examined how a change in the interdependency between athlete and opponent affected exercise regulation and information-seeking behaviour. Twelve participants performed in randomised, counterbalanced order a 4-km time-trial on a Velotron cycle ergometer with no virtual opponent (NO), a virtual opponent with no restrictions (low athlete-opponent interdependency; OP-IND), or a virtual opponent with the restriction that only 1 overtake would be allowed by the participant (high athlete-opponent interdependency; OP-DEP). Information-seeking behaviour has been evaluated using a SMI Eye tracker. Differences in pacing, performance and information-seeking behaviour were examined using repeated-measures ANOVA ($p<0.05$). Neither mean power output (NO: 298±35 W; OP-IND: 297±38 W; OP-DEP: 296±37 W) nor finishing time (NO: 377.7±17.4 sec; OP-IND: 379.3±19.5 sec; OP-DEP: 378.5±17.7 sec) differed between the experimental conditions. However, power output was lower in the first kilometre of OP-DEP (NO: 332±59 W; OP-IND: 325±62 W; OP-DEP: 316±58 W; both $p<0.05$), and participants decided to wait longer before they overtook their opponent (OP-IND: 137±130 sec; OP-DEP: 255±107 sec; $p=0.040$). Moreover, total fixation time spent (NO: 7.4±5.9 sec; OP-IND: 38.6±36.2 sec; OP-DEP: 37.4±19.2 sec; NO vs OP-IND: $p=0.013$, NO vs OP-DEP: $p<0.001$) on focussing on the avatar of the participant itself increased when an opponent was present, while total fixation time spent on the avatar of the opponent increased when participants were only allowed to overtake once (OP-IND: 23.3±16.6s; OP-DEP: 55.8±32.7s; $p=0.002$). A higher interdependency between athlete and opponent evoked a change in pacing behaviour in terms of in-race adaptations based on opponent's behaviour, and induces an increased attentional focus on the virtual opponent. The interdependency between athlete and opponent provide possible underlying mechanism for the pacing differences observed between different competitive sports.

6.1 Introduction

As energy resources are limited in human beings, exercisers are required to decide continuously about how and when to use their available amount of energy (Smits *et al.*, 2014). In this pacing decision-making process, the interaction between the athlete and his surroundings appears to be crucial (Hettinga *et al.*, 2017; Micklewright *et al.*, 2017; Smits *et al.*, 2014). In this sense, although there are multiple external variables that present social invitations for action to an athlete, opponents are arguably one of the most crucial ones in competitive sports (Hettinga *et al.*, 2017). Previously, experimental studies have already shown that an opponent could improve performance (Chapter 4; Tomazini *et al.*, 2015; Corbett *et al.*, 2012; Williams *et al.*, 2015a, 2015b), and how a different initial pace of the opponent could evoke a different initial pace in the exerciser (Chapter 4).

The previous chapter added onto this knowledge the importance of external cues and the competitive situation within a competitive sport. Yet also between competitive sports a great variability in chosen pacing behaviour can be noted. Specific demands of a sport, such as favourable positioning, competing for the optimal line, and minimising fall risk, could draw athletes away from the energetically favourable strategies (Hettinga *et al.*, 2017). A main underlying mechanism behind these changes in pacing behaviour between competitive sports could be a changing interdependency between the competitors. For example, the possibility of drafting, and the magnitude of associated energy-saving effects of drafting, appeared to be an important determinant for pacing behaviour and tactical decision-making in competitive sports (Konings *et al.*, 2016; Noorbergen *et al.*, 2016; Hettinga *et al.*, 2017). This energy-saving effects of drafting could in fact be perceived as an increased interdependency between athlete and opponent.

The present study will examine whether the same opponent, but a different interdependency between the athlete and the opponent would indeed affect exercise regulation and information-seeking behaviour in laboratory-controlled conditions. It was hypothesised that a higher interdependency between athlete and opponent would evoke different pacing decisions, in response to the opponent's pacing behaviour, and would alter the information-seeking behaviour of the exerciser.

6.2 Materials and methods

6.2.1 Participants

12 participants with at least two years of cycling experience at a moderate to high intensity (age: 45.8±7.0 years; body mass: 78.7±10.4 kg; height: 176.6±7.4 cm) participated in this study. All participants were moderate to highly physically active (two or more moderate to high-intensity training sessions per week) and familiar to pacing their exercise. Before participating all participants gave written informed consent and completed a health screening questionnaire (Physical Activity Readiness Questionnaire; Cardinal *et al.*, 1996). The study was approved by the university's local ethical committee in accordance to the Declaration of Helsinki..

6.2.2 Experimental procedures

Participants visited the laboratory at five different occasions and completed a 4-km cycling time trial in each visit. The 4-km time trial was preceded by a 5-min warm-up at a fixed load of 150 watt, followed by a 4-min inactive recovery period before starting the time trial. The first two 4-km time trials were used as familiarisation trials (FAM1 and FAM2). In the third to fifth visit participants had to perform one of the three experimental 4-km time trials in a randomised, counterbalanced order. The experimental time trials consisted of a 4-km time trial without virtual opponent (NO), a 4-km time trial with virtual opponent, without further instructions (low athlete-opponent interdependency; OP-IND), and a 4-km time trial with virtual opponent including the instruction the opponent could only be overtaken once by the participant (high athlete-opponent interdependency; OP-DEP).

The same opponent was used for both OP-IND and OP-DEP. This opponent was constructed based on the fastest familiarisation trial of the participant. In order to maximise the chances the opponent would be in front of the participant directly after the start, yet preventing a too big initial gap between participant and opponent, the opponent was set to adopt an initial pace that led to a 1-second lead after 250 m compared to the fastest familiarisation trial of the participant. Hereafter, the opponent adopted a pace of 95% of the power output as achieved in the fastest familiarisation trial.

Before every time trial, participants were instructed to provide maximal effort. No verbal coaching or motivation was given to the participants during any of the trials. In addition, participants were told that their opponent would be of similar level of performance in order to stimulate the participant to perceive the virtual opponent as a realistic and competitive one. Time trials were completed at the same time of the day (± 2 hours) to minimise circadian variation (Brisswalter *et al.*, 2007; Fernandes *et al.*, 2014), and 3–7 days apart to limit training adaptations. Participants were asked to maintain normal activity and sleep pattern throughout the testing period. In addition, participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 hours, and from caffeine and food consumption respectively, four and two hours before the start of the test. Participants were informed that the study was examining cycling performance during 4-km time trials. To prevent any pre-meditated influence on preparation or pre-exercise state, the specific feedback presented for each trial was only revealed immediately before the start of the time trial. All trials were conducted in ambient temperatures between 18-21°C.

6.2.3 Apparatus

Time trials were performed on a cycle ergometer (Velotron Dynafit, Racermate, Seattle, USA) that has been shown to be a reliable and valid tool to measure cycling performance and pacing behaviour (Astorino and Cottrell, 2012; Schoenmakers *et al.*, 2015; Hettinga *et al.*, 2015). Using the Velotron 3D software, a flat 4-km time trial course with no wind was programmed and projected onto a screen for all trials. The course had several gentle curves and (neutral) banners on the side of the course as marking points for the retrospective think aloud analysis after the OP-DEP trial (see Section 6.2.5).

During the time trials participants received feedback regarding their distance travelled, velocity, time, cadence, heart rate and gearing. In all time-trials a virtual avatar of the participant was projected onto the screen. In the opponent conditions, a virtual avatar of an opponent was projected onto the screen as well. Participant started every trial in the same gear, but were free to change their gear ratio throughout the time trial. Power output, velocity, distance, cadence, and gearing were monitored continuously during each trial (sample frequency = 4 Hz). In addition, heart rate was monitored every second (Polar M400, Polar Inc.). Rate of perceived exertion (RPE) on a Borg-scale of 6-20 (Borg, 1982) was asked after the warm-up, after each kilometre during the time trial, and directly after passing the finish line. For this, an A0-sized printed RPE scale was hang up next to the screen projector, clearly visible for the participants while sitting on the cycle ergometer.

6.2.4 Information-seeking behaviour

All participants wore a pair of SMI eye-tracking glasses during the experimental time trials in order to capture their eye movements during the time trial. The SMI eye-tracker was calibrated using a 3-point calibration before starting to record. Eye-tracking data was coded using the SMI BeGaze Analysis Software and 'Other' was used to code fixations for when participants were not looking at the one of the cycling avatars (Rider or Opponent), the screen (excluding the Rider and Opponent), the information feedback (Velocity, Distance, Cadence, Heartrate, Gearing or Time) or the RPE-scale. The number of fixations, the average duration of a fixation, and total fixation time spent was determined per kilometre for each categorised variable and in total.

6.2.5 Retrospective think aloud analysis

Directly after finishing their OP-DEP trial, participants were asked to sit in front of a video screen and were shown video footage of their own time trial. The video footage started 30 seconds before the participant overtook his opponent and was stopped 30 seconds after the participant overtook his opponent. Participants were asked to recall as much as possible about their thinking process during the minute shown on the video footage. The whole minute has been audio recorded and afterwards a transcript has been written out in regard to whatever the participant said in that particular minute. For further analysis, it has been coded for each transcript when the participant would refer to one of the variables that have also been evaluated for the eye-tracking data analysis.

6.2.6 Data analysis

Mean power output, cadence, heart rate and finish time were determined in order to examine performance. Differences in performance between conditions were assessed using a repeated-measures ANOVA. To assess differences in pacing behaviour between the conditions, average power output, cadence, heartrate and split times for each 1-km segment were calculated, and differences were tested using a two-way repeated-measures ANOVA (condition x segment). Post-hoc tests with Bonferroni correction were performed when significant results were found. Information-seeking behaviour was assessed using the total fixation time spent, the total number of fixations, and the average duration of a fixation for each of the coded variables over the whole time trial and per kilometre. Differences in information-seeking behaviour were tested using a two-way repeated-measures ANOVA (condition x segment). All analyses were performed using SPSS 19.0, and significance was accepted at $P < 0.05$. Data are presented as means ± SD.

6.3 Results

6.3.1 Performance analysis

Mean (±SD) finishing time, power output, heart rate, and cadence for the three experimental time trial conditions are shown in Table 6.1. No main effects were found for finishing time ($F = 0.428$; $p = 0.569$), power output ($F = 0.384$; $p = 0.605$), heart rate ($F = 0.389$; $p = 0.682$), or cadence ($F = 0.509$; $p = 0.608$).

Table 6.1 Mean ± SD values for the time trial performance variables completion time, power output, heart rate and cadence per experimental condition.

	NO	**OP-IND**	**OP-DEP**
Completion Time (sec)	377.7 ± 17.4	378.9 ± 19.7	378.5 ± 17.7
Power Output (W)	297.5 ± 47.2	296.7 ± 47.3	296.0 ± 44.3
Heart rate (bpm)	162.5± 13.8	162.1 ± 15.4	161.3 ± 15.1
Cadence (rpm)	101.3 ± 12.5	100.5 ± 10.2	99.7 ± 8.3

6.3.2 Pacing analysis

Mean power outputs per kilometre are shown in Figure 6.1. A main effect for segment (F = 8.287; p = 0.003), but not for condition (F = 0.384; p = 0.605) were found. An interaction effect for condition x segment (F = 2.334; p = 0.042) was revealed, indicating differences in pacing profile between conditions. Post hoc analysis revealed a higher power output during the first kilometre in NO compared to OP-DEP (p = 0.015), and a higher power output during the first kilometre in OP-IND compared to OP-DEP (p = 0.042). No differences in pacing were shown between NO and OP-IND.

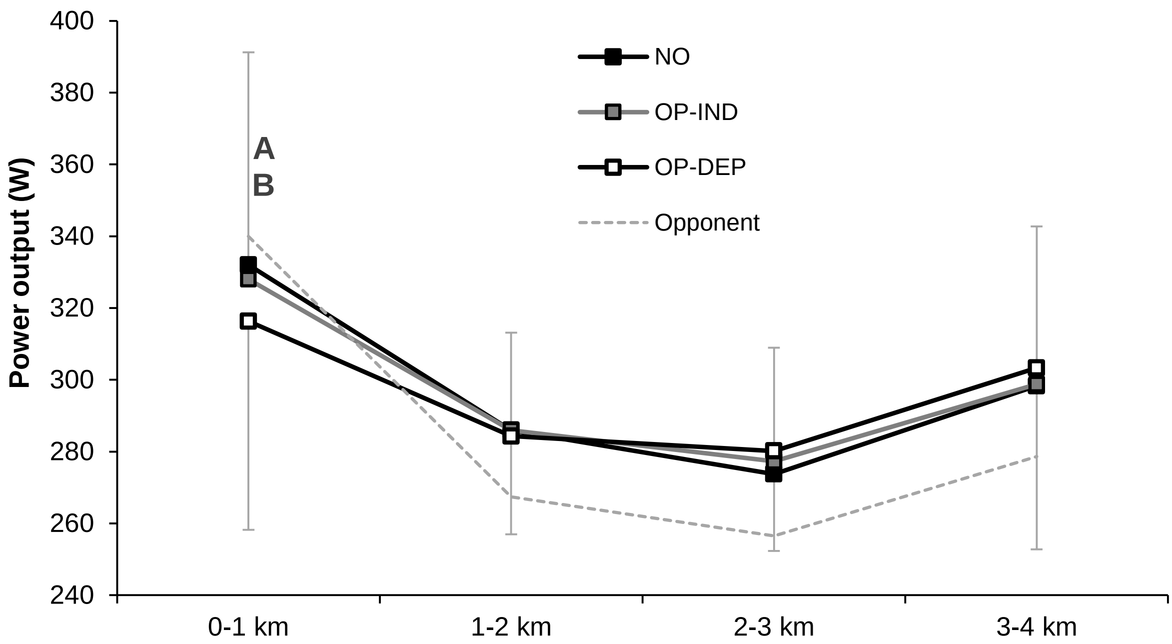

Figure 6.1 Average power output per kilometre segment for each experimental condition (NO, OP-IND, and OP-DEP).
[A] Difference between NO and OP-DEP (P < 0.05); [B] Difference between OP-IND and OP-DEP (P < 0.05),

A main effect for heart rate for segment (F = 196.1; p < 0.001), but neither a main effect for condition (F = 0.389; p = 0.682) nor an interaction effect condition x segment (F = 0.731; p = 0.521) were reported. No main effect for cadence for condition (F = 0.509; p = 0.608) or segment (F = 1.805; p = 0.195), and no interaction effect for condition x segment (F = 1.013; p = 0.397) was found.

Table 6.2 Mean ± SD values for the RPE of the participant per experimental condition per kilometre after starting their time trial, and directly after finishing.

	TT-1 km	TT-2 km	TT-3 km [A,B]	TT-Finish
NO	13.7 ± 1.8	15.8 ± 1.5	17.8 ± 1.1	19.5 ± 0.7
OP-IND	14.0 ± 1.7	16.2 ± 1.6	17.7 ± 1.4	19.2 ± 0.8
OP-DEP	13.3 ± 2.0	15.5 ± 1.6	16.5 ± 1.4	19.0 ± 0.9

[A] Difference between NO and OP-DEP ($P < 0.05$), [B] Difference between OP-IND and OP-DEP ($P < 0.05$).

Mean RPE scores per kilometre for each experimental condition are shown in Table 6.2. A main effect for segment ($F = 297.1$; $p < 0.001$) was reported, but no main effect for condition ($F = 0.835$; $p = 0.448$) was found. In addition, an interaction effect for condition x segment ($F = 2.180$; $p = 0.038$) was revealed. Post hoc analysis indicated a higher RPE score after three kilometre in NO compared to OP-DEP ($p = 0.003$), and a higher RPE score after three kilometre in OP-IND compared to OP-DEP ($p = 0.023$). No differences in RPE were found between NO and OP-IND.

6.3.3 Information-seeking analyses

Mean fixation time spent and the number of fixations in total and per categorised variable per experimental condition over the whole trial are shown in Table 6.3.

6.3.3.1 Fixation time spent

The analysis for mean fixation time spent revealed a main effect for condition for Rider ($F = 9.775$; $p = 0.005$), Opponent ($F = 15.47$; $p = 0.002$), Velocity ($F = 5.741$; $p = 0.010$), Cadence ($F = 5.243$; $p = 0.014$), and Total ($F = 5.707$; $p = 0.010$). Post-hoc analysis revealed an increased focus on the avatar of the rider during OP-IND compared to NO ($p = 0.013$), and during OP-DEP compared to NO ($p < 0.001$), but no difference between OP-IND and OP-DEP ($p = 0.870$). Time fixating at the virtual opponent was higher in OP-DEP compared to OP-IND ($p = 0.002$). Participants showed a decreased focus on the velocity feedback during OP-IND compared to NO ($p = 0.028$), and during OP-DEP compared to NO ($p = 0.014$). An increased amount of time was spent fixating at the cadence feedback in NO compared OP-DEP ($p = 0.007$). Finally, participants were looking in total for more information over the whole trial in OP-DEP compared to NO ($p = 0.008$), and in OP-DEP compared to OP-IND ($p = 0.031$). No effect for condition was reported for Screen ($F = 2.036$; $p = 0.177$), Distance ($F = 1.259$; $p = 0.290$), Heart rate ($F = 1.863$; $p = 0.179$), Gearing ($F = 1.175$; $p = 0.320$), Time ($F = 0.658$; $p = 0.528$), RPE ($F = 0.072$; $p = 0.931$), or Other ($F = 0.300$; $p = 0.648$)

A main effect for segment was revealed for Rider ($F = 4.364$; $p = 0.024$), Opponent ($F = 23.09$; $p < 0.001$), Velocity ($F = 6.452$; $p = 0.023$), Cadence ($F = 3.715$; $p = 0.021$), Gearing ($F = 6.365$; $p = 0.014$), RPE ($F = 11.98$; $p < 0.001$), Other ($F = 4.520$; $p = 0.034$), and Total ($F = 21.83$; $p < 0.001$). Post-hoc analysis revealed a decline in the time spent fixating at all these variables over the race, except Other and RPE. Time spent fixating at Other increased per kilometre, while time spent fixating at RPE is higher from the 1st until the 3rd kilometre, likely related to the moment of asking RPE after each kilometre. No effect for segment was found for Screen ($F = 1.376$; $p = 0.267$), Distance ($F = 1.190$; $p = 0.308$), Heart rate ($F = 1.213$; $p = 0.320$), or Time ($F = 1.586$; $p = 0.211$).

A main effect for condition x segment was revealed for Opponent ($F = 5.993$; $p = 0.002$), and Screen ($F = 4.746$; $p < 0.001$). Post-hoc analysis revealed that there is a stronger decline per kilometre in fixation time spent on the opponent during OP-DEP compared to OP-IND. Yet, participants still spent more time fixating at the opponent in every kilometre during OP-DEP compared to OP-IND (all $p < 0.05$; e.g. 1st km: OP-IND = 7.8 ± 3.9 and OP-DEP = 17.4 ± 8.4 sec; 4th km: OP-IND = 3.7 ± 3.9 sec and

Table 6.3 Mean ± SD values for the total fixation time spent (in seconds) and number of fixations per categorised variable per experimental condition over the whole trial.

	NO		OP-IND		OP-DEP	
	Fixation time spent	No of fixations	Fixation time spent	No of fixations	Fixation time spent	No of fixations
Rider [A,B,D,E,F]	7.4 ±5.3	24 ±14	38.6 ±12.9	88 ±38	37.4 ±12.1	123 ±48
Opponent [C,F]	NA	NA	23.3 ±16.6	65 ±30	55.8 ±32.7	130 ±51
Screen	28.6 ±37.7	52 ±35	12.6 ±16.7	34 ±28	11.3 ±9.2	39 ±25
Velocity [A,B,E]	31.1 ±29.8	55 ±37	19.7 ±21.1	38 ±28	15.7 ±28.4	31 ±35
Distance	32.5 ±36.3	69 ±34	23.4 ±16.1	59 ±22	19.1 ±13.2	54 ±24
Cadence [B]	13.7 ±9.8	37 ±25	9.1 ±8.0	31 ±22	6.4 ±4.6	25 ±13
Heartrate	3.5 ±2.8	14 ±7	3.1 ±2.1	13 ±7	2.5 ±2.3	10 ±7
Gearing	1.3 ±1.1	6 ±4	1.6 ±1.1	6 ±5	1.0 ±1.9	5 ±4
Time	9.8 ±7.4	27 ±14	8.1 ±7.8	21 ±14	7.3 ±6.0	21 ±13
RPE [E]	3.1 ±1.6	7 ±3	3.2 ±3.3	6 ±5	2.9 ±2.0	4 ±2
Other	18.2 ±16.8	28 ±21	15.6 ±18.0	23 ±21	15.0 ±24.2	21 ±27
Total [B,C,D,E,F]	149.1 ±51.5	318 ±94	161.6 ±49.4	389 ±85	174.6 ±42.0	462 ±98

[A] difference between NO and OP-IND in fixation time spent ($p < 0.05$), [B] difference between NO and OP-DEP in fixation time spent ($p < 0.05$), [C] difference between OP-IND and OP-DEP in fixation time spent ($p < 0.05$). [D] difference between NO and OP-IND in number of fixations ($p < 0.05$), [E] difference between NO and OP-DEP in number of fixations ($p < 0.05$), [F] difference between OP-IND and OP-DEP in number of fixations ($p < 0.05$).

OP-DEP = 7.7 ± 6.9 sec). In addition, participants spent less time fixating at the screen (excluding avatars) in the first two kilometres of OP-DEP compared to NO (p = 0.041 and p = 0.024, respectively). No differences were found in the second half of the time trial between conditions for Screen. No interaction effect was found for Rider (F = 1.254; p = 0.307), Velocity (F = 2.087; p = 0.124), Distance (F = 0.670; p = 0.560), Cadence (F = 1.230; p = 0.313), Heartrate (F = 1.492; p = 0.194), Gearing (F = 0.677; p = 0.525), Time (F = 0.558; p = 0.762), RPE (F = 0.455; p = 0.839), Other (F = 1.195; p = 0.326), or Total (F = 1.044; p = 0.405).

6.3.3.2 Number of fixations

The analysis for the number of fixations showed a main effect for condition for Rider (F = 32.95; p < 0.001), Opponent (F = 23.20; p = 0.001), Velocity (F = 4.214; p =

0.028), RPE ($F = 3.729$; $p = 0.040$), and Total ($F = 15.83$; $p < 0.001$). Post-hoc analysis revealed an increased number of fixations in total in OP-IND compared to NO ($p = 0.019$), in OP-DEP compared to NO ($p < 0.001$), and in OP-DEP compared to OP-IND ($p = 0.012$). Similarly, an increased number of fixations was shown on the rider in OP-IND compared to NO ($p < 0.001$), in OP-DEP compared to NO ($p < 0.001$), and in OP-DEP compared to OP-IND ($p = 0.004$). Moreover, the number of fixations on the opponent was higher during OP-DEP compared to OP-IND ($p = 0.001$). In contrast, a reduced number of fixations was found in OP-DEP compared to NO for the velocity feedback ($p = 0.041$) and the RPE scale ($p = 0.007$). No effect for condition was reported for Screen ($F = 1.428$; $p = 0.261$), Distance ($F = 2.655$; $p = 0.093$), Cadence ($F = 2.518$; $p = 0.104$), Heartrate ($F = 2.189$; $p = 0.136$), Gearing ($F = 0.249$; $p = 0.782$), Time ($F = 1.204$; $p = 0.319$), or Other ($F = 2.877$; $p = 0.078$)

A main effect for segment was revealed for Opponent ($F = 8.703$; $p < 0.001$), Velocity ($F = 5.107$; $p = 0.005$), Distance ($F = 5.804$; $p = 0.003$), Gearing ($F = 9.507$; $p < 0.001$), RPE ($F = 20.70$; $p < 0.001$), and Other ($F = 4.738$; $p = 0.007$). Post-hoc analysis revealed a reduction in the number of fixations over the race for looking at the opponent, the velocity feedback and the gearing. In contrast, the number of fixations looking at Other increased over the race, while the number of fixations at the distance feedback increased in the final kilometre compared to prior in the race. The number of fixations at RPE is higher from the 1st until the 3rd kilometre, again likely related to the moment of asking RPE after each kilometre. No effect for segment was found for Rider ($F = 3.118$; $p = 0.081$), Screen ($F = 0.836$; $p = 0.434$), Cadence ($F = 0.647$; $p = 0.590$), Heartrate ($F = 1.877$; $p = 0.153$), Time ($F = 1.190$; $p = 0.329$), or Total ($F = 1.505$; $p = 0.231$).

A main effect for condition x segment was revealed for Opponent ($F = 4.051$;

p = 0.015). Post-hoc analysis revealed that there is a steady decline per kilometre in the number of fixations on the opponent during OP-IND, while in OP-DEP there is only a decline in the number of fixations in the ultimate kilometre compared to the penultimate kilometre. In addition, participants fixated more often at the opponent in every kilometre during OP-DEP compared to OP-IND. No interaction effect was found for Rider (F = 0.787; p = 0.584), Screen (F = 2.651; p = 0.059), Velocity (F = 0.780; p = 0.588), Distance (F = 1.384; p = 0.234), Cadence (F = 0.627; p = 0.708), Heartrate (F = 0.674; p = 0.671), Gearing (F = 0.863; p = 0.464), Time (F = 0.128; p = 0.992), RPE (F = 0.682; p = 0.665), Other (F = 2.645; p = 0.083), or Total (F = 1.919; p = 0.091).

6.3.3.3 Mean duration per fixation

The analysis for the mean duration per fixation reported a main effect for condition for Velocity (F = 3.927; p = 0.035), Other (F = 4.167; p = 0.029), and Total (F = 5.496; p = 0.012). Post-hoc analysis reported a decreased duration per fixation when taking all variables together in OP-IND compared to NO (p = 0.038), and in OP-DEP compared to NO (p = 0.011). In addition, a reduced duration per fixation at the velocity feedback was shown in OP-DEP compared to NO (p = 0.022). Post-hoc analysis revealed no differences between conditions for Other. No effect for condition was reported for Rider (F = 3.755; p = 0.070), Opponent (F = 3.468; p = 0.089), Screen (F = 3.068; p = 0.095), Distance (F = 0.466; p = 0.532), Cadence (F = 3.389; p = 0.052), Heartrate (F = 0.104; p = 0.902), Gearing (F = 1.660; p = 0.213), Time (F = 0.120; p = 0.888), or RPE (F = 1.191; p = 0.323).

A main effect for segment was revealed for Rider (F = 4.066; p = 0.015), Opponent (F = 12.77 p < 0.001), Velocity (F = 8.842; p = 0.007), Gearing (F = 2.957; p = 0.047), RPE (F = 6.100; p = 0.011), and Total (F = 6.066; p = 0.002). Post-hoc analysis revealed a decline in the average duration per fixation for all of the above mentioned variables, except RPE. The average duration of a fixation at RPE is longer from the 1st until the 3rd kilometre. No effect for segment was found for Screen (F = 2.578; p = 0.070), Distance (F = 0.576; p = 0.555), Cadence (F = 2.894; p = 0.096), Heartrate (F = 2.343; p = 0.091), Time (F = 2.056; p = 0.163), or Other (F = 0.378; p = 0.770).

A main effect for condition x segment was revealed for Screen (F = 2.911; p = 0.014), Time (F = 2.247; p = 0.049), and Total (F = 3.061; p = 0.011). Post-hoc analysis revealed that the average duration per fixation when taking all variables together was shorter in OP-IND compared to NO in the first kilometre (p = 0.005), and in OP-DEP compared to NO in the first (p = 0.002) and second kilometre (p = 0.015). The average duration per fixation at the screen (excluding avatars) was lower in OP-DEP compared to NO in the second (p = 0.041) and third kilometre (p = 0.029). Post-hoc analysis showed no differences in average duration per fixation at the time feedback. No interaction effect was found for Rider (F = 1.818; p = 0.109), Opponent (F = 2.153; p = 0.112), Velocity (F = 1.103; p = 0.360), Distance (F = 0.619; p = 0.567), Cadence (F = 0.807; p = 0.500), Heartrate (F = 1.268; p = 0.284), Gearing (F = 1.096; p = 0.363), RPE (F = 2.241; p = 0.050), or Other (F = 1.815; p = 0.168).

6.3.4 Overtaking analysis

9 out of 12 participants were able to overtake their opponent in OP-IND and in OP-DEP, while 2 participants only overtook their opponent in OP-IND and 1 participant only overtook his opponent in OP-DEP. In this sense, all participants proved to be able to overtake (and beat) their opponent at least once. The average number of overtakes was 0.9±0.3 in OP-IND and 0.8±0.4 in OP-DEP (p=0.586). Participants decided to wait longer before they overtook their opponent in OP-DEP (overtake at 67 ± 28% of race completion) compared to OP-IND (overtake at 36 ± 34% of race completion; p=0.040).

Table 6.4 Mean ± SD of the fixation time spent per categorised variables prior and after the overtake took place, corrected for the duration of the segment (%).

	OP-IND		**OP-DEP**	
	Pre-overtake	Post-overtake	Pre-overtake	Post-overtake
Rider [A,C]	11.1 ± 11.5	4.9 ± 4.0	9.8 ± 5.3	10.3 ± 6.2
Opponent [A,B,C]	6.0 ± 4.1	4.6 ± 5.3	16.9 ± 7.8	5.7 ± 4.4
Screen	3.8 ± 4.7	5.3 ± 7.2	2.6 ± 2.2	5.3 ± 5.1
Velocity	5.7 ± 8.3	2.6 ± 4.3	5.5 ± 12.0	2.9 ± 5.9
Distance	5.7 ± 6.6	6.1 ± 4.2	3.7 ± 3.3	8.1 ± 8.3
Cadence	2.3 ± 2.5	1.5 ± 1.9	1.9 ± 1.5	1.2 ± 1.0
Heartrate	1.0 ± 0.8	0.4 ± 0.7	0.8 ± 0.8	0.4 ± 0.5
Gearing	1.7 ± 3.1	1.1 ± 2.9	0.4 ± 0.4	0.3 ± 0.6
Time	1.5 ± 1.9	2.4 ± 3.0	2.0 ± 2.1	2.0 ± 1.8
RPE	0.5 ± 0.4	0.4 ± 0.6	0.6 ± 0.4	0.3 ± 0.5
Other	5.7 ± 9.5	5.9 ± 6.3	3.5 ± 6.6	3.9 ± 5.0
Total [B]	45.2 ± 13.9	35.1 ± 14.0	47.8 ± 11.4	40.4 ± 16.5

[A] difference between OP-IND and OP-DEP in fixation time spent ($p < 0.05$), [B] difference between pre-overtake and post-overtake in fixation time spent ($p < 0.05$), [C] difference between pre-overtake and post-overtake between OP-IND and OP-DEP in fixation time spent ($p < 0.05$).

Mean fixation time spent per categorised variables prior and after the overtake took place can be found in Table 6.4. Analysis of the information-seeking behaviour of the participants revealed that the participants were looking for more information in total before the overtake compared to after the overtake ($F = 27.69$; $p = 0.001$), but no differences were found between OP-IND and OP-DEP ($F = 4.686$; $p = 0.059$). Interestingly, a main effect for condition was found for Rider ($F = 5.439$; $p = 0.045$) and Opponent ($F = 14.96$; $p = 0.004$), indicating the participants spent more time fixating on these variables in OP-DEP compared to OP-IND. In addition, a condition x segment interaction effect for Rider and Opponent was found. The time spent fixating at the avatar of the participant itself appeared to decline after the overtake compared to prior in OP-IND, but not in OP-DEP ($F = 9.306$; $p = 0.014$). In contrast, time spent fixating at the avatar of the opponent decreased after the overtake compared to prior in

Table 6.5 The information-seeking behaviour during the 10 seconds prior to the overtake of the virtual opponent in OP-DEP via eye-tracking analysis and retrospective talk aloud analysis (N=10).

.	**OP-DEP**		
	10 seconds prior to overtake		**Retrospective talk aloud**
	Fixation time spent (in sec)	Number of fixations	Frequency
Rider	1.3 ± 0.9	5 ± 2	25
Opponent	1.6 ± 0.8	5 ± 2	11
Screen	0.4 ± 0.4	1 ± 1	3
Velocity	0.4 ± 0.8	1 ± 2	19
Distance	0.6 ± 0.7	2 ± 2	23
Cadence	0.2 ± 0.2	1 ± 1	0
Heartrate	0.1 ± 0.2	0 ± 0	1
Gearing	0.0 ± 0.1	0 ± 0	5
Time	0.3 ± 0.7	0 ± 1	5
RPE	0.0 ± 0.0	0 ± 0	8
Other	0.1 ± 0.3	0 ± 1	2
Total	5.0 ± 1.4	16 ± 3	-

OP-DEP, but not in OP-IND ($F = 25.21$; $p = 0.001$). Finally, a main effect for segment was found for the fixation time spent at the virtual opponent ($F = 27.71$; $p = 0.001$), indicating a reduction after the overtake compared to prior. No differences were found for the other variables in fixation time spent.

The information-seeking behaviour during the 10 seconds prior to the overtake of the virtual opponent in OP-DEP and the outcomes of the retrospective talk aloud analysis can be found in Table 6.5. The retrospective think aloud analysis after OP-DEP revealed that prior to the overtake most of the participants (8 out of 10 who overtook their opponent in OP-DEP) monitored the distance between themselves and their opponent continuously in order to stay positioned closely behind their virtual opponent until the overtake took place (e.g. *"My constant focus most of the time was* *just that distance between myself* and *the opponent"*). The moment to overtake appeared to occur when the participant perceived himself capable to cover the remaining distance without significant deceleration (e.g. "*I basically knew that I had to stay behind the opponent until I was at a point where I could be comfortable I could maintain a pace to keep ahead*"), as indicated by 9 out of 10.

6.4 Discussion

The present study examined how a change in the interdependency between the athlete and the opponent would affect exercise regulation and information-seeking behaviour. It appeared that cyclists adopted a slower initial pace and decided to wait longer before overtaking their opponent when they became more dependent on their competitor. Furthermore, a change in information-seeking behaviour was revealed. That is, participants were looking for more information in OP-DEP, mainly due to an increased focus on the avatars of themselves and their opponents, while focussing less on their velocity and cadence feedback.

The presence of a virtual opponent has been shown to improve time-trial performance (Chapter 4; Williams *et al.,* 2015a, 2015b; Stone *et al.,* 2012; Corbett *et al.,* 2012). However, in the present study no such an effect has been found. This lack of an effect might be related to the received feedback by the participants during the time trials. In particular the timer feedback may have evoked a competitive environment in which the participants were able to start competing against their own previous performance, as they were aware of their own finishing times. Indeed, Schiphof-Godart *et al.,* (2017) showed that the performance effect when riding against a virtual opponent returned when the same feedback without the timer was presented to trained cyclists. In addition, the constructed virtual avatar in this study was set up to be slightly slower compared to the participant's best familiarisation trial (ca. 2-3 seconds) in order to make sure participants were able to overtake their opponent in normal conditions. As a result, simply beating the virtual opponent would not have led to an improvement in performance compared to riding alone. Interestingly, the faster initial pace of the opponent did not evoke a noticeable response in the participants when no restrictions were provided to the participant, in contrast to previous findings (see Chapter 4). Again, this finding may likely be related to the received feedback during the time trials in general, and the timer feedback in particular (Schiphof-Godart *et al.,* 2017).

Manipulation of the interdependency between competitors did appear to alter the pacing behaviour of the participants. Comparable effects were found by observational studies looking into pacing strategies during real-life competitions as shown in the literature review in Chapter 2. For example, the pacing strategies of athletes are similar to the optimal pacing strategies as predicted in modelling studies when the performance of the individual athlete is relatively independent of the other competitors, such as in time trial sports (Hettinga *et al.,* 2011; Hettinga *et al.,* 2012), or sports were individuals compete in separate lanes (Mauger *et al.,* 2012; Lipińska *et al.,* 2016a, 2016b; Hanon and Gajer, 2009; Muehlbauer and Melges, 2011). In contrast, exercisers tend to adjust their pacing behaviour based on their competitors when competing in the same lane (Noorbergen *et al.,* 2016; Hettinga *et al.,* 2016; Konings *et al.,* 2016; Moffatt *et al.,* 2014; Hanley, 2015; Hanley, 2016). This effect becomes even more apparent when the interdependency between competitors is further increased, for example via the aerodynamic beneficial effect of drafting behind an opponent (e.g. in cycling/speed skating; Moffatt *et al.,* 2014; Konings, Noorbergen, *et al.,* 2016), or during important events such as the Olympic Games (Thiel *et al.,* 2012). In this perspective, our findings support the hypothesis that the interdependency between competitors could be a crucial promotor for these differences in chosen pacing behaviour between different competitive sports. Similar to typically used strategies in cycling and short track speed skating competitions, our participants decided to wait longer before they overtook their opponent when they became more interdependent on their competitor.

The analysis of gaze behaviour provides a novel opportunity to analyse the information-seeking behaviour of exercisers (Boya *et al.*, 2017). In line with previous research (Brick *et al.*, 2016; Williams *et al.*, 2015b; Lohse and Sherwood, 2011), our findings support a change over the race in attentional focus from external to internal variables, indicated by the reduction in total fixation time spent and the number of fixations over the race for most of the variables. A notable exception in this case is the increase in number of fixations at the distance feedback in the final kilometre compared to prior in the race. A similar finding was reported by Whitehead *et al.*, (2017) using a think aloud procedure, showing an increased number of verbalisations related to distance in the last quartile of 16.1 km cycling time trials. Riding against a virtual opponent made the participants start looking for more information over the whole trial, in particular due to an increased focus on the avatar of the participant itself. At the same time a decline in attentional focus on the velocity feedback can be noted when riding against an opponent. These results seem to be in line with the self-reported reduced internal attentional focus of cyclists in the presence of a virtual competitor (Williams *et al.*, 2015b). The manipulation of the interdependency between athlete and opponent mainly affected the attentional focus on the virtual opponent. That is, when participants became more dependent on their opponent the total fixation time and the frequency of fixations at this virtual opponent increased drastically. In addition, an increase in the number of fixations, but not in total fixation time spent, on the avatar of the participant itself is noted in the high interdependency condition. This could be an indication of a frequent monitoring of the distance in between the avatar of the participant and the avatar of the opponent during the time trial.

Indeed, when analysing the overtake in the OP-DEP trial, 8 out of the 10 participants who managed to overtake their opponent in this condition mentioned to have monitored the distance between themselves and their opponent in order to stay positioned closely behind their virtual opponent until the overtake took place. Moreover, time spent fixating at the avatar of the opponent decreased after the overtake compared to prior in OP-DEP, but not in OP-IND. Interestingly, in OP-IND the attentional focus on the avatar of the participant itself appeared to decline after the overtake compared to prior, while it remained the same in OP-DEP.

The instruction to allow only one overtake of the virtual opponent in OP-DEP created a recognisable and similar decision-making moment in time for all the participants. In this sense, the time period right before the overtake may provide insight into the information that is used leading to the decision to overtake the other competitor. According to the eye tracking analysis, the most frequently searched information sources in the ten seconds prior to the overtake were both avatars, in combination with the distance feedback. This is supported by the retrospective talk aloud procedure, in which 9 out of 10 participants mentioned that they decided to overtake their opponent when they perceived themselves capable to cover the remaining distance without significant deceleration.

6.5 Conclusion

Our findings highlight that the information-seeking behaviour of exercisers during time trial exercise depends on the circumstances in which the exerciser has to act. The presence of competition, and even the relationship between the competitors in this competition, could affect which information you would like to present to the exerciser. Furthermore, not only the opponent's behaviour, but also the interdependency between the athlete and the opponent appeared to be crucial in the decision-making process involved in pacing, highlighting the importance of athlete-environment interactions in the context of pacing. In this perspective, the findings of the present study provide additional support for the assumption that the circumstances in which the exerciser has to act, affect how exercisers decide to act upon (the same) external variables presented towards the exerciser, such as an opponent. Finally, the interdependency between athlete and opponent could be a crucial underlying mechanism for the differences in pacing behaviour that can be observed between different competitive sports.

PART IV – THE INTERNAL STATE OF THE EXERCISER

CHAPTER 7

The effect of preceding high-intensity race efforts on pacing and performance of elite short track speed skaters

Citation

Konings, M.J. and Hettinga, F.J. (2018). The effect of preceding high-intensity race efforts on pacing and performance of elite short track speed skaters. International journal of sport physiology and performance. 1-23. DOI:10.1123/ijspp.2017-0637 [epub ahead of print]

. ---

Abstract

The present study examined whether preceding high-intensity race efforts in a competitive weekend affected pacing behaviour and performance in elite short track speed skaters. Finishing and intermediate lap times were gathered from 500, 1000 and 1500 m Short Track Speed Skating World Cups during the seasons 2011-2016. The effect of preceding races on pacing behaviour and performance was explored using two different analytic approaches. *Study 1*. The effect of competing in extra races due to the Repechage (Rep) system, leading to an increased number of high-intensity race efforts prior to the subsequent main tournament race, was explored (500 m: N = 32, 1000 m: N = 34; 1500 m: N = 47). An additional number of preceding high-intensity race efforts due to the Rep system reduced the qualification percentage in the first main tournament race for the next stage of competition in all events (500 m: Direct qualification = 57.3%, Rep = 25.0%; 1000 m: Direct = 44.2%, Rep = 28.3%; 1500 m: Direct = 27.1%, Rep = 18.2%), and led to a decreased pace in the initial two laps of the 500 m event. *Study 2*. Secondly, the performance of skaters over the tournament days was evaluated (500 m: N = 129, 1000 m: N = 54; 1500 m: N = 114). For both analytic approaches, a two-way repeated measures ANOVA was used to assess differences in pacing and performance within the skater over the races. Tournament day (Saturday vs Sunday) only affected the pacing behaviour of female skaters during the 1500 m event. In conclusion, high-intensity race efforts earlier on the day affected pacing and performance of elite skaters, while the effect of high-intensity race efforts from the previous day seem to be only marginal.

7.1 Introduction

Up until now, this thesis has demonstrated the effects of the behaviour of an opponent on pacing regulation, and illustrated that the decision how to act upon presented action possibilities is related to the competitive environment. In the upcoming chapters, the primary focus will be on the importance of the action capabilities of the exerciser and its effect on exercise regulation during competition. Many studies have suggested that the sensations of fatigue have a crucial impact on the decision-making process regarding exercise regulation and performance (Smits *et al*., 2014; Enoka and Duchateau, 2016; Marcora, 2008; Swart *et al*., 2009; Roelands *et al*., 2013). Indeed, many theories on pacing regulation emphasise the importance of fatigue sensation and willingness to tolerate discomfort (in anticipation of future rewards) for the regulation of the exercise intensity (Smits *et al.*, 2014).

Previous laboratory studies indicated that higher levels of muscle fatigue before the start of a race, caused by a pre-fatiguing protocol, affected performance and resulted in a slower initial pace (Amann and Dempsey, 2008; Correia-Oliveira *et al.*, 2014; De Morree and Marcora, 2013). In addition, Skorski *et al.* (2015) revealed that cyclists adopted a more conservative starting pace after an intensive training period. In this sense, an accumulation of fatigue has been shown to decrease maximal heart rate, blood lactate concentrations, and oxygen uptake (Meeusen *et al.*, 2013; Halson, 2014), effects most likely related to a reduced activation of the sympathetic nervous system (Jeukendrup *et al.*, 1992).

Nevertheless, how the effect of an accumulation of fatigue sensations impacts on the decision-making process involved in pacing during head-to-head competitive situations is not yet well known, let alone how this is relevant in real-life sports performance practice. In many sports, athletes have to complete several races within a short period of time during their competitions (e.g., stage races, heats), possibly leading to an accumulation of fatigue due to the repetitive high intensity efforts that are conducted, before the finals take place. For example, road cyclists compete on 90–100 competition days per year, comprising 1 day races, 1 week tour races, and 3 week tour races (Abbiss and Laursen, 2005). Similarly, elite short track speed skaters typically skate multiple races a day for three days in a row during a competition weekend.

To perform optimally in head-to-head competitions, one is required to balance the optimal distribution of the available energy resources against possible tactical advantages or disadvantages (Hettinga *et al.*, 2017). As a result, each race may not require the use of all available energy stores, and finishing times are irrelevant as long as you finish in front of your opponents (Konings *et al.*, 2016; Hettinga *et al.*, 2017). Indeed, in sports such as cross-country running (Hanley, 2014), middle-distance running (Renfree *et al.*, 2014b), rowing (Edwards *et al.*, 2016), track cycling (Moffatt *et al.*, 2014), and short track speed skating (Konings *et al.*, 2016; Noorbergen *et al.*, 2016), athletes did not adopt the theoretical optimal pacing strategy, most likely due to tactical considerations. As a result, the impact of preceding high-intensity efforts on pacing and performance could likely be smaller compared to what has been reported on time-trial exercise.

In the present study elite competitive data will be used to examine whether preceding high-intensity race efforts in a competitive weekend affects pacing behaviour and performance in elite short track speed skating. To do this, two different analytical approaches are employed, using the competition structure of short track speed skating world cups. Firstly, the effect of preceding high-intensity race efforts within a day on the first main tournament race are analysed, by using the repechage system as an 'intervention'. That is, those athletes who had to qualify via this system needed to complete an additional number of races during the day prior to the first main tournament race. Secondly, differences in pacing and performance between days within a competitive weekend are explored. On Sunday, more preceding high-intensity races have been completed than on Saturday, when athletes start relatively fresher. It is hypothesised that a higher number of preceding high-intensity race efforts would evoke a more conservative initial pace, possibly resulting in a decreased performance.

7.2 Methods

7.2.1 Participants and data acquisition

Finishing and intermediate lap times were gathered for men and women from all 500 m (4.5 laps), 1000 m (9 laps) and 1500 m (13.5 laps) Short Track Speed Skating World Cups during the seasons 2011/12 until 2015/16. In total, 28 indoor short track speed skating World Cup tournaments were analysed. This resulted in 9423 skating performances for the 500 m, 9320 skating performances for the 1000 m, and 7447 skating performances for the 1500 m that were examined. Lap times were measured using electronic time-measuring systems based on optical detectors that started automatically by the firing of a starting-gun and automatically recorded the time in which the finish line was reached by each competitor. The International Skating Union (ISU) demands that lap times are recorded with the accuracy of at least a hundredth of a second. Therefore, for every automatic timekeeping system a certificate stating the reliability and accuracy of the system had to be presented to the referee before the tournament, ensuring that all systems recorded with the accuracy of at least a hundredth of a second. No written consent was given by participants as all data used are publicly available at the ISU website (http://www.sportresult.com/federations/ISU/ShortTrack/)

and no interventions occurred during the data collection. The study was approved by the local ethical committee and was in accordance with the Declaration of Helsinki.

7.2.2 Study I – Repechage effect

Each short track world cup tournament consisted of qualification stages in which a skater had to qualify for the main tournament. One could proceed to the next stage of the tournament by finishing in first or second position, or as a fastest time qualifier who did not already qualify via their finish position in some stages of the tournament of some world cups. A schematic overview of a typical short track world cup race weekend can be found in Figure 7.1. The qualification stages took place in general on Friday, followed by the main tournament days on Saturday and Sunday. The main tournament starts with the quarterfinal for the 500 m and 1000 m event, while this is the semi-final for the 1500 m. Most short track speed skaters qualify for the main tournament directly via the qualification stages. However, there is an alternative way to reach the main tournament for the speed skaters who did not qualify on first hand, the so-called repechage system. All short track speed skaters who did not qualify directly for the main tournament can compete in this repechage competition. Using a similar system as the qualification stages, a short track speed skater has to proceed in two or three stages of the repechage competition. Finally, the first one or two finishers in the final stage of the repechage competition are added to the main tournament. These repechage races take place in the morning before the start of the main tournament races later on that day in the afternoon/evening. There was no repechage competition during the World Cups in the Olympic season 2013/14. Therefore, all races performed in this season were excluded from the analysis.

To examine the effect of the extra races involved in the repechage competition on pacing and performance of elite short track speed skaters during the first main tournament race (i.e. the quarter final race for the 500 and 1000 m event, and the semi-final race for the 1500 m event), skaters who have qualified themselves both directly (control condition) as well as via the repechage system ('intervention') were identified. This resulted in 32 skaters (17 men, 15 women) for the 500 m event, 34 skaters (16 men, 18 women) for the 1000 m event, and 47 skaters (23 men, 24 women) for the 1500 m event out of the collected database who fulfilled the criterion of qualification via both ways and were included into the analysis. Lap times and finishing times of these speed skaters in their first main tournament race (i.e. the quarter final race for the 500 and 1000 m event, and the semi-final race for the 1500 m event) were retrieved and analysed.

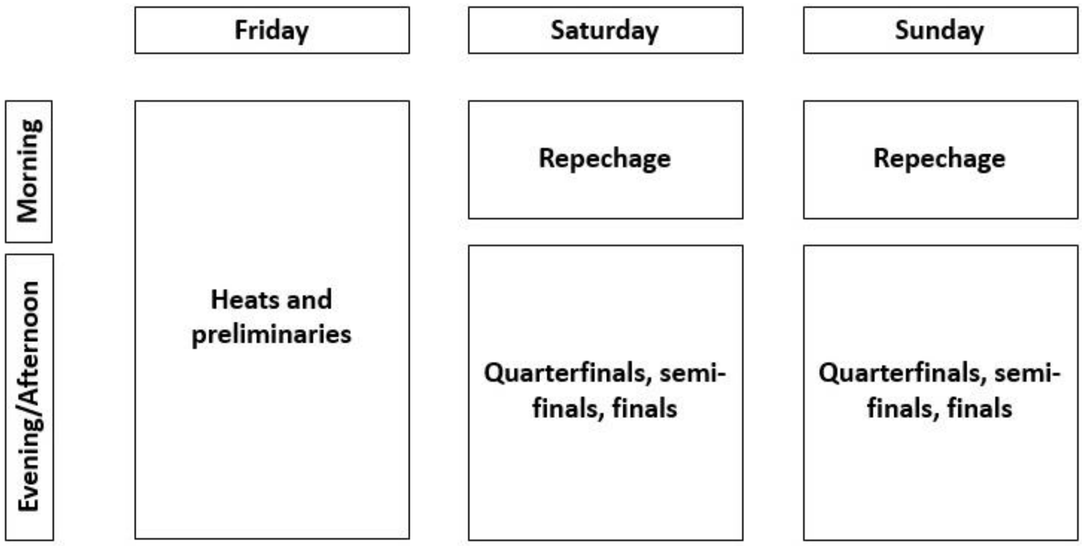

Figure 7.1 Schematic overview of a typical short track world cup race weekend.

7.2.2.1 Statistical analysis

Differences between direct qualification or qualification via the repechage competition on the pacing and performance of short track speed skaters in their subsequent first main tournament race were assessed using a two-way repeated measures ANOVA (Qualification x Laps) for each event. Sex was added as between-subject factor. A

Greenhouse-Geisser correction was used when sphericity could not be assumed. All analyses were performed using SPSS 19.0, and significance was accepted at $p < 0.05$. If appropriate, post-hoc analyses were performed using a Bonferroni correction. Finally, the percentage of short track speed skaters from both Qualification groups that qualified for the next stage of the tournament (i.e. semi-final for the 500 and 1000 m event; final for the 1500 m event) in the main tournament was determined. Chi-square tests were used to compare these percentages to the expected qualification percentage in that stage of the tournament. The expected values were set at 50% (typically two out of four competitors qualify for the next stage of the tournament) for the 500 and 1000 m and 33% (two out of six competitors) for the 1500 m.

7.2.3 Study II –Tournament day

During each short track world cup tournament, except for the world cups in the Olympic season 2013/2014, four individual events were organised per world cup. That is, each individual discipline (500, 1000, 1500 m) was organised at least once, but one of the disciplines was performed twice during the weekend. When the same discipline was organised twice in a weekend, the first one was always fully completed on Saturday, and the second one always on Sunday.

To examine the effect of the tournament day on pacing and performance of elite short track speed skaters during the main tournament, skaters who competed in the main tournament for the same event in the same competitive weekend on both days were identified. This resulted in 129 skaters (65 men, 64 women) for the 500 m event, 54 skaters (27 men, 27 women) for the 1000 m event, and 114 skaters (57 men, 57 women) for the 1500 m event out of the collected database who fulfilled the criterion and were included into the analysis. Lap times and finishing times of these speed skaters on both days were retrieved and analysed. In addition, the final stage of the tournament achieved by the short track speed skater was noted.

7.2.3.1 Statistical analysis

Differences in pacing and performance between tournament days were assessed using a two-way repeated measures ANOVA (Day x Laps) for each event. Sex and the final stage of competition achieved by the short track speed skater on Saturday were added as between-subject factors. A Greenhouse-Geisser correction was used when sphericity could not be assumed. All analyses were performed using SPSS 19.0, and significance was accepted at $p < 0.05$. If appropriate, post-hoc analyses were performed using a Bonferroni correction.

7.3 Results

7.3.1 Study I – Repechage effect

Mean (± SD) lap times and finishing times for direct qualification and qualification via repechage are shown in Table 7.1. Main effects for Qualification ($F = 4.89$; $p = 0.035$), Laps ($F = 2972.7$; $p < 0.001$), and Sex ($F = 437.2$; $p < 0.001$) were found for the 500 m event. An interaction effect was revealed for Qualification x Laps ($F = 3.49$; $p = 0.024$), indicating differences in pacing between direct and repechage qualification. No interaction effects were found for Qualification x Sex ($F = 0.23$; $p = 0.633$), Laps x Sex ($F = 1.10$; $p = 0.353$), or Qualification x Sex x Laps ($F = 1.13$; $p = 0.339$). Post-hoc analysis revealed that short track speed skaters were slower in the initial two laps of the 500 m when they qualified via the repechage compared to when they qualified directly for the quarterfinals.

Table 7.1 Mean ± SD of the lap times and finishing times in seconds for the short track speed skaters when qualified directly or qualified via the repechage (Rep) system for all events. Moreover, the percentage of short track speed skaters that qualified for the next stage of the tournament after short track speed skaters did or did not ride Rep.

	500 m (N=32)		**1000 m** (N=34)		**1500 m** (N=47)	
	Direct	**Rep**	**Direct**	**Rep**	**Direct**	**Rep**
Lap 1	7.26±0.32*	7.38±0.27	13.24±0.44	13.34±0.55	9.65±0.73	9.70±0.75
Lap 2	9.17±0.31*	9.24±0.35	10.02±0.30	10.09±0.39	13.15±1.29	13.17±1.10
Lap 3	8.70±0.30	8.75±0.33	9.78±0.36	9.78±0.39	12.10±1.01	11.95±0.94
Lap 4	8.85±0.31	8.88±0.37	9.66±0.35	9.65±0.37	11.45±0.80	11.37±0.88
Lap 5	9.11±0.31	9.10±0.34	9.56±0.35	9.52±0.39	10.90±0.72	10.85±0.71
Lap 6			9.46±0.34	9.48±0.39	10.46±0.64	10.39±0.59
Lap 7			9.45±0.40	9.44±0.38	10.10±0.51	10.08±0.52
Lap 8			9.51±0.37	9.54±0.36	9.87±0.42	9.90±0.44
Lap 9			9.77±0.37	9.74±0.36	9.77±0.40	9.79±0.40
Lap 10					9.63±0.31	9.65±0.36
Lap 11					9.53±0.31	9.59±0.37
Lap 12					9.52±0.34	9.59±0.39
Lap 13					9.64±0.38	9.72±0.45
Lap 14					9.92±0.45	10.11±0.67
Finish	43.00±1.53*	43.26±1.58	90.44±2.89	90.58±2.91	145.69±6.59	145.85±5.75
Qualify next stage	57.3%	25.0% †	44.2%	28.3% †	27.1%	18.2% †

*Significant difference compared to repechage qualification (P < 0.05)

†Significant difference compared to expected qualification rate for next stage (50.0% for 500 and 1000 m and 33.3% for 1500 m, respectively)

Main effects for Laps (F = 4093.8; p < 0.001) and Sex (F = 385.8; p < 0.001), but not for Qualification (F = 0.270; p = 0.607) were reported for the 1000 m event. No interaction effects were found for Qualification x Laps (F = 0.940; p = 0.422), Qualification x Sex (F = 0.402; p = 0.531), Laps x Sex (F = 1.88; p = 0.151), or Qualification x Sex x Laps (F = 0.476; p = 0.693) in the 1000 m event.

Main effects for Laps (F = 342.3; p < 0.001) and Sex (F = 108.0; p < 0.001), but not for Qualification (F = 0.09; p = 0.766) were reported for the 1500 m event. No interaction effects were found for Qualification x Laps (F = 0.974; p = 0.412), Qualification x Sex (F = 2.71; p = 0.107), Laps x Sex (F = 2.06; p = 0.130), or

Qualification x Sex x Laps (F = 1.53; p = 0.205) in the 1500 m event. The percentage of all short track speed skaters from both Qualification groups that qualified for the next stage of the tournament (i.e. semi-final for the 500 and 1000 m event; final for the 1500 m event) in the main tournament can be found in Table 7.1 for all events. The chi-square tests revealed a reduction in the percentage of short track speed skaters that qualified for the next stage of the tournament in relation to what could be expected for all events after qualification via the repechage system (500 m: p = 0.007; 1000 m: p = 0.024; 1500 m: p = 0.024), but not after direct qualification (500 m: p = 0.597; 1000 m: p = 0.608; 1500 m: p = 0.255).

7.3.2 Study II –Tournament day

Mean (± SD) lap times and finishing times for Saturday and Sunday races are shown in Table 7.2. Main effects for Laps (F = 4148.9; p < 0.001), Sex (F = 405.6; p < 0.001), and End stage (F = 7.01; p = 0.001), but not for Day (F = 2.11; p = 0.149), were found for the 500 m event. An interaction effect was reported for Laps x Sex (F = 10.40; p < 0.001), indicating differences in pacing between Sex. That is, female short track speed skaters appear to slow down more than their male counterparts in the final two laps, independent of tournament day. No effect was found for Day x Laps (F = 1.017; p = 0.388), Day x Sex (F = 0.509; p = 0.477), Day x End stage (F = 0.108; p = 0.898), Day x Laps x Sex (F = 0.369; p = 0.786), or Day x Laps x End stage (F = 1.129; p = 0.344).

Main effects for Laps (F = 899.5; p < 0.001) and Sex (F = 42.97; p < 0.001), but not for Day (F = 0.072; p = 0.789) or End stage (F = 0.477; p = 0.623), were revealed for the 1000 m event. Interaction effects were reported for Day x Sex (F = 5.879; p = 0.019), Day x Laps x Sex (F = 3.729; p = 0.022), and Day x Laps x Sex x End stage (F = 3.556; p = 0.006), indicating pacing and performance over the days differs between men and women. However, post-hoc analysis revealed no differences in pacing between days for men or women. Similarly, no performance effects between days were found, although there seems to be a tendency towards a faster performance for female short track speed skaters on Saturday (Finish time = 93.06 ± 1.58s) compared to Sunday (Finish time = 93.66 ± 2.09s; p = 0.057). No effect was found for Day x Laps (F = 0.992; p = 0.383), Day x End stage (F = 0.383; p = 0.684), Laps x Sex (F = 1.487; p = 0.229), Day x Laps x End stage (F = 0.632; p = 0.663).

Main effects for Laps (F = 370.5; p < 0.001) and Sex (F = 85.04; p < 0.001), but not for End stage (F = 1.433; p = 0.234), were revealed for the 1500 m event. The main effect for Day was non-significant (F = 3.885; p = 0.051). Interaction effects were found for Day x Laps (F = 4.027; p = 0.011) and Day x Laps x Sex (F = 3.468; p = 0.021), indicating a difference in pacing between days and pacing over the days differs between men and women (see Table 7.2 and Figure 7.2). No interaction effect was found for Day x Sex (F = 1.163; p = 0.283), Day x End stage (F = 3.353; p = 0.070), Laps x Sex (F = 1.302; p = 0.273), or Day x Laps x End stage (F = 0.934; p = 0.415).

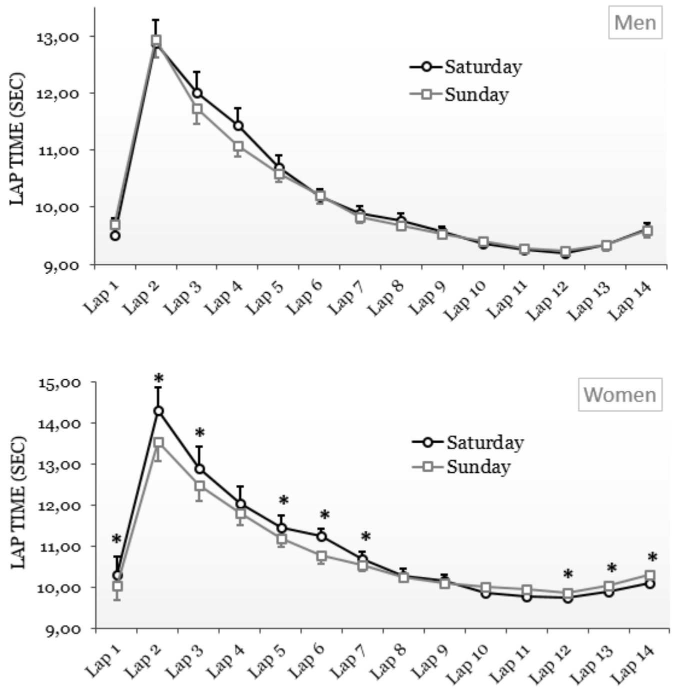

Figure 7.2 Mean (±95% CI) lap times per day for the 1500 m event for male (N=57) and female short track speed skaters (N=57).

* Significant difference in lap time between days (p < 0.05)

Table 7.2 Mean ± SD of the lap times and finishing times in seconds for the short track speed skaters on the Saturday and Sunday races for all events.

	500 m (N=129)		**1000 m** (N=54)		**1500 m** (N=114)	
	Saturday	**Sunday**	**Saturday**	**Sunday**	**Saturday**	**Sunday**
Lap 1	7.23±0.29	7.23±0.29	13.51±0.58	13.65±0.74	9.90±1.18	9.86±0.94
Lap 2	9.22±0.29	9.25±0.30	10.24±0.52	10.32±0.55	13.59±1.61	13.24±1.23
Lap 3	8.75±0.32	8.80±0.32	9.91±0.45	9.93±0.45	12.45±1.44*	12.12±0.06
Lap 4	8.93±0.33	8.94±0.35	9.70±0.31	9.65±0.39	11.74±1.17*	11.44±0.80
Lap 5	9.17±0.35	9.19±0.36	9.58±0.35	9.65±0.39	11.08±0.87*	10.89±0.65
Lap 6			9.48±0.35	9.49±0.40	10.71±0.70*	10.49±0.56
Lap 7			9.47±0.36	9.40±0.35	10.28±0.65	10.18±0.52
Lap 8			9.46±0.37	9.45±0.35	10.01±0.53	9.96±0.39
Lap 9			9.70±0.42	9.62±0.43	9.86±0.48	9.82±0.42
Lap 10					9.62±0.34	9.70±0.38
Lap 11					9.52±0.34	9.60±0.41
Lap 12					9.47±0.35*	9.55±0.38
Lap 13					9.61±0.39	9.68±0.47
Lap 14					9.85±0.46	9.95±0.59
Finish	43.30±1.46	43.43±1.49	91.04±2.70	91.13±3.16	147.69±7.45	146.48±5.63

*Significant difference between days ($p < 0.05$)

7.4 Discussion

The present study showed that the additional number of preceding high-intensity race efforts due to the repechage system led to a slower initial pace in the following quarterfinal of the 500 m event. Moreover, qualification to the main tournament via the repechage system, compared to when these same skaters qualified directly for the main tournament, resulted in a reduction of the percentage of skaters that qualified in the subsequent quarterfinal race (500 and 1000 m event) or semi-final race (1500 m event) for the subsequent stage of the tournament (i.e. semi-final for the 500 m and 1000 m event; final for the 1500 m event) in the main tournament for all events (See Table 7.1). In contrast, the tournament day did not evoke any differences in pacing or performance for male short track speed skaters, indicating there is enough time to recover from the high-intensity race efforts one day prior. However, some minor differences in the chosen pacing behaviour and performance were found for female short track speed skaters during the 1500 m event, indicating a faster initial pace and slower finishing pace on Sunday compared to Saturday.

Our findings indicate that the efforts required to utilise the second chance provided by the repechage system in short track speed skating could have a detrimental effect on the performance of skaters in the subsequent first main tournament race. For example, the start has been reported as crucial for the outcome of the race in the 500 m event (Haug *et al.,* 2015; Noorbergen *et al.,* 2016; Maw *et al.,* 2006). In this sense, the slower initial pace as found in the first main tournament race after skating the additional races of the repechage could impair the performance of the skater, and gives the skater a disadvantage compared to other competitors that did not had to skate these extra races. Interestingly, skating in the repechage competition several hours before the main tournament did not led to a change in pacing during the first main tournament race of the 1000 and 1500 m event. The lack of an effect in pacing could likely be related to the relatively slow, tactical start of most 1000 and 1500 m races (Konings *et al.,* 2016; Noorbergen *et al.,* 2016). Nevertheless, in terms of performance it still appears that the percentage of skaters that qualified in the first main tournament race for the next stage of competition in the main tournament did reduce significantly when they had competed in the repechage competition.

Intuitively, one may argue that the group qualified via the repechage system is of a qualitatively lower level of performance. However, the author would like to emphasise that the compared groups both consist of the exact same skaters, as only skaters were included into the analysis if they have qualified for the main tournament via both the repechage system as well as via direct qualification. In addition, in order to establish qualification via the repechage system, a skater is required to perform well in 2-3 subsequent races. An alternative explanation might be that due to the extra races of the repechage competition, the ability to overtake others in that decisive final part of the race is affected rather than the average pace. This would once again emphasise the importance of tactical positioning in head-to-head structured competition in general (Hettinga *et al.,* 2017; Jones and Whipp, 2002; Renfree *et al.,* 2014b; Hanley, 2014; Moffatt *et al.,* 2014), and in short track speed skating in particular (Noorbergen *et al.,* 2016; Konings *et al.,* 2016).

When comparing Sunday races to Saturday races, short track speed skaters did not seem to make any major adjustments in their pacing behaviour. In this perspective, a possible way to level the playing field for all contenders could be to complete the repechage races on the same day as the qualification races (typically the Friday; see Figure 7.1), rather than on the tournament day itself as happens currently. That is, our findings indicate that there is sufficient time from one day to the other to recover from the efforts of the day before. Completing the repechage races on Friday would then provide sufficient recovery time and an equal level of playing field for all contenders in the main tournament. The only difference in pacing between days was found for the women's 1500 m event. Surprisingly, the female 1500 m skaters adopted a faster initial pace on Sunday races in comparison to Saturday races. Possibly, differences in overtaking behaviour may be related to this sex difference. Female 1500 m skaters have been shown to overtake less frequently in the decisive final stages of a race compared to their male counterparts (Al *et al.,* 2016). Alternatively, the slower initial pace on Saturday races might be anticipation of the efforts required in upcoming races later on the day, or the day after.

As demonstrated in Chapter 5, several external cues could impact the chosen pacing behaviour of elite short track speed skaters. It was attempted to control for or minimise the effects of these variables in our analysis within reasonable limits. For example, only races in similar stages of competition were analysed. Moreover, proceeding to the next stage of the tournament as a fastest time qualifier was not possible in any of our included races. Furthermore, both groups in both analytical approaches consist of the exact same pool of participants, using a within-subject analysis.

7.5 Conclusion

The present study is the first to examine the effect of preceding high-intensity race efforts on pacing and performance in head-to-head competitions. As demonstrated in this study, completion of additional races on the same race day appears to evoke a change in the decision-making process involved in pacing and negatively affected the performance of elite short track speed skaters. At the same time, races completed on the day before do not seem to have a major impact on pacing and performance in elite short track speed skating competitions. In this perspective, a reschedule in the planning of the repechage races during the tournament weekend is advised to level the playing field for all contenders during the main tournament.

CHAPTER 8

Racing an opponent alters pacing, performance and muscle force decline, but not RPE

Citation

Konings, M.J., Parkinson, J., Zijdewind, I., and Hettinga, F.J. (2017). Racing an opponent alters pacing, performance and muscle force decline, but not RPE. International journal of sport physiology and performance. 1-24. DOI:10.1123/ijspp.2017-0220. [Epub ahead of print]
. --

Abstract

Performing against a virtual opponent has been shown to invite a change in pacing and improve time trial performance. This study explored how this performance improvement is established by assessing changes in pacing, neuromuscular function and perceived exertion. After a peak power output test and a familiarisation time trial, twelve trained cyclists completed two 4-km time trials in randomised order on a Velotron cycle ergometer. Time trial conditions were riding alone (NO), and riding against a virtual opponent (OP). Knee-extensor performance was quantified before and directly after the time trial using maximal voluntary contraction force (MVC), voluntary activation (VA) and potentiated doublet-twitch force (PT). Differences between the experimental conditions were examined using Repeated-measures ANOVAs. Linear regression analyses were conducted to associate changes in pacing to changes in MVC, VA and PT. OP was completed faster than NO (mean power output OP: 289.6 ± 56.1 W vs. NO: 272.2 ± 61.6 W; p = 0.020), mainly due to a faster initial pace. This was accompanied by a greater decline in MVC (MVCpre-vs-post: -17.5 ± 12.4% vs. -11.4 ± 10.9%, P = 0.032) and PT (PTpre-vs-post: -23.1 ± 14.0% vs. -16.2 ± 11.4%, P = 0.041) after OP compared to NO. No difference between conditions was found for VA (VApre-vs-post: -4.9 ± 6.7% vs. -3.4 ± 5.0%, P = 0.274). RPE did not differ between OP and NO. In conclusion, the improved performance when racing against a virtual opponent was associated with a greater decline in voluntary and evoked muscle force compared to riding alone, without a change in perceived exertion, highlighting the importance of human-environment interactions in addition to one's internal state for pacing regulation and performance.

8.1 Introduction

Based on the existing theories about pacing, it can be concluded that sensations of fatigue and a willingness to tolerate discomfort (in anticipation of future rewards) are important in this process of action regulation (Smits *et al.*, 2014). Concepts such as teleoanticipation (Ulmer, 1996) and template formation (Foster *et al.*, 2009) have been pointed out as crucial in the process. In addition, the importance of the interaction between the exerciser and environmental cues has been emphasised recently in the context of pacing (Smits *et al.*, 2014; Hettinga *et al.*, 2017). Perceptual cues provided by the environment can invite athletes to respond, thereby evoking adaptations of pacing behaviour (Smits *et al.*, 2014; Hettinga *et al.*, 2017). In this sense, an opponent can be perceived as an important environmental cue that represents action possibilities to an athlete in competitive sports (Hettinga *et al.*, 2017).

Indeed, the presence of a virtual opponent has been shown to improve cycling performance (Chapter 3; Corbett *et al.*, 2012; Williams *et al.*, 2015a, 2015b; Wilmore, 1968), and the pacing behaviour of the virtual opponent has been shown to affect the initial pace of cyclists in laboratory-controlled conditions (Chapter 3). The performance improvement related to the presence of an opponent appears to remain quite stable, regardless of the level of performance of the opponent (Williams *et al.*, 2015a). Yet a different level of performance of the opponent appeared to evoke different psychological responses (Williams *et al.*, 2015a). On top of this, the improvement in performance only seems to occur acutely when the opponent is present, as performance declines back to baseline levels in subsequent time trials riding alone (Jones *et al.*, 2016a). Possible mechanisms, such as an increased motivation (McCormick *et al.*, 2015) and a change in attentional focus from internal to external aspects (Williams *et al.*, 2015b), have been suggested in relationship to the performance improvement seen in the presence of a virtual opponent. However, it is yet unclear how this improved performance in the presence of a virtual opponent is established.

This study explored this effect by examining the performance improvements when riding against a virtual opponent compared to riding alone, and by relating these to neuromuscular adjustments in the knee extensors and perceived exertion. It is hypothesised that the presence of a virtual opponent could invite a change in pacing and evoke an improvement in performance, leading to a greater decline in voluntary muscle force after a 4-km time-trial compared to riding alone. In addition, it is explored whether a change in pacing and performance would be mainly related to alterations in contractile function or in muscle activation.

8.2 Methods

8.2.1 Participants

Twelve trained male cyclists with at least two years cycling experience at a moderate to high intensity (age: 36.8±10.0 years; body mass: 82.1±13.9 kg; height: 180.1±9.7 cm) participated in this study. Before participating all participants completed a health screening questionnaire (Physical Active Readiness Questionnaire; Cardinal *et al.*, 1996) and gave written informed consent. The study was approved by the university's local ethical committee in accordance with the Declaration of Helsinki.

8.2.2 Experimental procedures

Participants visited the laboratory on four separate occasions. During their first visit, participants performed a maximal incremental test on a Velotron cycle ergometer. In their second to fourth visit participants were asked to perform a self-paced 4-km cycling time trial as fast as possible. Prior to and after the time trials, maximal voluntary contraction, doublet-twitches at rest and voluntary activation of the quadriceps muscle were determined. The first 4-km time trial was always a familiarisation time trial (FAM). In the final two visits participants completed in a randomised order one of the two different experimental 4-km time trial conditions (see Section 8.2.3). No verbal coaching or motivation was given to the participants during any of the time trials. Before each time trial condition participants performed a 5-min warm-up at an intensity of 30% peak power output (PPO).

Time trials were completed at the same time of the day (±2 hours) for each participant to minimise circadian variation. Participants were asked to maintain normal activity and sleep pattern throughout the testing period. In addition, participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 hours, and from caffeine and food consumption four and two hours respectively, before the start of the test. Participants were informed that the study was examining the influence of external factors on performance during cycling time trials. To prevent any pre-meditated influence on preparation or pre-exercise state, the specific feedback presented for each trial was only revealed immediately before the start of the time trial. All trials were conducted in ambient temperatures between 18-21°C.

8.2.3 Procedures

8.2.3.1 Maximal incremental test

Participants attended the laboratory to complete a maximal incremental test on the Velotron cycle ergometer (Velotron Dynafit, Racermate, Seattle, USA) to measure PPO. A 5-min warm-up at 100W was followed by a 3-min rest period before starting the test. The incremental test had an initial workload of 100W and a workload increase of 25W every minute until volitional exhaustion. Participants were instructed to keep their cadence between 80-100 revolutions per minute (rpm). Participants were given strong verbal encouragement in the latter stages. The highest mean power output achieved during any 60 second period was recorded as the participant's PPO.

8.2.3.2 Familiarisation and *Experimental trials*

During the second visit, participants completed a self-paced familiarisation 4-km time trial. During the third and fourth visit, participants were asked to complete one of the two different experimental, self-paced 4-km time trial conditions. The experimental conditions were a time trial without virtual opponent (NO), and a time trial with virtual opponent (OP). Each 4-km time trial started 4 minutes after completion of the warm-up. Before the trials with a virtual opponent, participants were told that their virtual opponent would be of similar level of performance in order to make sure a participant would perceive his opponent as competitive. Although participants were unaware of this, the virtual opponent was in fact their own previous performance during FAM. Typically, a modification in pacing strategy towards a less aggressive start occurs after a familiarisation trial in time trials of relatively short duration. (Chapter 3; Corbett *et al.*, 2009) Therefore, using FAM as basis for the construction of the opponent most likely results in a competitor that uses a different pacing profile compared to our participant in the experimental time trial conditions.

Time trials were performed on an advanced cycle ergometer (Velotron Dynafit, Racermate, Seattle, USA) that has been shown to be a reliable and valid tool to measure cycling performance and pacing behaviour (Astorino and Cottrell, 2012). Using the Velotron 3D software, a straight and flat 4-km time trial course with no wind was programmed and projected onto a screen for all trials. During the time trials only feedback regarding the relative distance that still had to be covered was provided. In the opponent conditions, a virtual opponent was projected as well. Power output, velocity, distance, cadence, and gearing were monitored continuously during each trial (sample frequency = 4 Hz). In addition, heart rate was monitored every second (Polar M400, Polar Inc.). Rate of perceived exertion (RPE) on a Borg-scale of 6-20 (Borg, 1982, 1998) was asked after the warm-up, at 100 sec, 200 sec and 300 sec after starting the time trial, and directly after passing the finish line.

8.2.3.3 Neuromuscular function

Measures of neuromuscular function were evaluated prior and after the trial (within <3 min after finishing the time trial) using electrical stimulation of the right femoral nerve. Three variables were obtained to quantify muscle performance; maximal voluntary contraction force (MVC), voluntary activation (VA) and the potentiated doublet-twitch force (PT).

All of these three variables change following exertion. The PT is the highest force of the three repetitions evoked by paired-pulse electrical stimulation administered to the resting muscle, five seconds after the MVC (Gandevia, 2001). The VA is determined via the interpolated doublet-twitch technique and is estimated by changes in the interpolated doublet-twitch relative to the PT (see equation; Merton, 1954). The force evoked by the imposed electrical stimulation on top of the MVC is the interpolated doublet-twitch (IT), the force evoked by the electrical stimulation 5 sec after MVC is PT.

$$\boldsymbol{VA}(\%) = (\mathbf{1} - \frac{\boldsymbol{IT}}{\boldsymbol{PT}}) \cdot \mathbf{100}$$

Knee extensor force (N) during voluntary and evoked contractions was measured using a calibrated load cell dynamometer (Kin-Com dynamometer, Chattanooga Group Inc.; Hixon, TN, USA) fixed to a custom-built chair and connected to a noncompliant Velcro strap attached around the participant's right leg superior to the ankle malleoli. The height of the load cell was individually adjusted to ensure a direct line with the applied force. During all measurements, participants sat upright, with the hips and knees at 90° flexion, and were given specific instruction to remain seated. After the skin was shaved, two stimulation pads (Axelgaard ValuTrode 5x9 cm disposable surface electrodes) were placed on the leg and connected to a high voltage stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City, United Kingdom). The cathode pad was placed at the distal side of the middle of the inguinal crease (Stoter *et al.,* 2016). The anode pad was placed 2-3 cm proximal to the patella, with the knee in a bent position (Stoter *et al.,* 2016). The sequence of stimulation was controlled by a programmable output system (LabChart 7.0, AD Instruments, United Kingdom). The positions of the electrodes were marked with indelible ink to ensure consistent placement on repeat trials.

Before their time trial, participants completed three isometric MVC's separated by 60 sec rest. To determine stimulation intensity, paired-pulse stimuli (200 µs duration; 10 ms interval) were delivered in 25 mA stepwise increments from 150 mA and the current that evoked maximal doublet-twitch amplitude at rest was determined. To ensure a supramaximal stimulus, the final intensity was increased by 30% (mean ±SD current: 343±57 mA). Femoral nerve stimulation was delivered during and 5 sec after MVC to assess VA. Participants completed post-time trial exercise another three MVC's with femoral nerve stimulation. In line with other investigations that have assessed cycling exercise-induced fatigue of the knee extensors, the post-time trial measurements were completed within three minutes of exercise cessation (Thomas *et al.,* 2015). The rapid nature of this procedure is necessary to capture the decline in MVC force, voluntary activation, and potentiated doublet-twitch force induced by the exercise before it dissipates (Froyd *et al.,* 2013), and the duration was consistent between trials. During all MVC's participants received verbal encouragement.

8.2.4 Statistical analysis

A two-way repeated-measures ANOVA (condition x time) was used to assess the effect of each time trial on measures of neuromuscular function (comparison of before vs after trial) and to assess the differences between time trial conditions. A multiple linear regression analysis (Backward method) was performed to determine the relationship between the change in mean power output per kilometre during OP relative to NO and the absolute VA, and the change in differences in MVC, VA and PT before and after the time-trial in OP relative to NO. Significance was accepted at $P < 0.05$.

To examine 4-km time trial performance mean power output, heart rate, cadence, and finish time were calculated. Differences in performance between conditions were assessed using a one-way repeated-measures ANOVA (condition). To assess differences in pacing behaviour between the conditions, average power output, cadence, heart rate and split times for each 250 m segment were calculated, and differences were tested using a two-way repeated-measures ANOVA (condition x segment). The RPE was evaluated using a two-way repeated-measures ANOVA (condition x asking point). All analyses were performed using SPSS 19.0, and significance was accepted at $P < 0.05$. Data are presented as means ± SD.

8.3 Results

8.3.1 Performance analysis

The participants achieved a mean PPO of 351 ± 35 W in the maximal incremental test, and can be classified as trained cyclists based on the guidelines of De Pauw *et al*. (2013) A higher mean power output (OP: 289.6 ± 56.1 W vs. NO: 272.2 ± 61.6 W; $F = 7.5$; $p = 0.020$) and faster finishing times (OP: 382.2 ± 31.9 sec vs. NO: 393.6 ± 21.9 sec; $F = 5.1$; $p = 0.046$) were reported after OP compared to NO. Completion time of FAM

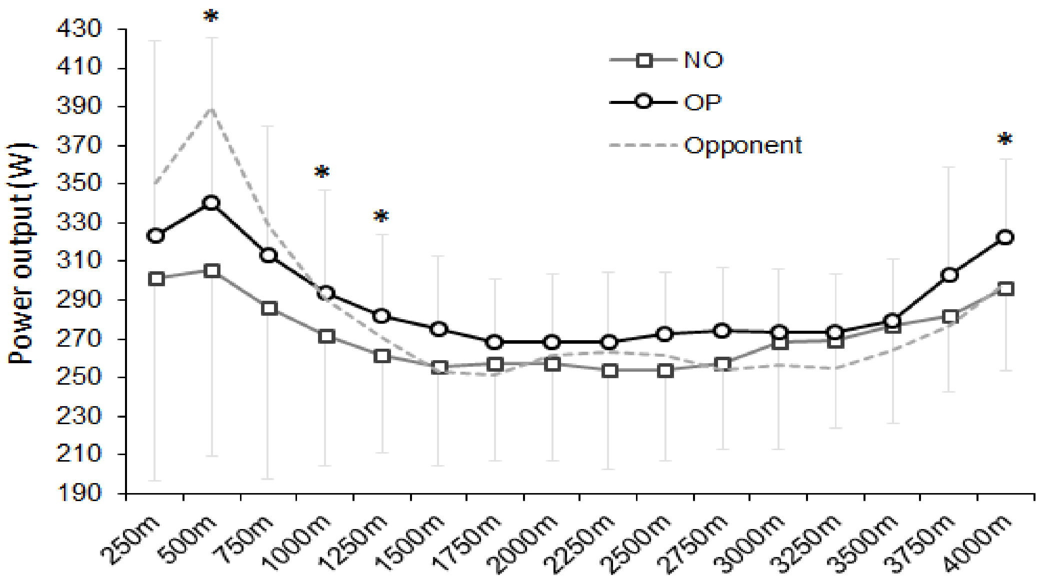

Figure 8.1 Average power output per 250 m segment for both experimental conditions. In addition, the average power output per 250 segment of the virtual opponent in the experimental condition OP is displayed.

* significant difference between OP and NO (P < 0.05)

and NO did not differ (p = 0.241), In contrast, participants completed their time trial faster in OP compared to the FAM/virtual opponent (p = 0.003). Mean heart rate over the time trials was higher during OP compared to NO (OP: 164.6 ± 9.0 bpm vs. NO: 158.9 ± 12.4 bpm; F = 6.6; p = 0.026). No differences in mean cadence were found between OP and NO (OP: 103.9 ± 10.2 rpm vs. NO: 104.7 ± 12.5 rpm; F = 0.2; p = 0.669).

8.3.2 Pacing analysis

Mean (± SD) power outputs per 250 m section are shown in Figure 8.1. Main effects for condition (F = 7.5; p = 0.020) and segment (F = 5.0; p < 0.001), and an interaction effect for condition x segment (F = 1.9; p = 0.029) were found, indicating differences in pacing profile between conditions. Post hoc analysis revealed a faster initial pace during OP compared to NO, with higher power outputs between 250-500 m (p = 0.040), 750-1000 m (p = 0.022), and 1000-1250 m (p = 0.024). In addition, a faster end spurt (3750-4000 m) was noticed in OP compared to NO (p = 0.001). Finally, regression analysis showed that the difference in mean power output between OP and NO during the first kilometre could explain 47.9% of the total variance in the relative difference in mean power output between OP and NO over the whole time-trial ($R^2 = 0.479$, $\beta = 0.692$, $p = 0.013$). Participants adopted a slower initial pace in NO (0-250 m: p = 0.065; 250-500 m: p = 0.001; 500-750 m: p = 0.005), but not during OP, in comparison to FAM (and thus the virtual opponent in OP; 0-250 m: p = 0.187; 250-500 m: p = 0.148; 500-750 m:p = 0.216). In addition, participants were faster in OP compared to FAM between 1250-1500 m (p = 0.032), 2500-2750 m (p = 0.022), 3250-3500 m (P = 0.046), and 3750-4000 m (p = 0.018).

Mean (±SD) heart rates per 250 m section are shown in Figure 8.2. A main effect was found for condition (F = 6.6; p = 0.026) and segment (F = 149.8; p < 0.001). An interaction effect was reported for condition x segment (F = 1.8; p = 0.035). Post hoc tests showed heart rate values were higher in OP compared to NO from 250 m until 1750 m. A main effect for segment (F = 18.756; p < 0.001), but no main effect for condition (F = 0.2; p = 0.669) and no interaction effect for condition x segment

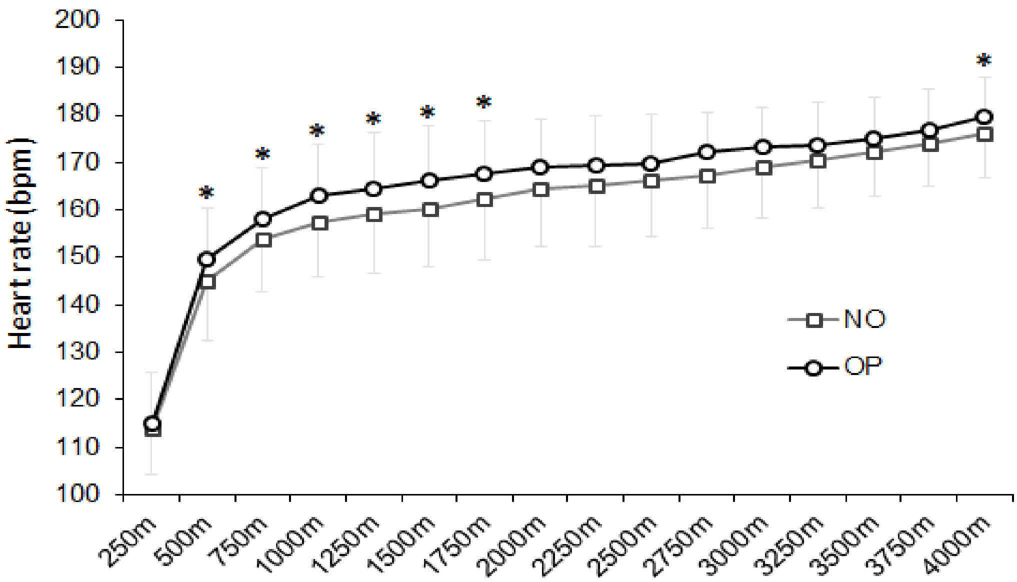

Figure 8.2 Average heart rate per 250 m segment for both experimental conditions.

* significant difference between OP and NO (P < 0.05)

(F = 0.7; p = 0.767) was found for cadence. Mean (± SD) RPE scores per point of asking for each experimental condition are shown in Table 8.1. A main effects point of asking (F = 29.2; p < 0.001), but no main effect for condition (F = 4.2; p = 0.065), and no interaction effect for condition x point of asking (F = 0.7; p = 0.560) were found.

Table 8.1 Mean ± SD values for the RPE of the participant per experimental condition after completing their warm-up and time trial, and 100 sec, 200 sec and 300 sec after starting their time trial.

	Warm-up	**$TT_{100\ sec}$**	**$TT_{200\ sec}$**	**$TT_{300\ sec}$**	**TT_{Finish}**
NO	8.6 ± 1.6	13.3 ± 1.5	15.1 ± 1.4	16.8 ± 1.7	18.7 ± 1.4
OP	9.0 ± 1.8	13.7 ± 2.0	15.7 ± 1.4	17.4 ± 1.7	18.7 ± 1.1

8.3.3 Neuromuscular adjustments

Mean (±SD) differences in MVC, PT and VA in the post-test versus the pre-test per experimental condition can be found in Table 8.2. In addition, a typical example of the assessment of neuromuscular function of the knee extensors during and after a MVC using the interpolated doublet-twitch technique is shown in Figure 8.3. A main effect was found for time (F = 23.8; p < 0.001), but not for condition (F = 0.3; p = 0.596) for the MVC. The main effect for time showed a decrease in MVC force in the post-test compared to the pre-test. Furthermore, an interaction effect was reported for condition x time (F = 6.1; p = 0.032) for the MVC, revealing that the force decline was relatively greater after OP compared to NO.

A main effect for time (F = 41.4; p < 0.001), but not for condition (F = 0.6; p = 0.440) was found for the PT, indicating smaller potentiated doublet-twitch force after the time trials compared to before the time trials. An interaction effect for condition x time (F = 5.4; p = 0.041) showed the decline in potentiated doublet-twitch force was greater after OP compared to NO. A main effect for time (F = 11.8; p = 0.006), but not for condition (F = 0.5; p = 0.484) was reported for VA. Moreover, no interaction effect for condition x time (F = 1.4; p = 0.274) was found for the VA, indicating no difference in voluntary activation was found between NO and OP.

Table 8.2 Mean ± SD values for the neuromuscular function of the knee extensors in terms of maximal voluntary contraction force (MVC), potentiated doublet-twitch force (PT) and voluntary activation (VA) prior and after both 4 km time trial conditions.

	NO			OP		
	Pre-TT	Post-TT	Decrease %	Pre-TT	Post-TT	Decrease %
MVC[A,B] (N)	715±182	633±169	11.4±10.9	717±199	592±170	17.5±12.4
PT [A,B] (N)	425±70	356±83	16.2±11.4	431±83	331±75	23.1±14.0
VA [A] (%)	80.2±9.8	76.7±8.1	3.4±5.0	83.0±8.8	78.1±11.8	4.9±6.7

[A] main effect for Trial (pre vs post), [B] interaction effect for Trial*Condition

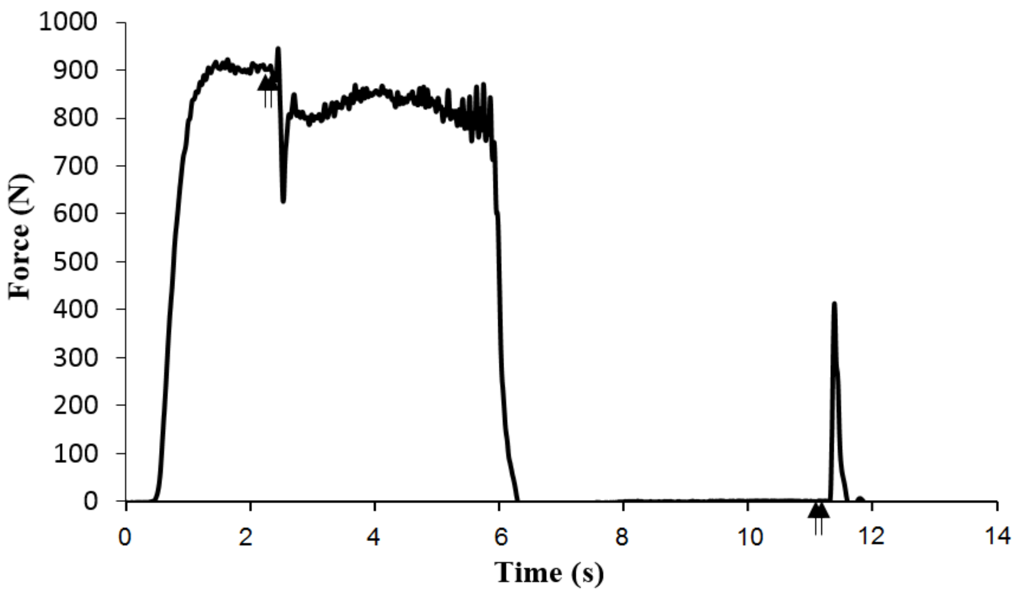

Figure 8.3 Typical example of the raw data for one of the 5 sec MVCs, including the superimposed doublet-twitch during the MVC and the potentiated doublet-twitch 5 sec after the MVC. The double arrows indicate the moment of applying the paired-pulse electrical stimuli to the right femoral nerve.

The outcomes of the linear regression analyses used to assess the relationship between the change in power output per kilometre during OP relative to NO, and the change in differences in MVC, VA, and PT before and after the time-trial in OP relative to NO can be found in Table 8.3. Negative standardised beta coefficients were found between the relative change in power output during the first kilometre in OP compared to NO and both ΔPT ($\beta = -0.50$, $p = 0.036$) as well as ΔVA ($\beta = -0.49$, $p = 0.045$) after OP compared to NO. These negative beta-values indicate that a relatively faster initial pace in OP is associated to a relatively greater decline in PT and increased reduction in VA after OP compared to NO. The combination of the relative change in PT and VA could explain 60.9% of the total variance in the relative change in power output during the first kilometre in OP compared to NO. The relative change in MVC in OP compared to NO and the absolute voluntary activation did not significantly contribute to the model.

Table 8.3 Multiple linear regression analysis was used to assess the relationship between the change in mean power output per kilometre during OP relative to NO (ΔPO**),** and the change in MVC, VA, and PT before and after the time-trial in OP relative to NO (ΔMVC, ΔVA, ΔPT respectively). R^2 and Standardised beta coefficients are presented.

Multiple linear regression		ΔPO 1km	ΔPO 2km	ΔPO 3km	ΔPO 4km
		ΔPT and **ΔVA**†	-°	-°	-°
R^2		0.609	-	-	-
β	Δ*PT*	-0.50	-	-	-
	Δ*VA*	-0.49	-	-	-
Sign	ΔPT	0.036*	-	-	-
	ΔVA	0.045*	-	-	-

*significant standardised beta coefficient ($P < 0.05$)

†ΔMVC and absolute VA were removed out of the multiple linear regression analysis as they did not contribute significantly to any of the variables

° all variables were removed out of the multiple linear regression analysis

8.4 Discussion

Trained cyclists were able to improve their mean power output and finishing time in a self-paced 4-km time trial when riding against a virtual opponent. This performance improvement was accompanied by a greater decline in MVC force and PT force, while no difference between time trial conditions was found for the voluntary activation. In addition, linear regression analyses showed that the faster initial pace of the participants in OP relative to NO, most likely evoked by their virtual opponent (see Chapter 4), is associated with a relative greater reduction in doublet-twitch amplitude and voluntary activation after OP relative to NO. Remarkably, participants still perceived a similar level of exertion in both experimental conditions, despite the higher mean power output, the greater decline in MVC force and potentiated doublet-twitch force, and the higher mean heart rate that was found when riding against a virtual opponent.

Previous research has shown before that a virtual opponent could affect pacing behaviour (Chapter 4) and improve performance (Chapter 4; Williams *et al.*, 2015a, 2015b; Corbett *et al.*, 2012; Wilmore, 1968; Tomazini *et al.*, 2015) In this perspective, the presence of a virtual opponent has been related to a greater external distraction, possibly deterring perceived exertion (Williams *et al.,* 2015b). The improvements during a 2-km head to head competition with virtual opponent were shown to be accompanied by a greater anaerobic energy contribution while aerobic contribution remained the same (Corbett *et al.*, 2012). The present study adds onto this knowledge that the performance improvement in the presence of a virtual opponent is also accompanied by a greater decline in voluntary and evoked muscle force.

Many studies have suggested that muscle fatigue has a crucial impact on the decision-making process regarding exercise regulation and performance (Smits *et al.*, 2014; Enoka and Duchateau, 2016; Swart *et al.*, 2009; Roelands *et al.,* 2013). In this respect, afferent feedback generated during high-intensity exercise has been suggested as a potential way to protect intramuscular homeostasis (Amann and Dempsey, 2008; Swart *et al.,* 2009). For instance, when receiving similar pacing instructions, athletes demonstrated different pacing behaviour in different sports while similar neuromuscular adjustments were found at the end of the trial (Stoter *et al.,* 2016). In addition, impairing lower limb muscle afferent feedback via group III/IV muscle afferents resulted in a faster initial pace (Sidhu *et al.,* 2017). In this perspective, the present findings indicate the possible effect of afferent feedback on the decision-making process involved in pacing might be counteracted by motivational aspects and/or attentional strategies related to the presence of a virtual opponent. In addition, linear regression analyses showed that the faster initial pace of the participants in OP relative to NO, most likely evoked by their virtual opponent, was associated to a relative higher reduction in doublet-twitch amplitude after OP. This supports the idea that perceptual affordances provided by the environment could invite athletes to respond differently (Smits *et al.,* 2014; Hettinga *et al.,* 2017), and might be able to overrule to a certain extent the influence of afferent feedback on the decision-making process involved in pacing.

According to Amann and Dempsey (2008) afferent feedback via group III/IV muscle afferents can also lead to an increased reduction in the voluntary activation of the muscle. However, no difference in the voluntary activation has been found after OP compared to NO. In this respect, it is known that the contribution of the decline in muscle activation to performance fatigability is more apparent in time trials of longer duration, while the contribution of the reduction in contractile function is relatively higher in high-intensity time trials of shorter duration (Thomas *et al.,* 2015; Thomas *et al.,* 2016; Froyd *et al.,* 2016; MacIntosh and Shahi, 2011). Interestingly, despite no difference in voluntary activation was found after our experimental conditions, a higher initial pace in OP relative to NO appeared to be associated to a relative higher reduction in voluntary activation after OP compared to NO.

Due to methodological reasons, adjustments in neuromuscular function caused by the time trial exercise could only be measured after time trial completion but not during the race. This limitation is common in the literature of studying adjustments in neuromuscular function caused by locomotor exercise modes and assumes that the neuromuscular adjustments observed after exercise are also present during the exercise (Thomas *et al.,* 2015; Froyd *et al.,* 2013). In addition, linear regression analyses were used to assess the relationship between the change in mean power output per kilometre during OP relative to NO, and the change in differences in MVC, VA and PT before and after the time-trial in OP relative to NO. The outcomes of the linear regression analyses indicated that a relatively faster initial pace in OP relative to NO was associated with a relatively larger decline in PT and an increased reduction in VA. The combination of the relative change in PT and VA could explain 60.9% of the total variance in the relative change in mean power output during the first kilometre in OP compared to NO. As a significant recovery of muscle function can occur two minutes after exercise (Froyd *et al.*, 2013), it is possible that the changes in neuromuscular function caused by the time trial exercise were underestimated. Nevertheless, the time taken to assess neuromuscular function was consistent within participants between their trials. Moreover, a significant reduction in all three measured neuromuscular variables was observed after all time trials, while the decline in MVC and PT force was influenced by the time trial condition. These observations indicate that the methods used were appropriate to determine differences in the neuromuscular function after the time trial exercise in the different experimental conditions. Finally, the reported potentiated doublet-twitch force in this study appeared to be relatively high. This is most likely related to the neuromuscular stimulation of quadriceps, as this effect has been reported earlier for this muscle group (Behm *et al.*, 2002).

8.5 Conclusion

Trained cyclists were able to improve their performance in the presence of a virtual opponent, in line with previous research (Chapter 3; Wilmore, 1968; Williams *et al.*, 2015a, 2015b; Corbett *et al.*, 2012; Tomazini *et al.*, 2015). The present study has shown that the improved performance during head-to-head competitions compared to individual self-paced cycling time-trials is associated to a greater decline in MVC force and potentiated doublet-twitch force while still perceiving a similar rate of perceived exertion as when riding alone. An external environmental stimulus appears to be able to evoke the execution of certain actions that were not perceived as possible or necessary when riding alone. In this respect, an opponent may not only present action possibilities towards an exerciser, it may also alter an exerciser's perceived action capabilities. To understand the regulation of the exercise intensity, it is crucial to incorporate human-environment interactions in our thinking about how pacing decisions are made in real life competitive situations in sports, and what information is used to inform such decisions (Smits *et al.*, 2014; Hettinga *et al.*, 2017).

CHAPTER 9

The effect of different fatigue protocols on pacing regulation with and without an opponent

Abstract

The present study examined the effect of different fatigue protocols (cycling protocol vs eccentric protocol) on exercise regulation with and without an opponent. *Study 1:* Twelve trained cyclists performed four experimental, self-paced 4-km time trial conditions on an advanced cycle ergometer in a randomised, counterbalanced order. Participants started the time trial in a non-fatigued state (NF) or performed prior to the time trial a 10-min cycling protocol at 67% PPO (FA). In the time trials, participants had to ride alone (NO) or against a virtual opponent (OP). As such the experimental conditions were: 1) NF-NO, 2) NF-OP, 3) FA-NO and 4) FA-OP. Repeated-measures ANOVAs ($p < 0.05$) were used to examine differences in pacing and performance in terms of power output. A faster initial pace was adopted in the first kilometre during NF-OP (318 ± 72 W) compared to NF-NO (291 ± 81 W; $p = 0.026$), leading to an improved finishing time during NF-OP compared to NF-NO ($p = 0.046$). Differences in neither pacing nor performance were found between FA-NO and FA-OP. *Study 2:* Ten trained cyclists performed four experimental 4-km time trial conditions in randomised, counterbalanced order. However, the fatiguing protocol now existed of an eccentric fatiguing protocol (80 drop jumps; DJ) or a control resting condition (CO). As such the experimental conditions were 1) CO-NO, 2) CO-OP, 3) DJ-NO and 4) DJ-OP. A faster initial pace was adopted during CO-OP (341±56W) versus CO-NO (324 ± 50 W; $p = 0.029$), and during DJ-OP (327 ± 81 W) versus DJ-NO (304 ± 58 W; $p = 0.009$). Moreover, improved finishing times were revealed during CO-OP versus CO-NO ($p = 0.019$), and during DJ-OP versus DJ-NO ($p = 0.022$). In conclusion, the evoked response by the opponent to adopt a faster initial pace diminished when moderately fatigued via a cycling protocol in advance of their 4-km time trial, but not when locomotor muscle fatigue was induced via an eccentric fatiguing protocol.

9.1 Introduction

During competition, athletes are required to continuously make decisions about how and when to invest their available energy resources (Smits *et al.,* 2014). This goal-directed regulation of the exercise intensity is also known as pacing (Edwards and Polman, 2013). Yet the underlying mechanism behind this decision-making process involved in pacing are still strongly debated. Nevertheless, despite the variety of proposed pacing theories, what they all seem to agree on is the importance of sensations of fatigue and a willingness to tolerate discomfort, in anticipation of future rewards.

In terms of the studies performed related to pacing, the focus up until quite recently has been mainly onto how exercisers are able to pre-plan pacing strategies, and concepts as teleoanticipation (Ulmer, 1996) and template formation (Foster *et al.*, 2009). In this sense, afferent feedback via group III/IV muscle afferents has been suggested as an important variable in the decision-making process regarding exercise regulation and performance.(Smits *et al.*, 2014; Enoka and Duchateau, 2016; Swart *et al.*, 2009; Roelands *et al.,* 2013) Indeed, impairing lower limb muscle afferent feedback via group III/IV muscle afferents did lead to a faster initial pace (Blain *et al.,* 2016). Nevertheless, others have questioned the importance of afferent feedback via group III/IV muscle afferents on pacing regulation (Marcora, 2010). For example, De Morree and Marcora (2013) showed that an eccentric fatiguing protocol, designed to induce a substantial strength loss in the knee extensor muscles without inducing significant metabolic stress and consequent accumulation of muscle metabolites (Skurvydas *et al.*, 2000; Skurvydas *et al.,* 2002; Marcora *et al.,* 2008), resulted in a reduced pace but not to a change in pacing strategy (De Morree and Marcora, 2013). In contrast, the induction of moderate to high levels of (perceived) fatigue prior to the start of a race via a cycling protocol appears to evoke a more conservative starting pace (Amann and Dempsey, 2008; Correia-Oliveira *et al.,* 2014; De Morree and Marcora, 2013).

Although feedback regarding the internal bodily state is crucial in exercise regulation, the importance of whatever is happening in the external world around the exerciser has been highlighted recently as crucial in the context of pacing (Smits *et al.*, 2014; Micklewright *et al.*, 2017; Hettinga *et al.*, 2017). In this sense, the previous chapters illustrated that an external variable, such as an opponent, does impact upon pacing behaviour and performance. That is, it has been shown that the presence of a (virtual) opponent could invite exercisers to alter their pacing behaviour (Chapter 3 and 4) and could even improve time trial performance (Chapter 4 and 8; Corbett *et al.*, 2012; Williams *et al.*, 2015a, 2015b). In the previous chapter, it was demonstrated that this performance improvement was established due to cyclists being able to handle higher levels of muscle fatigue in the presence of an opponent, without a change in perceived exertion. This supports the idea that perceptual affordances provided by the environment might be able to counteract to a certain extent the influence of afferent feedback on the decision-making process involved in pacing.

In the present study the interaction between external stimuli and internal bodily state in the context of pacing will be further explored. This will be done by manipulating the level of pre-fatigue status (internal bodily state) and the presence of an opponent (external stimulus). In the first study a moderate level of fatigue will be induced via a cycling protocol, while in the second study locomotor muscle fatigue will be induced via an eccentric fatiguing protocol. It is hypothesised that the faster initial pace and enhanced performance evoked by the opponent's presence will disappear when a moderate level of fatigue is induced to the participant via a cycling protocol in advance of the time trial. However, the initial evoked pacing response related to the opponent is expected to return when muscle fatigue is induced via an eccentric fatiguing protocol and the consequential absence of afferent feedback from the locomotor muscles during the fatiguing task.

9.2 Material and Methods

9.2.1 STUDY 1: The impact of a pre-fatiguing cycling protocol on pacing with and without opponent

9.2.1.1 Participants

Twelve moderate physically active participants with at least two years cycling experience at a moderate to high intensity (age: 36.8±10.0 years; body mass: 82.1±13.9 kg; height: 180.1±9.7 cm) participated in this study. Before participating all participants gave written informed consent and completed a health screening questionnaire (Physical Active Readiness Questionnaire; Cardinal *et al.,* 1996). The study was approved by the ethical committee of the University of Essex in accordance with the Declaration of Helsinki.

9.2.1.2 Experimental procedures

Participants visited the laboratory on six separate occasions. During their first visit, participants performed a maximal incremental test. In their second to sixth visit participants were asked to perform a self-paced 4-km time-trial at maximal effort (see Section 9.2.1.3). For every time trial, participants were instructed to complete the time trial as fast as possible. No verbal coaching or motivation was given to the participants during any of the time trials. To minimise circadian variation, time trials were completed at the same time of the day (±2 hours). Participants were asked to maintain normal activity and sleep pattern throughout the testing period. In addition, participants were asked to refrain from any alcohol consumption and strenuous exercise in the preceding 24 hours, and from caffeine and food consumption respectively, four and two hours before the start of the test. Participants were informed that the study was examining the influence of external factors on performance during cycling time trials. To prevent any premeditated influence on preparation or pre-exercise state, the specific feedback presented for each trial was only revealed immediately before the start of the time trial. All trials were conducted in ambient temperatures between 18-21°C.

Time trials were performed on an advanced cycle ergometer (Velotron Dynafit, Racermate, Seattle, USA). Using the Velotron 3D software, a straight and flat 4-km time trial course with no wind was programmed and projected onto a screen for all trials. Only relative distance feedback was provided during the time trials. In the opponent conditions, a virtual opponent was projected as well. Power output, velocity, distance, cadence, and gearing were monitored continuously during each trial (sample frequency = 4 Hz). In addition, heart rate was monitored every second (Polar M400, Polar Inc.). Rate of perceived exertion (RPE) was asked after the fatiguing protocol, at 100 sec, 200 sec and 300 sec after starting the time trial, and directly after passing the finish line on a Borg-scale of 6-20 (Borg, 1982, 1998).

9.2.1.3 Experimental design

A schematic overview of the study design can be found in Figure 9.1. Participants completed in their first visit an incremental test to determine peak power output (PPO). A 5-minute warm-up at 100 W was followed by a 3-minute rest period before starting the test. The incremental test had an initial workload of 100 W and a workload increase of 25 W every minute until volitional exhaustion. RPE was recorded 10 seconds before every stage completion and directly after the point of volitional exhaustion. Participants were instructed to maintain a cadence within 80-100 rpm and given strong verbal

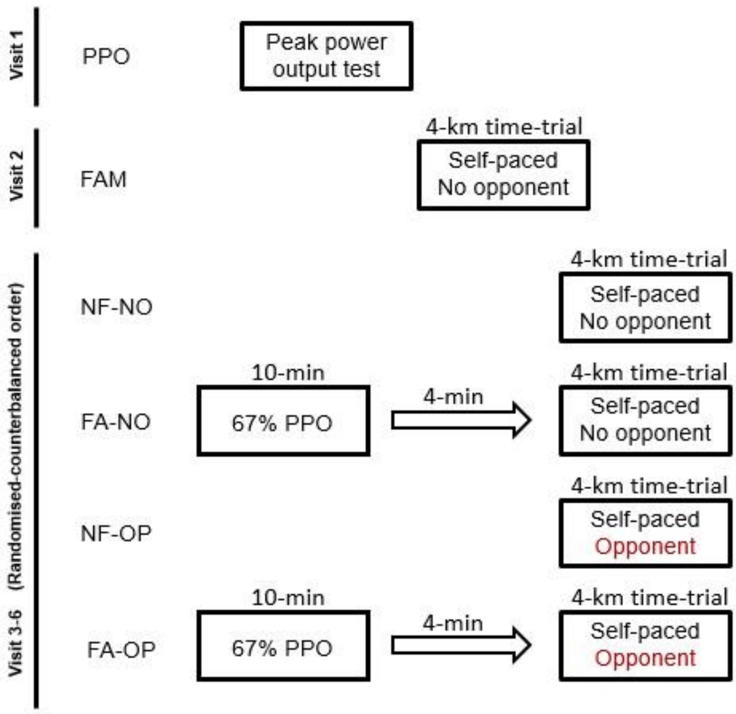

Figure 9.1 Schematic overview of experimental set-up study 1. Visit 3-6 were performed in randomised counterbalanced order and each visit was separated by at least 48 h.

encouragement in the latter stages. The highest mean power output achieved during any 60 second period was recorded as the participant's PPO.

During their second visit participants performed a self-paced familiarisation 4-km time trial (FAM). During their third to sixth visit participants had to complete each visit one of the four experimental 4-km time trial conditions in a randomised, counterbalanced order. In the experimental time trial conditions the internal (pre-fatigue status) and/or external (opponent presence) status of the athlete-environment relationship were manipulated (see Figure 9.1). In the trials involving the fatiguing protocol, the 4-km time trials started 4-min after completion of the fatiguing protocol. Before the trials with a virtual opponent, participants were told that their opponent would be of similar level of performance in order to make sure a participant would perceive his opponent as competitive. Although participants were unaware of this, the opponent was in fact their own previous performance during FAM.

9.2.1.4 Statistical analysis

Mean power output, heart rate, cadence, and finish time were calculated to examine 4-km time trial performance. Differences in performance between conditions were assessed using a repeated-measures ANOVA. To assess differences in pacing behaviour between the conditions, average power output, heart rate, cadence, and split times for each kilometre segment were calculated, and differences were tested using a two-way repeated-measures ANOVA (conditions x segment). In addition, RPE was evaluated using a two-way repeated-measures ANOVA (conditions x asking point). A Greenhouse-Geisser correction was used when sphericity could not be assumed. Post-hoc tests were performed when significant main or interaction effect were found for performance and/or pacing behaviour. All analyses were performed using SPSS 19.0, and significance was accepted at $P < 0.05$. Data are presented as means ± SD.

9.2.2 STUDY II: The impact of a pre-fatiguing eccentric protocol on pacing regulation with and without opponent

9.2.2.1 Participants

Ten moderate physically active participants with at least two years cycling experience at a moderate to high intensity (age: 34.0±15.2 years; body mass: 78.1±9.0 kg; height: 181.4±4.9 cm) participated in this study. Before participating all participants gave written informed consent and completed a health screening questionnaire (Physical Active Readiness Questionnaire; (Cardinal *et al.*, 1996). The study was approved by the university's local ethical committee in accordance with the Declaration of Helsinki.

9.2.2.2 Experimental procedures

In study 2 the same procedures as in study 1 were used apart from the following: First of all, participants visited the laboratory on five separate occasions. Participants performed a self-paced familiarisation 4-km time trial (FAM) during their first visit to the laboratory. In their second to fifth visit participants were asked to perform a self-paced 4-km time trial at maximal effort (see Section 9.2.2.3). During the time trials feedback regarding distance covered, cadence, heart rate and gearing was provided. Rate of perceived exertion (RPE) on a Borg-scale of 6-20 (Borg, 1982, 1998) was asked after the eccentric fatiguing protocol/control condition, prior to starting the time trial, after each kilometre, and directly after passing the finish line.

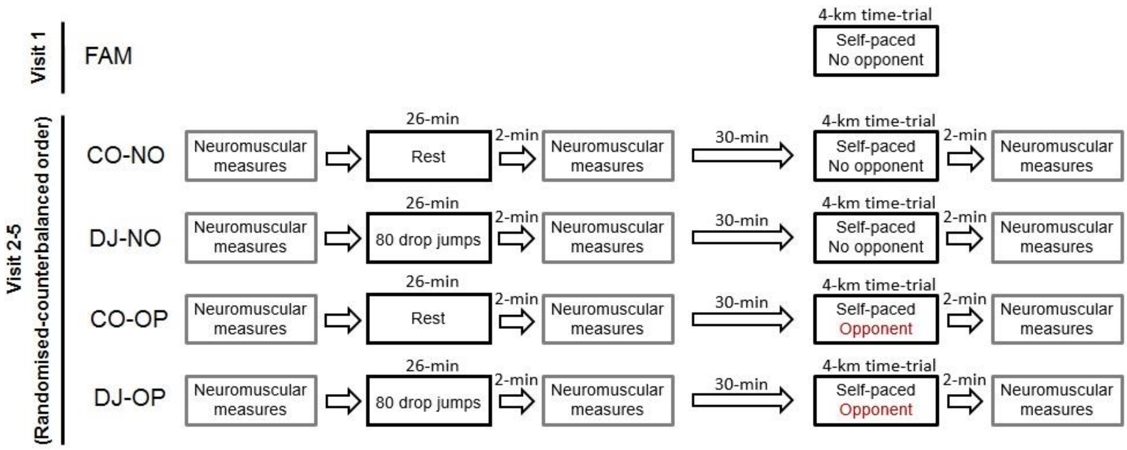

Figure 9.2 Schematic overview of experimental set-up study 2. Visit 2-5 were performed in randomised counterbalanced order and each visit was separated by at least 48 hours after a control protocol and by at least 10 days after a drop jump protocol.

9.2.2.3 Experimental design

A schematic overview of the study design can be found in Figure 9.2. Participants familiarised themselves with the cycle ergometer and experimental set-up during their first visit to the laboratory. During their second to fifth visit participants had to complete on each visit one of the four experimental 4-km time trial conditions in a randomised, counterbalanced order. The fatiguing protocol now existed of an eccentric fatiguing protocol (80 drop jumps; DJ) or a control resting condition (CO). As such the experimental conditions were 1) CO-NO, 2) CO-OP, 3) DJ-NO and 4) DJ-OP. In the trials involving the eccentric fatiguing protocol, participants dropped 80 times from a 60-cm high platform down to 90° knee angle before jumping upward as high as possible. Between each drop jump there was a 20 second rest period to allow for recovery, through oxidative phosphorylation, of the ATP and phosphocreatine expended during each drop jump (Skurvydas *et al.*, 2000; Skurvydas *et al.*, 2002). Furthermore, the eccentric fatiguing protocol does not induce any respiratory muscle fatigue, another factor, that might affect breathing pattern and exercise performance (Mador and Acevedo, 1991). The total duration of the eccentric fatiguing protocol was 26 minutes and 20 seconds. The control condition consisted of resting comfortably for 26 minutes. Prior to and two minutes after completing the assigned protocol, locomotor muscle force of the knee extensors was assessed with three MVCs using the interpolated twitch technique. After the second isometric test, a 30-min rest period was prescribed to allow for further cardiorespiratory and metabolic recovery after the 80 drop jumps, while at the same time controlling for the confounding effects of delayed onset muscle soreness (DOMS), which usually peaks 48 hours after eccentric exercise because of an increased sensitivity of the small muscle afferent neurons to mechanical stimuli (Taguchi *et al.*, 2005). After this rest period, participants completed their 4-km time trial. Finally, within two minutes after completing the time trial, locomotor muscle force was assessed again with three MVCs using the interpolated twitch technique.

9.2.2.4 Neuromuscular function

Measures of neuromuscular function were evaluated prior and directly after the assigned protocol, and directly after finishing the time trial using electrical stimulation of the right femoral nerve. Three variables were obtained to quantify muscle performance: maximal voluntary contraction force (MVC), voluntary activation (VA) and the potentiated doublet-twitch force (PT). To determine stimulation intensity, paired-pulse stimuli (200 µs duration; 10 ms interval) were delivered in 25 mA stepwise increments from 150 mA and the current that evoked maximal doublet-twitch amplitude at rest was determined. To ensure a supramaximal stimulus, the final intensity was increased by 30% (mean±SD current: 337±41 mA). Femoral nerve stimulation was delivered during and 5 seconds after the MVC to assess VA. Participants completed post-protocol and post-time trial exercise another three MVC's with femoral nerve stimulation. During all MVC's participants received strong verbal encouragement.

The PT is the highest force of the three repetitions evoked by paired-pulse electrical stimulation administered to the resting muscle, five seconds after the MVC (Gandevia, 2001). The VA is determined via the interpolated doublet-twitch technique and is estimated by changes in the interpolated doublet-twitch relative to the PT (see equation; Merton, 1954). The force evoked by the imposed electrical stimulation on top of the MVC is the interpolated doublet-twitch (IT), the force evoked by the electrical stimulation 5 sec after MVC is PT.

$$\boldsymbol{VA}(\%) = (\mathbf{1} - \frac{\boldsymbol{IT}}{\boldsymbol{PT}}) \cdot \mathbf{100}$$

Knee extensor force (N) during voluntary and evoked contractions was measured using a calibrated load cell dynamometer (Kin-Com dynamometer, Chattanooga Group Inc.; Hixon, TN, USA) fixed to a custom-built chair and connected to a noncompliant Velcro strap attached around the participant's right leg superior to the ankle malleoli. The height of the load cell was individually adjusted to ensure a direct line with the applied force. During all measurements, participants sat upright, with the hips and knees at 90° flexion, and were given specific instruction to remain seated. After the skin was shaved two stimulation pads (Axelgaard ValuTrode 5x9 cm disposable surface electrodes) were placed on the leg and connected to a high voltage stimulator (DS7AH; Digitimer Ltd., Welwyn Garden City, United Kingdom). The cathode pad was placed at the distal side of the middle of the inguinal crease (Stoter *et al.,* 2016). The anode pad was placed 2-3 cm proximal to the patella, with the knee in a bent position (Stoter *et al.,* 2016). The sequence of stimulation was controlled by a programmable output system (LabChart 7.0, AD Instruments, United Kingdom). The positions of the electrodes were marked with indelible ink to ensure consistent placement on repeat trials.

9.2.2.4 Statistical analysis

Mean power output, heart rate, cadence, and finish time were calculated to examine 4-km time trial performance. Differences in performance between conditions were assessed using a repeated-measures ANOVA. To assess differences in pacing behaviour between the conditions, average power output, heart rate, cadence, and split times for each kilometre segment were calculated, and differences were tested using a two-way repeated-measures ANOVA (conditions x segment). In addition, RPE was evaluated using a two-way repeated-measures ANOVA (condition x asking point). A Greenhouse-Geisser correction was used when sphericity could not be assumed. Post-hoc tests were performed when significant main or interaction effect were found for performance and/or pacing behaviour. A two-way repeated-measures ANOVA (condition x time) was used to assess the effect of each time trial on measures of neuromuscular function (comparison of prior protocol vs after protocol vs after time trial) and to assess the differences between time trial conditions. All analyses were performed using SPSS 19.0, and significance was accepted at $P < 0.05$. Data are presented as mean ± SD.

9.3 Results

9.3.1 STUDY 1

9.3.1.1 Performance analysis

Mean (±SD) finishing time, power output, heart rate, and cadence for the four experimental time trial conditions are shown in Table 9.1. A main effect was found for finishing times ($F = 3.523$; $p = 0.026$), power output ($F = 4.127$; $p = 0.014$), heart rate ($F = 9.204$; $p < 0.001$), and cadence ($F = 3.911$; $p = 0.017$). Post hoc analysis revealed only a difference in finishing time between NF-NO and NF-OP ($p = 0.046$). Participants showed lower mean power outputs in NF-NO compared to NF-OP ($p = 0.020$) and FA-NO ($p = 0.024$), respectively. No differences in mean power output were found between FA-NO and FA-OP ($p = 0.486$), or between NF-OP and FA-OP ($p = 0.370$). Mean heart rate over the time trials was lower during NF-NO compared to NF-OP ($p = 0.026$), FA-NO ($p = 0.004$), and FA-OP ($p = 0.006$). In addition, mean heart rate was higher during both FA-NO ($p = 0.031$) as well as FA-OP ($p = 0.036$) compared to NF-OP. No differences in mean heart rate were found between FA-NO and FA-OP

Table 9.1 Mean ± SD values for the time trial performance variables completion time, power output, heart rate and cadence per experimental condition in Study 1.

	NF-NO	NF-OP	FA-NO	FA-OP
Completion Time [A] (sec)	393.60 ± 31.9	382.21 ± 18.8	382.90 ± 22.4	386.10 ± 23.7
Power Output [A,B] (W)	272.2 ± 61.6	289.6 ± 56.1	289.1 ± 53.9	285.0 ± 60.6
Heart rate [A,B,C,D,E] (bpm)	158.9 ± 12.4	164.6 ± 9.0	168.5 ± 9.0	168.8 ± 10.1
Cadence [B,C,D] (rpm)	104.7 ± 12.5	103.9 ± 10.2	99.9 ± 8.3	101.3 ± 10.6

[A] Difference between NF-NO and NF-OP (P < 0.05); [B] Difference between NF-NO and FA-NO (P < 0.05),
[C] Difference between NF-NO and FA-OP (P < 0.05); [D] Difference between NF-OP and FA-NO (P < 0.05),
[E] Difference between NF-OP and FA-OP (P < 0.05)

(p = 0.800). Finally, post hoc analysis showed that the participants adopted a lower cadence during FA-NO compared to NF-NO (p = 0.044) and NF-OP (p = 0.023), and during FA-OP compared to NF-NO (p = 0.048). No differences in cadence were found between NF-NO and NF-OP (p = 0.669), or between FA-NO and FA-OP (p = 0.287).

9.3.1.2 Pacing analysis

Mean power outputs per kilometre are shown in Figure 9.3. Main effects for condition (F = 4.127, P = 0.014), and segment (F = 5.821, P = 0.026), and an interaction effect for condition x segment (F = 2.643, P = 0.017) were found, indicating differences in pacing profile between conditions. Post hoc analysis revealed a faster initial pace during NF-OP compared to NF-NO, with higher power outputs between 0-1 km (p = 0.026). In addition, a faster end spurt (3-4 km) was noticed in NF-OP compared to NF-NO (p = 0.031). No differences in pacing were reported between NF-NO and FA-NO, NF-OP and FA-OP, or between FA-NO and FA-OP.

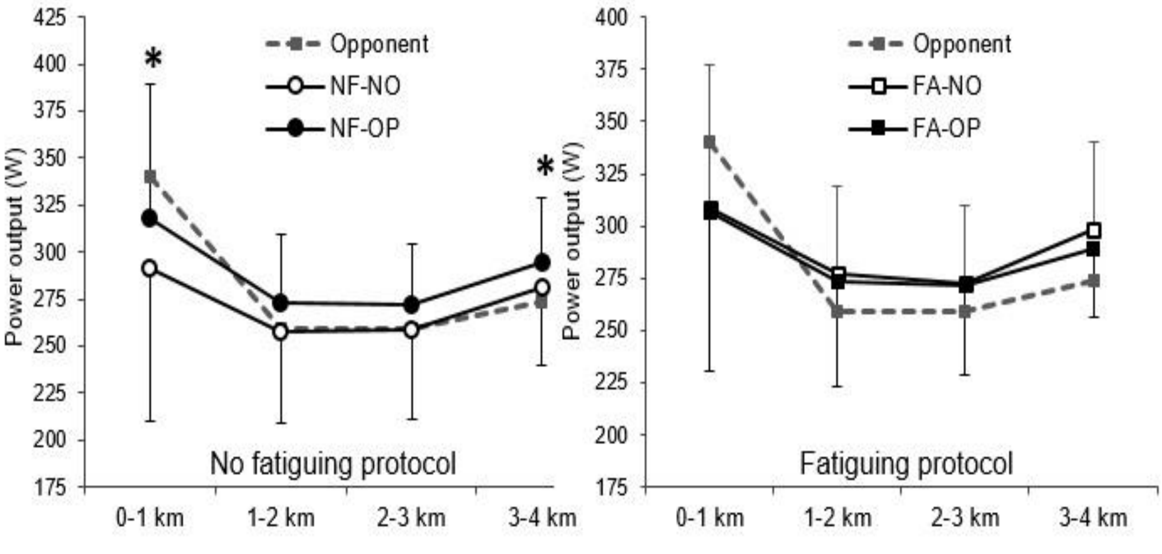

Figure 9.3 Average power output per kilometre segment for each experimental condition in Study I. In addition, the average power output per kilometre of the virtual opponent in the experimental conditions NF-OP and FA-OP is displayed.

*Difference between NF-NO and NF-OP (P < 0.05)

A main effect for heart rate was found for condition (F = 8.681, P < 0.001) and segment (F = 132.3, P < 0.001). An interaction effect was reported for condition x segment (F = 6.365, P = 0.001). Post hoc tests showed heart rate values were higher in the time trials in which a pre-fatiguing protocol had to be completed during the first (all P < 0.01) and second kilometre. In addition, heart rate was higher in NF-OP compared to NF-NO in the first kilometre. A main effect for condition (F = 3.911, P = 0.017), and segment (F = 20.99, P < 0.001), but no interaction effect for condition x segment (F = 1.027, P = 0.427) was found for cadence.

Mean RPE scores per point of asking for each experimental condition are shown in Table 9.2. Main effects for condition (F = 3.622, P = 0.024), and point of asking (F = 137.2, P < 0.001), and an interaction effect for condition x point of asking (F = 2.967, P = 0.028) were found. Post-hoc analysis revealed higher RPE scores after 100 seconds into the time trial in both FA-NO and FA-OP compared to NF-NO (p = 0.001 and p = 0.001, respectively) and NF-OP (p = 0.009 and p = 0.042, respectively). In addition, RPE was higher after 200 seconds into the time trial in both FA-NO and FA-OP compared to NF-NO (p = 0.020 and p = 0.001, respectively).

Table 9.2 Mean ± SD values for the RPE of the participant per experimental condition in Study 1 after completing their assigned protocol (rest or 10 min at 67% peak power output) and time trial, and 100 sec, 200 sec and 300 sec after starting their time trial.

	Protocol ^{A,B,C,D}	**TT_{100sec}** ^{A,B,C,D}	**TT_{200sec}** ^{A,B}	**TT_{300sec}**	**TT_{Finish}**
NF-NO	6.6 ± 0.7	13.3 ± 1.5	15.1 ± 1.4	16.8 ± 1.7	18.7 ± 1.4
NF-OP	7.0 ± 0.8	13.7 ± 2.0	15.7 ± 1.4	17.4 ± 1.7	18.7 ± 1.1
FA-NO	13.5 ± 1.3	14.8 ± 1.7	16.1 ± 1.5	17.6 ± 1.5	18.8 ± 1.1
FA-OP	14.1 ± 1.5	14.8 ± 1.7	16.3 ± 1.4	17.2 ± 1.3	18.8 ± 1.1

^{A} Difference between NF-NO and FA-NO (P < 0.05), ^{B} Difference between NF-NO and FA-OP (P < 0.05),
^{C} Difference between NF-OP and FA-NO (P < 0.05), ^{D} Difference between NF-OP and FA-OP (P < 0.05)

9.3.2 STUDY 2

9.3.2.1 Performance analysis

Mean (±SD) finishing time, power output, heart rate, and cadence for the four experimental time trial conditions in Study 2 are shown in Table 9.3. A main effect was found for finishing times (F = 5.497; p = 0.019), power output (F = 6.640; p = 0.001), and heart rate (F = 3.080; p = 0.032), but not for cadence (F = 1.680; p = 0.179). Post hoc analysis revealed a difference in finishing time between CO-NO and CO-OP (p = 0.019), CO-NO and DJ-NO (p = 0.014), CO-OP and DJ-OP (p = 0.047), CO-OP and DJ-NO (p = 0.011), and DJ-NO and DJ-OP (p = 0.022). Only between CO-NO and DJ-OP no difference in finishing time was reported (p = 0.311). Similarly, participants showed a lower mean power output in CO-NO compared to CO-OP (p = 0.023), DJ-NO compared to CO-NO (p = 0.007), DJ-OP compared to CO-OP (p = 0.034), DJ-NO compared to CO-OP (p = 0.005), and DJ-NO and DJ-OP (p = 0.010). No differences in mean power output were found between CO-NO and DJ-OP (p = 0.297). Finally, post-hoc analysis only revealed a difference between DJ-NO and DJ-OP in terms of average heart rate (p = 0.043).

Table 9.3 Mean ± SD values for the time trial performance variables completion time, power output, heart rate and cadence per experimental condition in Study 2.

	CO-NO	CO-OP	DJ-NO	DJ-OP
Completion Time ^{A,B,C,D,E} (sec)	372.0 ± 16.6	368.6 ± 14.1	380.5 ± 23.0	374.1 ± 18.8
Power Output ^{A,B,C,D,E} (W)	309.5 ± 35.6	316.2 ± 32.8	294.4 ± 45.7	305.5 ± 40.4
Heart rate ^{E} (bpm)	160.0 ± 15.6	162.0 ± 16.4	160.1 ± 15.1	162.4 ± 15.3
Cadence (rpm)	99.0 ± 3.8	98.9 ± 4.5	97.9 ± 5.7	98.6 ± 5.5

^{A} Difference between CO-NO and CO-OP (P < 0.05); ^{B} Difference between CO-NO and DJ-NO (P < 0.05); ^{C} Difference between CO-OP and DJ-NO (P < 0.05); ^{D} Difference between CO-OP and DJ-OP (P < 0.05); ^{E} Difference between DJ-NO and DJ-OP (P < 0.05)

9.3.2.2 Pacing analysis

Mean power outputs per kilometre are shown in Figure 9.4. Main effects for condition ($F = 6.640$, $P = 0.001$), and segment ($F = 11.310$, $P = 0.005$), and an interaction effect for condition x segment ($F = 3.546$, $P = 0.025$) were found for power output, indicating differences in pacing behaviour between conditions. Post hoc analysis revealed a faster initial pace during CO-OP compared to CO-NO, with a higher mean power output between 0-1 km ($p = 0.029$). In addition, a higher mean power output between 0-1 km was reported during DJ-OP compared to DJ-NO ($p = 0.009$). Moreover, the average power output in CO-NO between 1-2 km was higher compared to DJ-NO ($p = 0.032$). No differences in pacing were reported between CO-OP and DJ-OP.

Main effects for condition ($F = 3.080$, $P = 0.032$), and segment ($F = 170.8$, $P < 0.001$) were found for heart rate, but no interaction effect for condition x segment ($F = 1.449$, $P = 0.161$). In addition, neither main effects for condition ($F = 1.680$, $P = 0.179$) and segment ($F = 0.314$, $P = 0.635$), nor an interaction effect for condition x segment ($F = 0.911$, $P = 0.434$) was found for cadence.

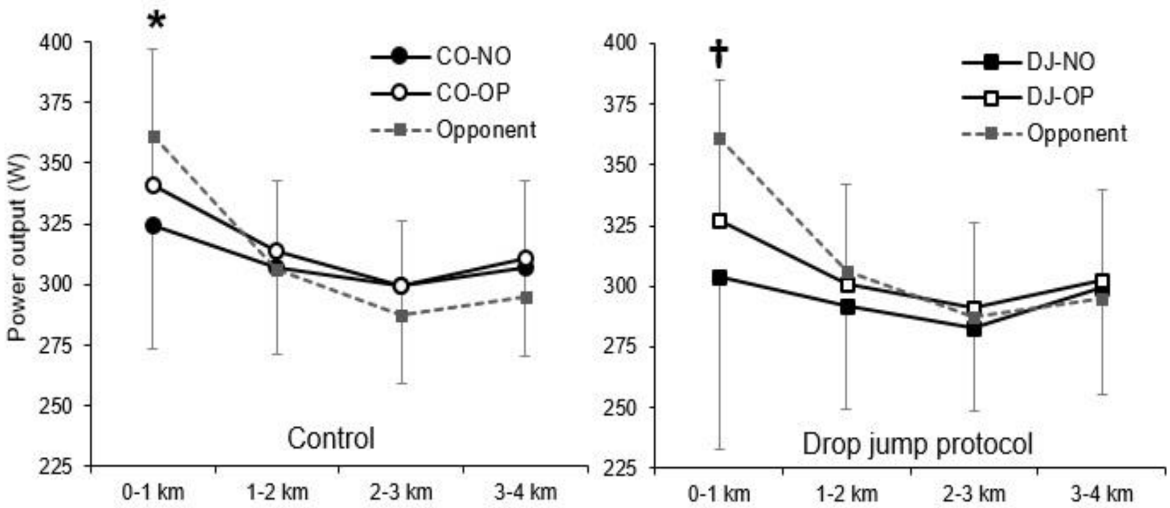

Figure 9.4 Average power output per kilometre segment for each experimental condition in Study II. In addition, the average power output per kilometre of the virtual opponent in the experimental conditions CO-OP and DJ-OP is displayed. *Difference between CO-NO and CO-OP ($P < 0.05$); †Difference between DJ-NO and DJ-OP ($P < 0.05$)

Mean RPE scores after the eccentric fatiguing protocol, prior the time trial start, and per kilometre for each experimental condition in Study 2 are shown in Table 9.4. RPE showed a main effect for condition (F = 9.033; P < 0.001), and segment (F = 209.7; P < 0.001), and an interaction effect for condition x segment (F = 9.787 ; P = 0.001). Post-hoc analysis revealed a higher RPE after the eccentric fatiguing exercise (DJ-NO and DJ-OP) compared to the control condition (CO-NO and CO-OP; all P < 0.01). However, no differences in RPE between the experimental conditions were found right before, during or directly after finishing the time trial.

Table 9.4 Mean ± SD values for the RPE per experimental condition in Study 2 after completing their assigned protocol (rest or 80 drop jumps), prior to their time trial, and per kilometre after starting their time trial, and directly after finishing.

	Protocol A,B,C,D	**TT-0 km**	**TT-1 km**	**TT-2 km**	**TT-3 km**	**TT-Finish**
CO-NO	6.6 ± 0.7	7.4 ± 1.1	14.4 ± 1.1	15.9 ± 1.5	17.4 ± 1.0	19.0 ± 0.9
CO-OP	6.9 ± 0.9	7.7 ± 1.3	14.6 ± 1.6	16.5 ± 1.9	17.8 ± 0.9	19.2 ± 1.0
DJ-NO	11.4 ± 3.7	7.7 ± 1.5	14.1 ± 2.2	16.0 ± 1.4	17.1 ± 1.1	18.8 ± 0.9
DJ-OP	12.1 ± 1.7	8.2 ± 1.3	15.2 ± 1.6	16.4 ± 1.6	17.8 ± 0.8	19.1 ± 0.9

[A] Difference between CO-NO and DJ-NO (P < 0.05), [B] Difference between CO-NO and DJ-OP (P < 0.05), [C] Difference between CO-OP and DJ-NO (P < 0.05), [D] Difference between CO-OP and DJ-OP (P < 0.05)

9.3.2.3 Neuromuscular adjustments

Mean (±SD) MVC force, PT force and VA prior and after the fatiguing protocol, and after the time trial per experimental condition can be found in Figure 9.5. A main effect was found for time (F = 31.93; p < 0.001) and condition (F = 3.200; p = 0.039) for the MVC force. Post-hoc analysis showed no differences between conditions. The main effect for time showed a decrease in MVC force after each point in time. Furthermore, an interaction effect was reported for condition x time (F = 9.736; p < 0.001) for the MVC force. Post-hoc analyses revealed that the force decline after versus prior the fatiguing protocol was relatively greater in in DJ-NO and DJ-OP compared to CO-NO and CO-OP (all $p < 0.01$). Moreover, the relative MVC force decline after the time trial versus prior the fatiguing protocol was greater after CO-OP compared to CO-NO ($p = 0.048$), DJ-OP compared to DJ-NO ($p = 0.025$), DJ-NO compared to CO-NO ($p = 0.026$), DJ-OP compared to CO-NO ($p = 0.002$), and DJ-OP compared to CO-OP ($p = 0.010$).

The VA showed a main effect for time ($F = 7.421$; $p = 0.001$), and condition ($F = 36.79$; $p < 0.001$). Post-hoc analyses indicated a higher voluntary activation in DJ-NO and DJ-OP compared to CO-NO ($p = 0.026$ and $p = 0.002$, respectively). In addition, the main effect for time indicated a decrease in VA after each point in time. Finally, an interaction effect was reported for condition x time ($F = 5.369$; $p < 0.001$). Post-hoc analyses showed a greater reduction in VA after the fatiguing protocol compared to prior in DJ-NO and DJ-OP compared to CO-NO and CO-OP (all $p < 0.05$). However, no differences were found between conditions after the time trial compared to prior the protocol.

The PT force showed a main effect for time ($F = 30.89$; $p < 0.001$), but not for condition ($F = 2.124$; $p = 0.121$), indicating smaller potentiated doublet-twitch forces after each point in time. Furthermore, an interaction effect for condition x time was revealed ($F = 12.69$; $p < 0.001$). Post-hoc analyses showed that the force decline after the fatiguing protocol versus prior was relatively greater in in DJ-NO and DJ-OP compared to CO-NO and CO-OP (all $p < 0.001$). Moreover, a greater relative force decline post-time trial versus prior the protocol was reported in CO-OP versus CO-NO ($p = 0.030$), DJ-NO versus CO-NO ($p = 0.008$), DJ-OP versus CO-NO ($p = 0.001$), and DJ-OP versus DJ-NO ($p = 0.045$), while the difference in DJ-OP versus CO-OP nearly reached significance ($p = 0.054$).

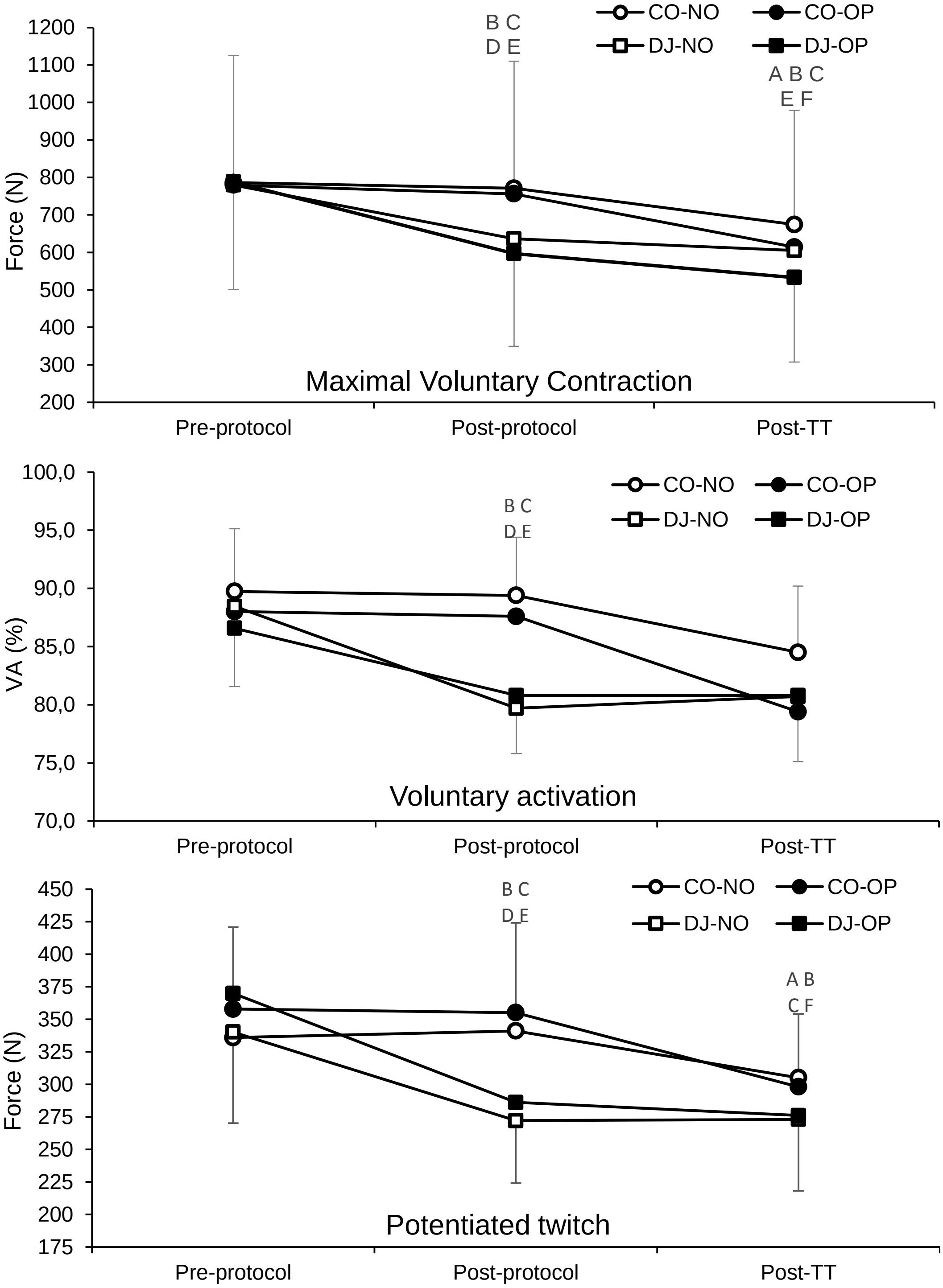

Figure 9.5 Neuromuscular function of the knee extensors in terms of maximal voluntary contraction force (MVC; upper panel), potentiated doublet-twitch force (PT; middle) and voluntary activation (VA; lower) before and after the fatiguing protocol, and after the 4 km time trial.

[A] Difference in relative decline related to prior protocol between CO-NO and CO-OP ($P < 0.05$); [B] Difference in relative decline related to prior protocol between CO-NO and DJ-NO ($P < 0.05$), [C] Difference in relative decline related to prior protocol between CO-NO and DJ-OP ($P < 0.05$), [D] Difference in relative decline related to prior protocol between CO-OP and DJ-NO ($P < 0.05$), [E] Difference in relative decline related to prior protocol between CO-OP and DJ-OP ($P < 0.05$), [F] Difference in relative decline related to prior protocol between DJ-NO and DJ-OP ($P < 0.05$)

9.4 Discussion

The present study examined the interaction between external stimuli and internal bodily state in the context of pacing regulation. This has been done by manipulating the level of pre-fatigue status (internal bodily state) and the presence of an opponent (external stimulus). It has been shown that the faster initial pace and enhanced performance evoked by the opponent's behaviour disappeared after the induction of a moderate level of fatigue via a cycling protocol prior to the time trial. However, participants did adopt a faster initial pace and were able to improve their performance when riding against an opponent when isolated locomotor muscle fatigue was induced via an eccentric fatiguing protocol. Our findings illustrate the importance of the interaction of afferent feedback, external stimuli and perceived exertion on the regulation of the exercise intensity.

Previous research exploring the effect of a competitor on pacing and performance have focused mainly on the effect of presenting or manipulating the opponent (Chapter 4; Williams *et al.*, 2015a, 2015b; Jones *et al.*, 2016b; Corbett *et al.*, 2012; Tomazini *et al.*, 2015; Shei *et al.*, 2016). In line with previous research (Chapter 4; Williams *et al.*, 2015a, 2015b; Corbett *et al.*, 2012), our findings revealed that trained cyclists were able to improve their performance when an opponent was present in unfatigued conditions. Moreover, they confirmed that presenting a faster starting opponent could indeed invite a cyclist to adopt a faster initial pace in unfatigued conditions (see Chapter 4). The present study adds onto the existing knowledge by not only manipulating the external stimulus (i.e. the opponent), but also the internal status of the athlete prior to the time trial.

9.4.1 The effect of a moderate intensity cycling protocol when riding against an opponent

The presence of an opponent did not lead to an improvement in performance when participants were fatigued via a cycling protocol prior to their 4-km time trial. In addition, the evoked response by the opponent to adopt a faster initial pace disappeared. Crucial factor in this lack of an effect seems to be the increased level of perceived exertion in the initial stages of the time trial after the fatiguing protocol compared to the unfatigued time trials. The importance of perceived exertion as a key regulator in pacing has been highlighted frequently (De Koning, Foster, Bakkum, *et al.,* 2011; St Clair Gibson *et al.,* 2006; Abbiss *et al.,* 2015; Joseph *et al.,* 2008). Similarly, perception of exertion has often been related to performance (Marcora and Staiano, 2010; St Clair Gibson *et al.,* 2006). It was shown in Chapter 8 that the enhanced performance when riding against an opponent resulted into a greater decline in voluntary and evoked muscle force, but did not affect perceived exertion. In addition, a change in attentional focus from internal to external, deterring perceived exertion when an opponent was present, has been reported (Chapter 6; Williams *et al.,* 2015b).

Previous studies showed that the induction of moderate to high levels of (perceived) fatigue before the start of a race, caused by either a pre-fatiguing protocol (Amann and Dempsey, 2008; Correia-Oliveira *et al.,* 2014; De Morree and Marcora, 2013) or intensive training periods (Skorski *et al.,* 2015), evoked a more conservative starting pace. Surprisingly, the induction of a moderate level of fatigue via the cycling protocol in advance of the time-trial, did not negatively affected time trial performance in this study. Nevertheless, there are several indications that the 10-min fatiguing protocol did induced a moderate level of fatigue in our participants. For example, relatively higher heart rate values and higher RPE scores in the initial phase of the time-trial were reported in the pre-fatigued time trial conditions. Moreover, the fatiguing protocol was intended to induce a moderate level of fatigue in the participants, not to exhaust them. Still, previous research reported a 10-min fatiguing protocol at 67% of PPO resulted into a decreased performance (Amann, 2011). A possible explanation for the lack of decrement in performance might be a post-activation potentiation (PAP) after the fatiguing protocol. However, while the acute effect of PAP in endurance athletes after different running exercises has been reported (Boullosa and Tuimil, 2009; García-Pinillos *et al.,* 2015), it is unknown whether PAP would influence performance and pacing during endurance activities (Del Rosso *et al.,* 2016).

9.4.2 The effect of an eccentric exercise protocol when riding against an opponent

The primary aim of the eccentric fatiguing exercise was to isolate locomotor muscle fatigue, in order to examine the effect of locomotor muscle fatigue on pacing regulation with and without an opponent. In this respect, an eccentric fatiguing protocol has been shown to induce a significant reduction in muscle strength, without significant metabolic stress and consequent accumulation of muscle metabolites (Skurvydas *et al.,* 2000; Skurvydas *et al.,* 2002; Marcora *et al.,* 2008; De Morree and Marcora, 2013). In addition, eccentric exercise has been shown to not alter the afferent activity of muscle spindles and Golgi tendon organs (Gregory *et al.,* 2002; Gregory *et al.,* 2004). Furthermore, due to the very low aerobic demands of the drop jump protocol, it does likely only induce very low levels of respiratory muscle fatigue. Finally, participants started their time trials 30 minutes after the eccentric fatiguing protocol to avoid the confounding effects of DOMS (Twist and Eston, 2009; Marcora and Bosio, 2007).

Our results in the time trials riding alone confirm the findings of De Morree and Marcora (2013), who used a comparable eccentric fatiguing protocol. The eccentric fatiguing protocol did lead to a decrement in performance when riding alone compared to the control condition. In addition, the eccentric fatiguing protocol induced a degree of locomotor muscle fatigue similar to that observed after the cycling time trial in the control conditions, and as observed in De Morree and Marcora (2013). As suggested by De Morree and Marcora (2013), the slower pace in the eccentric fatigued time trials will likely be a behavioural response to the increased level of perceived exertion caused by the locomotor muscle fatigue.

In contrast to the moderate-intensity cycling protocol, when locomotor muscle fatigue was induced via an eccentric fatiguing protocol participants did adopt a faster initial pace and were able to improve their performance when riding against an opponent. Moreover, similar to our findings in Chapter 8, riding against an opponent evoked a faster initial pace, improved performance and resulted into greater decrements in MVC and PT force after the time trial, without changing the perceived exertion of our participants during the time trial, even after the eccentric fatiguing protocol. As a result, the performance when riding against a virtual opponent after an eccentric fatiguing protocol did not even differ compared to riding alone without the fatiguing protocol.

9.4.3 Interaction of external stimuli, internal bodily state and perceived exertion

Our results indicate that locomotor muscle fatigue is most likely not (directly) the cause of the lack of behavioural response to the opponent as shown after the moderate-intensity cycling protocol. That is, when only locomotor muscle fatigue is induced via the eccentric fatiguing protocol, the opponent effect is still apparent. In this respect, the lack of a behavioural response to the opponent after the moderate-intensity cycling protocol is likely related to an increased afferent feedback from the fatigued locomotor muscles or the increase in respiratory muscle fatigue induced by the cycling protocol. Indeed, both afferent feedback via Group III and IV muscle afferents (Amann, 2011;

Blain *et al.*, 2016) and respiratory muscle fatigue (Romer and Polkey, 2008) have been shown to influence exercise performance. However, the greater decline in MVC force and in particular PT force when riding against an opponent, suggests that the presence of a virtual opponent may counteract at least to a certain extent the influence of afferent feedback on the decision-making process involved in pacing.

Despite the different fatigue-inducing interventions prior to the time trials, perceived exertion still appears to be the key regulator of the exercise intensity in all of them. Indeed, exercising in conditions such as hypoxia (Périard and Racinais, 2016; Johnson *et al.*, 2009), hyperoxia (Tucker *et al.*, 2007), or hot temperatures (Périard and Racinais, 2016) alters power output, but not rate of perceived exertion over the race compared to control conditions. In this sense, the presence of a virtual opponent seems to reduce one's perception of exertion, possibly related to motivational processes (McCormick *et al.*, 2015) or attentional distractions (Lohse and Sherwood, 2011), consequently leading to an improvement in performance. Based on the increased level of peripheral fatigue after riding against an opponent, even after an eccentric fatiguing protocol prior the time trial, it could be argued that the effect of an external stimulus on perceived exertion is mainly related to the ability to counteract afferent feedback to a certain extent. In this perspective, our findings support the assumption that an exerciser's perceived action capabilities in terms of exercise regulation are mainly dependent on the exerciser's perceived level of exertion.

9.5 Conclusion

The present study has shown once again that providing an external stimulus (i.e. presence of an opponent) could evoke a different response in terms of pacing. However, the evoked response by the opponent to adopt a faster initial pace appeared to diminish when the internal status of the participants was altered due to a moderately fatiguing cycling protocol before the start of the time trial. This lack of behavioural response to the opponent appears not to be related to an increased level of locomotor muscle fatigue, as the pacing response to the behaviour of an opponent is still apparent after an eccentric fatiguing protocol. In this respect, our findings highlight the complex interplay between external stimuli and internal bodily state, and the importance of perceived exertion in the decision-making process involved in pacing.

PART V – SUMMARY AND DISCUSSION

CHAPTER 10

General discussion

10.1 Introduction

The goal-directed regulation of the exercise intensity over an exercise bout has been shown to be an essential determinant for performance. In order to achieve an optimal distribution of energy, exercisers are required continuously to make decisions about how and when they are going to invest their limited available energy resources (Smits *et al.*, 2014). As indicated by previous research, exercisers seem to be in general well capable in choosing an appropriate pacing strategy in non-competitive time-trial exercise. Yet the regulatory mechanisms of the chosen exercise intensity during exercise are still strongly debated. There are several different theories around that try to explain the decision-making process involved in pacing. However, despite the variety of proposed pacing theories, what all seem to agree on is the importance of sensations of fatigue and a willingness to tolerate discomfort, in anticipation of future rewards.

Interestingly, in terms of the studies performed related to pacing, we can see that the main focus until recently has been on the exerciser itself, and manipulations that affected the internal bodily state of the exerciser, often neglecting what is happening around the exerciser. Moreover, the critical review of literature in Chapter 2 has shown that most of the existing theories regarding exercise regulation and previous experimental and modelling studies focused solely on time-trial exercise (Hettinga *et al.*, 2017). These studies provided interesting insights into the theoretical optimal pacing strategies for a given distance and onto how the exercise intensity is regulated in a non-competitive time-trial setting, where the influence of external stimuli is minimised due to the laboratory set-up. As a result, the ecological validity of these studies to competitive sports can be questioned as in many sports completion of the event in the fastest possible finishing time is not the primary goal. In contrast, when all contenders start at the same time and the winner of the event is the one who passes the finish line first, it is not the absolute, but the relative finishing time that is of importance. Indeed, observational studies, describing the adopted pacing strategies in real-life competitive sports, clearly indicated that in many sports athletes decide to adopt a pacing strategy different from the theoretical optimal one based on drafting possibilities and expectations or actions of any opponent who affect their winning chances (Konings *et al.,* 2016; Hettinga *et al.,* 2017; Hanley, 2015; Renfree *et al.*, 2014b; Edwards *et al.,* 2016).

The lack of pacing studies focussing on what is happening around the exerciser has increasingly been brought to attention in the last few years by different research groups, arguing that the outcome of the decision-making process involved in pacing is based on the combination of an athlete's internal state and the external cues around the athlete. The present thesis attempted to address this issue by highlighting the external world around the exerciser and its effect on pacing via arguably the most important external variable in real-life competitions: the opponent. As addressed in Chapter 1 and 2, we explored the effect of an opponent via an examination and manipulation of three different aspects: the opponent, the competitive environment, and the athlete itself. In the next section, we will evaluate the outcomes for these three different aspects based on the findings of the previous chapters.

10.2 The effect of competition on pacing regulation

10.2.1 The opponent

Chapter 3 and 4 of this thesis focussed on the question how the behaviour of another competitor impacts on pacing regulation. Previous research provided already indications for an effect of competitors on pacing regulation. Yet these studies did not prove that exercisers alter their pacing because of other competitors, but rather had shown they changed their pacing behaviour from the theoretical optimum, possibly due to the other competitors. For example, it has been shown before that elite short track speed skaters appear to be highly variable in their initial pace. Chapter 3 revealed that this high variability could be explained by the speed skaters adjusting their pacing behaviour in this phase based on the behaviour of their opponents, as the variability in pace between the competitors within a race is rather low. Yet one could still have argued these pacing adjustments are made to profit from sport-specific side-effects related to the opponent (e.g. the ability to draft) rather than because of the opponent itself.

Therefore, an laboratory study was designed in Chapter 4 to provide experimental evidence for the influence of the behaviour of an opponent on exercise regulation. The outcomes of this study revealed that even in a situation where changing the pacing behaviour based on the virtual opponent had neither a beneficial nor a detrimental effect for the exerciser, participants still adjusted their initial pace based on the behaviour of their competitor. That is, a faster starting opponent evoked a faster initial pace compared to a slower starting opponent. Both chapters indicated that the effect of an opponent on pacing behaviour compared to riding alone mainly seems to occur in the initial stages of a race. In addition, the participants were also able to improve their performance in the presence of virtual opponent. This performance improvement related to the presence of an opponent appears to remain quite stable, regardless of the level of performance of the opponent (Williams *et al.*, 2015a) or the pacing behaviour of the opponent (Chapter 4). Yet a different level of performance of the opponent appeared to evoke different psychological responses (Williams *et al.*, 2015a). Possible mechanisms, such as an increased motivation (McCormick *et al.*,

2015) and a change in attentional focus from internal to external aspects (Williams *et al.,* 2015b), have been suggested in relationship to the performance improvement seen in the presence of a virtual opponent. Yet it remained unclear how this performance improvement was established, a point we will come back to in section 10.2.3. In this sense, the visual perception of the opponent seems to be crucial for finding performance improvements such as those reported in Chapter 4. Participants in previous research involving a non-visible opponent were not able to improve performance, even if a monetary reward was offered (Hulleman *et al.,* 2007). These findings indicate that an opponent could indeed be an invitation for action, and support the assumption that perceptual affordances provided by the environment could influence the decision-making process involved in pacing regulation.

10.2.2 The competitive situation

Chapter 5 and 6 focussed on the question how the presence of competitors interacted with other external perceptive aspects in the regulation of the exercise intensity. As mentioned in the previous section, part of the high variability in initial pace during elite short track speed skating competitions could be explained by the pace adjustments of the competitors within a race to each other. However, this does not explain why the chosen initial pace between races varies greatly. Apart from the opponents as most obvious invitation for action in competition, many other external cues will be presented simultaneously to an exerciser in real-life competitive situations (Hettinga *et al.,* 2017; Smits *et al.,* 2014). Therefore, it seems likely that the response of an exerciser to an opponent is not only based on the opponent itself, but also on the context in which the opponent is presented to the exerciser. Indeed, in Chapter 5 several novel external cues were highlighted, such as the number of competitors in a race, the stage of competition, the tournament, and the start position, that need to be incorporated in understanding the complex decision-making process involved in pacing. In this respect, the competitive environment seems to affect pacing regulation via the presentation of affordances (e.g. an opponent) towards the exerciser and due to its influence on the action selection process that determines which affordances the athlete acts upon. Interestingly, similar as the effect of an opponent, the different competitive environments appeared to evoke a change in pacing mainly during the initial phase of a race.

Not only within a competitive sport, but also between different competitive sports the chosen pacing behaviour shows great variation. For example, sport disciplines with a relatively high beneficial effect of drafting behind an opponent (e.g. short track speed skating, cycling), are characterised by a slow, tactical development of the race (Noorbergen *et al.*, 2016; Konings *et al.*, 2016; Moffatt *et al.*, 2014). That is, a strategy that will assist in saving energy for the final acceleration at the end of a race. In contrast, sport disciplines where the beneficial effect of drafting is much less predominant such as race walking or middle-distance and long-distance running, are characterised by adopting a fast initial pace that they cannot be sustained until the end of the race by most of the sub-elite runners (Hanley *et al.*, 2011; Hanley, 2013; Hanley, 2014; Deaner *et al.*, 2015; Thiel *et al.*, 2012; Renfree and St Clair Gibson, 2013; Hanley, 2016). Chapter 6 examined whether the main underlying mechanism behind these differences could be the interdependency between the athlete and the opponent. Indeed, our findings revealed that cyclists adopted a significantly slower initial pace when they became more dependent on their competitor.

A consistent finding in relation to the effect of a competitor (and other external cues) was that it mainly seemed to affect the initial chosen pacing behaviour. This might be related to the perceived level of exertion of the exerciser, a variable that in general gradually inclined throughout the race (De Koning, Foster, Bakkum, *et al.*, 2011). Indeed, perceptual judgements about action possibilities provided by the environment appear to change at high levels of exertion (Bhalla and Proffitt, 1999; Pijpers *et al.*, 2007). For example, hills were judged to be steeper when participants were exhausted (Bhalla and Proffitt, 1999), and perceived maximum reaching height declined with a high perceived exertion (Pijpers *et al.*, 2007). However, these perceptual changes occurred only with higher levels of perceived exertion, as no changes in perceived action possibilities were reported at moderate levels of perceived exertion (Pijpers *et al.*, 2007). Moreover, a higher level of fatigue has been shown to alter the attentional focus from external to internal related variables (Brick *et al.*, 2016; Whitehead *et al.*, 2017). This is confirmed by our own eye tracking data in which the amount of time spent fixating at the presented feedback steadily declined over the race, regardless of the experimental condition. Nevertheless, trained cyclists did start looking for more information when riding against an opponent. An effect that became even more pronounced the more dependent the participant was to this virtual opponent.

10.2.3 The internal state of the exerciser

The primary focus of Chapter 7, 8 and 9 was on the importance of the internal state of the exerciser, the (perceived) action capabilities of the exerciser and its effect on exercise regulation during competition. For example, in several competitive sports athletes are required to complete multiple races within a few days, possibly leading to an accumulation of fatigue. In Chapter 7 the effect of preceding high-intensity race efforts on the pacing and performance of elite short track speed skaters was analysed. The findings highlighted the effect of preceding high-intensity efforts on pacing and performance and could have an crucial impact on the future race schedule as used during a competitive weekend, in order to provide an equal playing field for all contenders.

Chapter 8 explored how the performance improvement in the presence of a virtual opponent was established. This was done by relating performance improvements when riding against a virtual opponent compared to riding alone to neuromuscular adjustments in the knee extensors and perceived exertion. Trained cyclists appeared to be able to establish an improved performance, maintain a higher mean power output, and were able to handle a greater decline in muscle force in the presence of a virtual opponent. In this respect, the possible effect of afferent feedback on the decision-making process involved in pacing might be counteracted by motivational aspects (McCormick *et al.,* 2015) and/or attentional strategies (Brick *et al.,* 2016; Williams *et al.,* 2015b) related to the presence of a virtual opponent. Indeed, the presence of an opponent has been shown to alter information-seeking behaviour (Chapter 6). Despite the differences in physiological and neuromuscular variables, perceived exertion did not differ between riding alone or riding against an opponent. These findings highlight again perceived exertion as a key component in exercise regulation (Smits *et al.,* 2014; Marcora, 2008; Crewe *et al.*, 2008). In this perspective, the exerciser's perceived action capabilities in terms of exercise regulation seem to be strongly related to the exerciser's perceived level of exertion during maximal time trial exercise.

Although the importance of fatigue and fatigability has been emphasised in the context of exercise regulation and performance (Smits *et al.,* 2014; Amann *et al.,* 2013; Marcora, 2008; Enoka and Duchateau, 2016; Noakes, 2012), the number of studies that have examined the effect of high-intensity efforts in advance of a demanding, self-paced exercise task is surprisingly limited. Amann and Dempsey (2008) showed that a pre-fatiguing protocol of 67% of peak power output resulted into a decrease in 5-km time trial performance and a more conservative initial pace. An effect that could be related to the reduced excitability of the motor neurons caused by exercise-induced fatigue (Weavil *et al.,* 2016). In addition, a decreased 15-min cycling trial performance has been shown when performed after a pre-exercise of 100 drop jumps (De Morree and Marcora, 2013). However, the eccentric exercise 30 minutes in advance of the trial did not affect the pacing profile (De Morree and Marcora, 2013).

Chapters 9 attempted to add onto this knowledge by manipulating not only the initial level of fatigue, but also the external stimulus. This chapter illustrated the reciprocal interaction between the exerciser and the world around the exerciser. On one hand, an opponent might suppress an increase in the perception of exertion, despite decrements in neuromuscular function as shown in Chapter 8. On the other hand, after a pre-fatiguing cycling protocol, a virtual opponent could not evoke a change in pacing anymore. Interestingly, an eccentric fatiguing protocol, inducing a severe level of muscle fatigue without an increase in perceived exertion at the start of the race, showed still similar effects as riding against an opponent in unfatigued state in terms of pacing and performance. This indicates that locomotor muscle fatigue is likely not the reason why the effect disappeared after the pre-fatiguing cycling protocol, but is instead possibly related to an increased level of afferent feedback or respiratory muscle fatigue.

10.3 Practical applications

A better understanding of how athletes respond to their opponents could assist coaches and athletes to optimally prepare themselves for the tactical decision-making involved in athletic competitions (Smits *et al.,* 2014; Renfree *et al.,* 2014a). As demonstrated in this thesis, findings as reported in time trial exercise cannot not be 1:1 translated to actual real-life competitions. Tactical considerations, for example related to positioning or drafting possibilities, affects pacing decisions and draws athletes away from the energetically favourable strategies as would be performed in time trial exercise (Hettinga *et al.,* 2017). It was demonstrated that the behaviour of the other contenders in the race is an important determinant in elite short track speed skating competitions. For example, elite short track speed skaters adjusted their pacing response during competition heavily based on the actions and pacing behaviour of the other competitors in their race. Moreover, several external cues such as the number of competitors in a race, the stage of competition, the possibility of time qualification, competition importance and the interdependency between athlete and opponent have been identified to alter the pacing decisions of exercisers during competition.

In this sense, in order to provide coaches, athletes and practitioners with a guideline for measuring the effectiveness of an intervention previous studies have examined the within-athlete race-to-race variability of athletes, in which an improvement equal to 0.3 of the CV in within-athlete race-to-race variability is commonly accepted as the smallest worthwhile enhancement in performance (Malcata and Hopkins, 2014; Hopkins *et al.,* 1999). Although the importance of a guideline to determine whether an intervention of any kind actually leads to an quantifiable and worthwhile improvement in performance is recognised and emphasised, this thesis illustrated that in middle-distance and endurance sport disciplines with a strong interaction of tactical nature between the competitors this particular way of determining the smallest worthwhile enhancements has its limitations. That is, the smallest worthwhile enhancement of the finishing time in the 1500 m short track speed skating event would be 1.80 seconds. At first sight, this improvement could be achieved by just adopting a pacing strategy aimed at completing the event as fast as possible instead of the commonly chosen pacing strategy right now. However, in terms of performance quantified using finishing position, this tactical strategy is likely to have a detrimental effect. Yet there might be alternative ways in which it is still possible to determine a smallest worthwhile enhancement. The lap with the lowest within-athlete race-to-race variability could be used, for example, in which athletes tend to follow their own strategy and are not too much influenced by the actions of the opponents. Interestingly, for both the 1000 m as well as the 1500 m, this lap corresponds to the lap in which short track speed skaters in general achieve their fastest lap time. Using this approach, the smallest worthwhile enhancement for the 1000 m would be 0.08 sec in lap 7, and 0.09 sec in lap 11 for the 1500 m.

Another finding of the present thesis is that cyclists in the presence of a virtual opponent were able to establish an improved performance, maintain a higher mean power output, and were able to handle a greater decline in muscle force in comparison to riding alone. In this sense, the use of a visual avatar in a simulated competitive situation could be a beneficial, novel tool to use during high-intensity training sessions. Besides the obvious possibility to train together with others in high-intensity training sessions, more advanced, innovative strategies may be used by coaches to benefit from the beneficial effects of competition on performance. GPS cycle computers or running watches provide, for example, the possibility to monitor and share one's own performances. This information can be used to compare one's own current performance with previous performances or (pre-selected) performances from peers, even with real-time feedback when using fitness applications such as Strava.

Although this thesis used specifically a virtual avatar of an opponent, it can be argued that other external cues could in potential achieve similar effects. In fact, motivational and stimulating music has been shown, for example, to enhance affect and reduce ratings of perceived exertion (Karageorghis and Priest, 2012; Lima-Silva *et al.*, 2012). Moreover, observers from the opposite sex (Winchester *et al.*, 2012) and verbal encouragement (McCormick *et al.*, 2015) have also been revealed to impact perceived exertion. Finally, even a finish line could be perceived as an important external cue inviting for action, leading to the typical increase in power output/velocity typically seen at the end of race. In this respect, an important underlying mechanism for the performance improvements in the presence of an external cue appears to be the (relative) reduction in perceived exertion. Therefore, coaches are advised to use external cues in their design of training sessions for an optimal training effect. As stated above, the use of (virtual) opponents, verbal encouragement, the presence of an audience, stimulating music, or adding a clearly visible finish line are examples of external cues that can be used to achieve an alternation in perceived exertion. At the same time, coaches need to be aware of the effects of competitive elements and external cues during training sessions designed to be of a relative low-intensity when their athletes are training in a group.

Our analysis in Chapter 7 revealed the potential negative effects of preceding high-intensity race efforts during the repechage races on the performance of elite short track speed skaters later on the day. These findings could have a crucial impact on the future race schedule as used during a competitive weekend. It is recommended to complete the repechage on the first day of the tournament weekend rather than prior on the same day, in order to provide an equal playing field for all contenders.

Finally, the focus of this thesis has been on the regulation of exercise intensity in healthy, physical active people. Yet this does not imply that our findings are exclusively applicable or relevant for this specific population. Although the regulation of exercise intensity is an essential determinant for sport performance, pacing is not exclusive to sports and race performances (Edwards and Polman, 2013). A better understanding of the decision-making process involved in pacing behaviour could possibly even contribute to our general understanding of the way people pace their activities in daily life or how exercise intensity is regulated when achieving demanding goals in a rehabilitation context (Edwards and Polman, 2013). In this sense, the use of external cues providing invitations for action may be useful in the promotion of a physical active lifestyle.

10.4 The regulation of exercise intensity during competition

The present thesis has explored the integration of human-environment interactions in pacing regulation. It has shown that the behaviour of an opponent is an essential determinant in the regulation of exercise intensity, using a combination of observational and experimental studies. A behavioural response to adjust the initial pace based on the behaviour of other competitors was revealed. However, the adjustment in the initial pacing response related to other competitors appeared to depend as well on the competitive situation and the current internal state of the exerciser.

The necessity to incorporate human-environment interactions into the regulation of exercise intensity has been highlighted frequently in recent years (Hettinga *et al.,* 2017; Smits *et al.,* 2014; Renfree *et al.,* 2014a; Micklewright *et al.,* 2017). As indicated in Chapter 2, an important reason why this appears to be so difficult, is the constructivist view towards the coupling between perception and action rooted in most of present models attempting to explain pacing regulation. For example, the concept of a template is used in several pacing models (Tucker, 2009; Foster *et al.,* 2009). The robustness of these proposed (RPE) templates in time trial exercise at maximal effort is remarkable (Schallig *et al.,* 2017). In fact, even the performance improvement when riding against an opponent can possibly be explained by such a template model, as the presence of an opponent affected pacing, performance and muscle force decline, but not perceived exertion. However, where the template model appears to work excellently in time trial exercise at maximal effort, it struggles to explain the regulation of exercise intensity during real-life head-to-head competitions. In particular, the flexibility in terms of the tactical decision-making component involved in pacing, necessary to act or react onto the behaviour of an opponent, seems to be incompatible with the concept of a rather rigid template. In fact, even a change in the interdependency between exerciser and opponent was already sufficient to take people off their RPE template as used in the other time trials as shown in Chapter 6.

As alternative to the constructivist view, an ecological approach towards pacing was proposed by Smits *et al.*, (2014). According to this ecological approach, the outcome of the decision-making process involved in pacing is based on the action possibilities presented towards the exerciser during the competition. As stated in Chapter 2, this approach would ease the incorporation of human-environment interactions into the regulation of exercise intensity. In this respect, several variables have been identified in this thesis that could potentially be seen as invitations for action or could affect the action selection based on all multiple affordance presented towards the exerciser during competition, such as the behaviour of opponents, the possibility of fastest time qualification, the number of competitors or the stage of competition. In addition, previous research had shown already that an ecological concept such as optical flow does affect exercise regulation (Parry *et al.*, 2012; Parry and Micklewright, 2014).

Yet also this ecological approach towards pacing is not without any flaws. There is undeniable a strong anticipatory, strategic component in pacing regulation (Ulmer, 1996; Noakes, 2000). However, it seems possible to incorporate the anticipatory, strategic component into the ecological approach towards exercise regulation, without the need of something robust as a template. In this respect, exercisers may be able to learn based on previous experiences which of the information, both interoceptive as exteroceptive, or action possibilities presented towards the exerciser are useful and/or should be acted upon in each particular situation (Pijpers *et al.,* 2007; Smits *et al.,* 2014). Indeed, previous experience has been shown multiple times to be crucial for optimal pacing regulation (Micklewright *et al.*, 2010; Mauger *et al.*, 2009; Lambrick *et al.*, 2013; Tucker, 2009; Micklewright *et al.*, 2012), and different information-seeking behaviour is reported in experienced cyclists compared to novices (Boya *et al.,* 2017).

In this perspective, it has been proposed recently that pacing could be perceived as a self-regulatory skill of learning, that needs to be developed over the years (Elferink-Gemser and Hettinga, 2017). For example, in a longitudinal study, elite long track speed skaters distinguished themselves from non-elite skaters by the development of their pacing strategy already from an earlier age (13-15 years old) towards to the pacing strategies as used in elite 1500 m speed skating competitions, an effect that became even more apparent later on in their adolescence (Wiersma *et al.,* 2017). Furthermore, athletes with an intellectual impairment appeared to have difficulties to efficiently self-regulate their pace (Van Biesen *et al.,* 2016; Van Biesen *et al.,* 2017), emphasising the cognitive resources that are required in the regulation of exercise intensity.

This would support the idea that the selection of the most appropriate (pacing) action based on all perceived action possibilities is a skill that can be learned and developed over the years. Hence, the direct coupling between perception and action rather than in distinct serial stages within a governor region, as argued by the ecological-psychological approach towards pacing, can be consistent with the assumption that exercise intensity is regulated based on afferent and efferent information in an anticipatory way that does not exceed the limits of the body (Smits *et al.,* 2014). The affordance presented by the environment to the exerciser will always be there to be perceived (Gibson, 1979), providing the opportunity to incorporate human-environment interactions and tactical decision-making onto the regulation of exercise intensity (Smits *et al.*, 2014; Hettinga *et al.*, 2017). However, which affordances the exerciser selects to realize among the variety of affordances that are presented simultaneously and continuously, will also be based on the exerciser's motivation, previous experience, the internal state of the exerciser and/or the perceived level of exertion as demonstrated in this thesis. In addition, Pijpers *et al.*, (2007) showed that the internal state of an exerciser and the perceived level of exertion are indeed likely to play a more important role in the selection of the multiple affordances that are presented simultaneously the exerciser, rather than on the perception of the affordance itself.

Finally, our findings indicate that understanding the interaction between external cues and the internal bodily state may be a key for pushing the limits of human performance. Presenting external cues, such as a virtual avatar of an opponent, may assist in accessing a part of the exercise reserve that is not possible in "normal" conditions. Although these possibilities of pushing the limits of human performance are exciting, at the same time, it raises ethical questions regarding the potential effects for the general health and wellbeing of athletes. Why people nearly always appear to reserve part of their energy is an important question for understanding the regulation of exercise intensity, however interventions focussed on this topic and the possible consequences are not without any risk. It is beyond the scope of this thesis to answer this ethical dilemma, but is without a doubt something that coaches, practitioners and researchers need to consider in future research.

10.5 Thesis limitations

Although the research presented in this thesis has reached its aims, all research has its limitations and shortcomings. First of all, this thesis focused specifically on the effect of a competitor on pacing regulation. However, other individuals that are present during a competitive exercise task could obviously also have a range of different roles rather than solely the role of a competitor. The use of pacemakers, for example, is typical in several long-distance running events. In fact, even the presence of an observing experimenter has been shown to impact perceptual responses and performance (Winchester *et al.*, 2012). In this respect, the performance effect in the presence of an opponent might be due to the well-known concept of social facilitation. This idea of social facilitation states that the mere presence of other people will enhance the performance in speed and accuracy of well-practiced tasks (Zajonc, 1965). Within the body of work presented in this thesis it is not possible to rule out whether it is the presence of an individual that alters performance, or whether a competitor evokes a different performance effect compared to a pacemaker. In hindsight, an extra condition in one of the experimental studies, presenting the virtual avatar as a pacemaker instead of competitor, could have covered the above question.

Another potential limitation of the present thesis is the relative lack of focus on the psychological responses and effects of a competitor on the exerciser. This has partly been a deliberate decision, whereas there have been previous studies that focused in particular on this psychological aspect of a competitor. Williams *et al.* (2015b) showed, for example, that a different level of performance of the opponent appeared to affect one's self-efficacy to compete with their opponent. Moreover, the improvement in performance achieved when riding against a virtual opponent has been related to a more positive affect (Williams *et al.,* 2015b). In addition, Whitehead *et al.* (2017) revealed that associative themes, including fatigue and pain, were verbalised more frequently in the earlier stages of a time trial, whereas verbalisations about distance significantly increased in the last kilometre. Nevertheless, despite the already existing knowledge from previous research, questionnaires focused on concepts as risk perception, goal orientations (e.g. ego versus task orientation), and personality traits could have added potentially more information about individual differences in the effect of a competitor on pacing regulation.

In a similar fashion, although several different physiological measurements have been taken throughout the experimental studies in this thesis (e.g. power output, maximal voluntary contraction, voluntary activation, potentiated twitch, and perceived exertion), certain additional measurements may have been appropriate in some of the chapters. In Chapter 7 and 9, for example, differences in neuromuscular function could only be measured prior and after the time trial exercise. Statistical analyses have been employed to provide some link between what happen during the time trial and the outcomes of the measures of neuromuscular function. In this respect, lactate measurements and electromyography data from during the time trial could have been helpful to gain further insight into this process. In addition, due to a protocol error no measures of neuromuscular function were taken of the fatiguing exercise (i.e. 10 minutes at 67% PPO) used in the first study of Chapter 9. Furthermore, oxygen uptake could have been interesting measure during the experimental 4-km time trials. This particular measure has not been performed in this thesis for two reasons. First of all, the measure of oxygen uptake would require the participants to wear a mask throughout the time trial. This could potentially hinder an optimal sight to the course projected on a screen in front of them for some of the participants, which was an essential element for the experimental design. Secondly, the effect of a competitive time trial on aerobic and anaerobic energy contribution has been studies before by Corbett *et al.* (2012), revealing an increased anaerobic energy contribution when an opponent is present in 2-km time trials.

Finally, three of the chapters focused on pacing behaviour in elite short-track speed skating competitions. Inherent to the observational design of these studies, it was not possible to manipulate the competitive setting or collect additional physiological or psychological data. Additionally, it is still possible that some information in regard to the behaviour of the short-track speed skater cannot be retrieved due to variations within a lap. However, the acquired lap times are of a relatively high frequency (i.e. a lap time every 111.12m; a minimum of five data point per race). Moreover, the extensive big data set of short-track speed skating performances did allow to perform novel, innovative pacing analyses as illustrated in this thesis.

10.6 Future research directions

Future research is advised onto different competitive scenario's and its effect on pacing, and in particular onto the effect of presenting a virtual opponent that is deliberately designed to beat the participant. The used virtual opponents in this thesis were constructed in such a way that the participant had a likely chance to beat the virtual opponent. However, the action possibilities that athletes perceive appear to change with the momentum of the race (Den Hartigh *et al.*, 2017). That is, a positive momentum (i.e. catching up or increasing the lead) had a positive effect on one's perceived action possibilities in a golf putting task, while the opposite effect was reported for a negative momentum (i.e. getting behind or competitor catching up; Den Hartigh *et al.,* 2017). In fact, although a positive team momentum (i.e. catching up or increasing the lead) showed positive psychological effects on collective efficacy and task cohesion in a simulated rowing competition, a negative team momentum (i.e. getting behind or competitor catching up) did led to stronger negative changes (Den Hartigh *et al.,* 2014). Moreover, a negative momentum resulted into a rapid decline in exerted efforts of the rowing team, whereas a more appropriate regulation of exercise intensity was found during the positive momentum (Den Hartigh *et al.,* 2014). In this respect, good examples of experimental studies that manipulated the lead or chase position are Peveler and Green (2010) in cycling and Bath *et al.* (2012) in running.

The majority of studies about pacing until now, including the studies presented in this thesis, have focused on experienced individuals with excellent self-regulatory abilities. Previous experience has been shown multiple times to be crucial for an optimal regulation of exercise intensity (Micklewright *et al.,* 2010, 2012; Lambrick *et al.,* 2013), and more goal-directed information-seeking behavior is reported in experienced exercisers compared to novices (Boya *et al.,* 2017). In this perspective, to experienced exercisers the regulation of pacing behaviour might seem an easy task, but it might be more difficult for children, persons with an intellectual impairment or those who have only very limited resources available or have conditions associated with high fatigue complaints (Smits *et al.,* 2014). For individuals, ranging from highly active to sedentary, this regulatory process of pacing distribution could require pre-planning to distribute more effort to different tasks depending on their priorities, capabilities and willingness to push the physical limitations of their bodies (Smits *et al.,* 2014). As such, the process of successful regulation of effort distribution demands significant levels of cognitive skills (e.g. distance and time perception, attentional focus, pre-planning strategies, perceived exertion). Factors related to intellectual capacity, such as using previous experiences, knowledge of future physiological requirements, understanding of self-physiology, deductive reasoning and interactions with external factors, all influence this process (Smits *et al.,* 2014; Van Biesen *et al.,* 2016, 2017). Therefore, to explore how we can optimally develop and improve the skill to self-regulate our pacing decisions over time, it is essential to understand the cognitive factors that are underlying successful pacing distribution and management of fatigue over a task.

The few studies that did specifically address the ability to distribute effort over an exercise task in children or individuals with II showed that the skill to regulate effort over time might be more difficult to master than previously thought when studying highly experienced exercisers. The ability to regulate pace over time, for example, was revealed to be positively related to both the age and cognitive development of schoolchildren (Micklewright *et al.,* 2012; Lambrick *et al.,* 2013), and it was found that schoolchildren find it easier to use spatial cues during a pacing task compared with temporal cues (Chinnasamy *et al.,* 2013). Moreover, recent work showed that an intellectual impairment had a negative effect on the ability to efficiently distribute effort over an exercise bout (Van Biesen *et al.,* 2016a, 2017). In this respect, people with an intellectual impairment are also known to have deficits in a range of higher-order cognitive skills (e.g., problem-solving, logical reasoning), executive function skills (e.g., planning, inhibition) and adaptive behavior skills (e.g., interpersonal interactions, communication strategies such as self-talk) that might be particularly relevant to the regulation of exercise intensity (Van Biesen *et al.,* 2016b, 2018). However, there is still a general lack of evidence and more thorough investigation is required. More specifically; it remains unclear if and to what extent impairments in intellectual functioning, executive functioning, and adaptive behavior constrain the ability to regulate pacing over time during exercise. In this respect, the experimental settings as presented in this thesis could provide the opportunity to present challenging exercise tasks towards individuals of different intellectual capacity in a relatively well-controlled and structured situation, and seems to provide several novel opportunities to further elucidate the ability to regulate exercise intensity.

Although this review specifically focused on the effect of competitors on pacing, it can be argued that other external cues could evoke in potential similar effects. Motivational and stimulating music for example has been shown to enhance affect and reduce ratings of perceived exertion (Karageorghis and Priest, 2012; Lima-Silva *et al.*, 2012). In fact, our findings indicate that understanding the interaction between external cues and the internal bodily state may even be the key for pushing the limits of human performance. In this sense, future research is advised to explore and identify meaningful performer–environment relationships for pacing and how these relationships might change as a function of practice, training or habituation. Moreover, future research about the importance of trait characteristics onto how individuals react to an opponent is warranted. Finally, the differences in pacing behaviour during competitive and cooperative tasks, for example via studies focusing on potential differences in perceiving an individual or avatar as an opponent or a pacer, deserves more attention.

10.7 Summary

The regulation of exercise intensity is an intriguing area of sport science research, and a complex one as demonstrated by the multitude of different theories regarding pacing that are around attempting to explain how this is done. Previous research revealed optimal pacing strategies in time trial exercise and the importance of feedback regarding the internal bodily state. The present thesis adds onto this knowledge by highlighting the external world around the exerciser and its effect on pacing regulation. How external variables, in addition to feedback regarding the internal bodily state, affect pacing regulation was demonstrated by focusing on arguably the most important external variable in real-life competitions: the opponent.

In a critical review of literature we showed that, despite the differences between the presented pacing models, some factors appeared to be shared by most of them. For example, the importance of sensations of fatigue and the perceived level of exertion and/or effort, knowledge about the endpoint and the expected remaining distance/duration, and a willingness to tolerate discomfort in anticipation of future rewards. Remarkably, nearly all current theories regarding pacing regulation seem to be rooted in a constructivist approach towards perception and action. However, as argued in Chapter 1 and 2, an ecological approach towards exercise regulation seems to be the most appropriate to incorporate human-environment interactions onto pacing regulation (Smits *et al.,* 2014). According to the ecological approach, the outcome of the decision-making process involved in pacing is based on the action possibilities presented towards the exerciser during the competition, providing the opportunity to incorporate human-environment interactions and tactical decision-making into the regulation of exercise intensity (Smits *et al.,* 2014; Hettinga *et al.,* 2017).

In the previous chapters it has been shown how opponents could invite exercisers to adjust their pacing behaviour in real-life competitions (Chapter 3) and in a controlled laboratory situation (Chapter 4). Several external factors were identified affecting the decision-making process involved pacing during competition, such as the number of competitors, the stage of competition or the possibility of time fastest qualification (Chapter 5). Moreover, it has been illustrated that even the same opponent could evoke different pacing responses and alter the information-seeking behaviour, depending on the competitive situation that is presented towards the exerciser (Chapter 6). It has been demonstrated how an accumulation of preceding high-intensity race efforts could impact the pacing and performance of elite athletes during their competition (Chapter 7). Finally, the reciprocal interaction in pacing decision-making between the effect of an opponent and the internal state of the exerciser was demonstrated, providing novel insights into the regulatory mechanism of exercise regulation. On one hand, an opponent might suppress an increase in the perception of exertion, despite decrements in neuromuscular function (Chapter 8). On the other hand, after a pre-fatiguing cycling protocol, a virtual opponent could evoke neither a change in pacing nor performance. Interestingly, an eccentric fatiguing protocol, inducing a severe level of muscle fatigue without an increase in perceived exertion at the start of the race, showed still similar effects as riding against an opponent in unfatigued state in terms of pacing and performance (Chapter 9).

Finally, in the present chapter, we discussed how the direct coupling between perception and action rather than in distinct serial stages within a governor region, as argued by the ecological-psychological approach towards pacing, can be consistent with the assumption exercise intensity is regulated based on afferent and efferent information in an anticipatory way that does not exceed the limits of the body (Smits *et al.*, 2014). That is, affordances presented by the environment to the exerciser will always be there to be perceived (Gibson, 1979), providing the opportunity to incorporate human-environment interactions and tactical decision-making into the regulation of exercise intensity (Smits *et al.*, 2014; Hettinga *et al.*, 2017). However, which affordances the exerciser selects to realise among the variety of affordances that are presented simultaneously and continuously, will also be based on the exerciser's motivation, previous experience, the internal state of the exerciser and/or the perceived level of exertion. The present findings of this thesis emphasise the importance of what is happening around the exerciser on the outcome of the decision-making process involved in pacing, and highlight the necessity to incorporate human-environment interactions into any model that attempts to explain the regulation of exercise intensity.

References

Abbiss, C.R., Peiffer, J.J., Meeusen, R. and Skorski, S. (2015). Role of ratings of perceived exertion during self-paced exercise: What are we actually measuring? *Sports Medicine*, **45**(9), 1235–1243.

Abbiss, C.R. and Laursen, P.B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Medicine*, **38**(3), 239–252.

Abbiss, C.R. and Laursen, P.B. (2005). Models to explain fatigue during prolonged endurance cycling. *Sports Medicine*, **35**(10), 865–898.

Al, M., Konings, M.J., De Jong, R. and Hettinga, F.J. (2016). Overtaking behaviour in elite and sub-elite 1500m short track speed skaters [abstract]. *In: Book of Abstract European College of Sport Sciences 2016, Vienna, Austria*, **21**, 115-116.

Amann, M. (2011). Central and peripheral fatigue: Interaction during cycling exercise in humans. *Medicine and Science in Sports and Exercise*, **43**(11), 2039–2045.

Amann, M., Venturelli, M., Ives, S.J., McDaniel, J., Layec, G., Rossman, M.J. and Richardson, R.S. (2013). Peripheral fatigue limits endurance exercise via a sensory feedback-mediated reduction in spinal motoneuronal output. *Journal of Applied Physiology*, **115**(3), 355–364.

Amann, M. and Dempsey, J.A. (2008). Locomotor muscle fatigue modifies central motor drive in healthy humans and imposes a limitation to exercise performance. *Journal of Physiology*, **586**(1), 161–173.

Astorino, T. and Cottrell, T. (2012). Reliability and validity of the Velotron racermate cycle ergometer to measure anaerobic power. *International Journal of Sports Physiology and Performance*, **33**(3), 205–210.

Bath, D., Turner, L.A., Bosch, A.N., Tucker, R., Lambert, E.V., Thompson, K.G. and St Clair Gibson, A. (2012). The effect of a second runner on pacing strategy and RPE during a running time trial. *International Journal of Sports Physiology and Performance*, **7**, 26–32.

Behm, D., Whittle, J., Button, D. and Power, K. (2002). Intermuscle differences in activation. *Muscle and Nerve*, **25**(2), 236–243.

Bhalla, M. and Proffitt, D. (1999). Visual-motor recalibration in geographical slant perception. *Journal of Experimental Psychology, Human Perception and Performance*, **25**(4), 1076–1096.

Bishop, D.J., Bonetti, D. and Dawson, B. (2002). The influence of pacing strategy on VO2 and supramaximal kayak performance. *Medicine and Science in Sports and Exercise*, **34**(6), 1041–1047.

Blain, G.M., Mangum, T.S., Sidhu, S.K., Weavil, J.C., Hureau, T.J., Jessop, J.E., Bledsoe, A.D., Richardson, R.S. & Amann, M. (2016). Group III/IV muscle afferents limit the intramuscular metabolic perturbation during whole body exercise in humans. *Journal of Physiology*, **594**(18), 5305–5315.

Borg, G.A. (1998). Borg's perceived exertion and pain scales, *Champaign, IL, US: Human Kinetics.*

Borg, G.A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, **14**(5), 377–381.

Bossi, A.H., Matta, G.G., Millet, G.Y., Lima, P., Pertence, L.C., de Lima, J.P. and Hopker, J.G. (2017). Pacing strategy during 24-hour ultramarathon-distance running. *International Journal of Sports Physiology and Performance*, **12**(5), 590–596.

Boullosa, D.A. and Tuimil, J.L. (2009). Post activation potentiation in distance runners after two different field running protocols. *Journal of Strength and Conditioning Research*, **23**(5), 1560–1565.

Boya, M., Foulsham, T., Hettinga, F.J., Parry, D., Williams, E.L., Jones, H.S., Sparks, S.A., Marchant, D.C., Ellison, P., Bridge, C.A., McNaughton, L.R. and Micklewright, D. (2017). Information acquisition differences between experienced and novice time trial cyclists. *Medicine and Science in Sports and Exercise*, **49**(9), 1884–1898.

Brick, N.E., Campbell, M.J., Metcalfe, R.S., Mair, J.L. and MacIntyre, T.E. (2016). Altering pace control and pace regulation: Attentional focus effects during running. *Medicine and Science in Sports and Exercise*, **48**(5), 879–886.

Brisswalter, J., Bieuzen, F., Giacomoni, M., Tricot, V. and Falgairette, G. (2007). Morning to evening differences in oxygen uptake kinetics in short duration cycling exercise. *Chronobiology International*, **24**(3), 495–506.

Brown, M.R., Delau, S. and Desgorces, F.D. (2010). Effort regulation in rowing races depends on performance level and exercise mode. *Journal of Science and Medicine in Sport*, **13**(6), 613–617.

Cardinal, B.J., Esters, J. and Cardinal, M.K. (1996). Evaluation of the revised physical activity readiness questionnaire in older adults. *Medicine and Science in Sports and Exercise*, **28**(4), 468–472.

Carlsson, M., Assarsson, H. and Carlsson, T. (2016). The influence of sex, age, and race experience on pacing profiles during the 90 km Vasaloppet ski race. *Open Access Journal of Sports Medicine*, **7**, 11–19.

Chinnasamy, C., St. Clair Gibson, A., Micklewright, D. (2013). Effect of spatial and temporal cues on athletic pacing in schoolchildren. *Medicine and Science in Sports and Exercise*, **45**(2), 395-402.

Cisek, P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philosophical transactions of the Royal Society of London*, **362**, 1585–1599.

Codrons, E., Bernardi, N.F., Vandoni, M. and Bernardi, L. (2014). Spontaneous group synchronization of movements and respiratory rhythms. *PLoS ONE*, **9**(9), e107538.

Corbett, J. (2009). An analysis of the pacing strategies adopted by elite athletes during track cycling. *International Journal of Sports Physiology and Performance*, **4**(2), 195–205.

Corbett, J. Barwood, M.J., Ouzounoglou, A., Thelwell, R. and Dicks, M. (2012). Influence of competition on performance and pacing during cycling exercise. *Medicine and Science in Sports and Exercise*, **44**(3), 509–515.

Corbett, J., Barwood, M.J. and Parkhouse, K. (2009). Effect of task familiarisation on distribution of energy during a 2000 m cycling time trial. *British Journal of Sports Medicine*, **43**(10), 770–774.

Correia-Oliveira, C.R., Santos, R.A., Silva-Cavalcante, M.D., Bertuzzi, R.C., Kiss, M.A., Bishop, D.J. and Lima-Silva, A.E. (2014). Prior low- or high-intensity exercise alters pacing strategy, energy system contribution and performance during a 4-km cycling time trial. *PLoS ONE*, **9**(10), e110320.

Crewe, H., Tucker, R. and Noakes, T.D. (2008). The rate of increase in rating of perceived exertion predicts the duration of exercise to fatigue at a fixed power output in different environmental conditions. *European Journal of Applied Physiology*, **103**(5), 569–577.

De Koning, J.J., Foster, C., Lampen, J., Hettinga, F.J. and Bobbert, M.F. (2005). Experimental evaluation of the power balance model of speed skating. *Journal of Applied Physiology*, **98**, 227–233.

De Koning, J.J., Foster, C., Bakkum, A., Kloppenburg, S., Thiel, C., Joseph, T., Cohen, J. and Porcari, J.P. (2011). Regulation of pacing strategy during athletic competition. *PLoS ONE,* **6**(1), p.e15863.

De Koning, J.J., Foster, C., Lucía, A., Bobbert, M.F., Hettinga, F.J. and Porcari J.P. (2011). Using modeling to understand how athletes in different disciplines solve the same problem: Swimming versus running versus speed skating. *International Journal of Sports Physiology and Performance,* **6**(2), 276–280.

De Koning, J.J., Bobbert, M.F. and Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *Journal of Science and Medicine in Sport*, **2**(3), 266–277.

De Koning, J.J., De Groot, G. and Van Ingen Schenau, G.J. (1992). A power equation for the sprint in speed skating. *Journal of Biomechanics*, **25**(6), 573–580.

De Morree, H.M. and Marcora, S.M. (2013). Effects of isolated locomotor muscle fatigue on pacing and time trial performance. *European Journal of Applied Physiology*, **113**(9), 2371–2380.

De Pauw, K., Roelands, B., De Geus, B. and Meeusen, R. (2013). Guidelines to Classify subject groups in sport-science research. *International Journal of Sports Physiology and Performance*, **8**(2), 111–122.

Deaner, R.O., Carter, R.E., Joyner, M.J. and Hunter, S.K. (2015). Men are more likely than women to slow in the marathon. *Medicine and Science in Sports and Exercise*, **47**(3), 607–616.

Deaner, R.O. and Lowen, A. (2016). Males and females pace differently in high school cross-country races. *Journal of Strength and Conditioning Research*, **30**(11), 2991–2997.

Den Hartigh, R.J., Gernigon, C., Van Yperen, N.W., Marin, L. and Van Geert, P.L. (2014). How psychological and behavioral team states change during positive and negative momentum. *PLoS ONE*, **9**(5), p.e97887.

Den Hartigh, R.J., van der Sluijs, J., Zaal, F.T. and Gernigon C. (2017). Psychological momentum shapes athletes' affordances. *In Congress of the French Society of Sport Psychology (SFPS). Montpellier, France. [abstract]*

Dwyer, D.B., Ofoghi, B., Huntsman, E., Rossitto, D., McMahon, C. and Zeleznikow, J. (2013). The elimination race in track cycling: patterns and predictors of performance. *Journal of Science and Cycling*, **2**(2), 6–12.

Edwards, A.M., Guy, J.H. and Hettinga, F.J. (2016). Oxford and Cambridge Boat Race: Performance, pacing and tactics between 1890 and 2014. *Sports Medicine*, **46**(10), 1553–1562.

Edwards, A.M. and Polman, R.C. (2013). Pacing and awareness: Brain regulation of physical activity. *Sports Medicine*, **43**(11), 1057–1064.

Elferink-Gemser, M.T. and Hettinga, F.J. (2017). Pacing and self-regulation: Important skills for talent development in endurance sports. *International Journal of Sports Physiology and Performance*, **12**(6), 831–835.

Enoka, R.M. and Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and Science in Sports and Exercise*, **48**(11), 2228–2238.

Esteve-Lanao, J., Lucía, A. and Foster, C. (2008). How do humans control physiological strain during strenuous endurance exercise? *PLoS ONE*, **3**(8), e2943.

Fernandes, A.L. Lopes-Silva, J.P., Bertuzzi, R.C., Casarini, D.E., Arita, D.Y., Bishop, D.J. and Lima-Silva, A.E. (2014). Effect of time of day on performance, hormonal and metabolic response during a 1000-M cycling time trial. *PLoS ONE*, **9**(10), e109954.

Flyger, N. (2009). Variability in competitive performance of elite track cyclists. *ISBS-Conference Proceedings Archive,* **1**(2), 27–40. Available at: https://ojs.ub.uni-konstanz.de/cpa/article/view/3441.

Foster, C., De Koning, J.J., Hettinga, F.J., Lampen, J., Dodge, C., Bobbert, M.F. and Porcari, J.P. (2004). Effect of competitive distance on energy expenditure during simulated competition. *International Journal of Sports Medicine*, **25**, 198–204.

Foster, C., Hendrickson, K., Peyer, K., Reiner, B., De Koning, J.J., Lucía, A., Battista, R.A., Hettinga, F.J., Porcari, J.P. and Wright, G. (2009). Pattern of developing the performance template. *British Journal of Sports Medicine*, **43**(10), 765–769.

Foster, C., De Koning, J.J., Hettinga, F.J., Lampen, J., La Clair, K.L., Dodge, C., Bobbert, M.F. and Porcari, J.P. (2003). Pattern of energy expenditure during simulated competition. *Medicine and Science in Sports and Exercise*, **35**(5), 826–831.

Froyd, C., Beltrami, F.G., Millet, G.Y. and Noakes, T.D. (2016). Central regulation and neuromuscular fatigue during exercise of different durations. *Medicine and Science in Sports and Exercise*, **48**(6), 1024–1032.

Froyd, C., Millet, G.Y. and Noakes, T.D. (2013). The development of peripheral fatigue and short-term recovery during self-paced high-intensity exercise. *Journal of Physiology*, **591**(5), 1339–1346.

Gandevia, S.C. (2001). Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews*, **81**(4), 1725–1789.

García-Pinillos, F., Soto-Hermoso, V.M. and Latorre-Román, P.A. (2015). Acute effects of extended interval training on countermovement jump and handgrip strength performance in endurance athletes. *Journal of Strength and Conditioning Research*, **29**(1), 11–21.

Garland, S.W. (2005). An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. *British Journal of Sports Medicine*, **39**(1), 39–42.

Gibson, J.J. (1972). A Theory of Direct Visual Perception. In: J. Royce and W. Rozenboom, eds. The Psychology of Knowing. *New York: Gordon and Breach.*

Gibson, J.J. (1979). The ecological approach to visual perception, *Boston: Houghton Mifflin*.

Gibson, J.J. (1966). The Senses Considered as Perceptual Systems, *Boston: Houghton Mifflin*.

Gregory, J.E., Brockett, C., Morgan, D., Whitehead, N. and Proske, U. (2002). Effect of eccentric muscle contractions on Golgi tendon organ responses to passive and active tension in the cat. *Journal of Physiology*, **538**, 209–218.

Gregory, J.E., Morgan, D. and Proske, U. (2004). Responses of muscle spindles following a series of eccentric contractions. *Experimental Brain Research*, **157**(2), 234–240.

Gregory, R. (1974). Concepts and Mechanisms of Perception, *London: Duckworth*.

Halson, S.L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine*, **44**(Suppl 2), S139-147.

Hanley, B. (2013). An analysis of pacing profiles of world-class racewalkers. *International Journal of Sports Physiology and Performance*, **8**(4), 435–441.

Hanley, B. (2016). Pacing, packing and sex-based differences in Olympic and IAAF World Championship marathons. *Journal of Sports Sciences*, **34**(17), 1675–1681.

Hanley, B. (2015). Pacing profiles and pack running at the IAAF World Half Marathon Championships. *Journal of Sports Sciences*, **33**(11), 1189–1195.

Hanley, B. (2014). Senior men's pacing profiles at the IAAF World Cross Country Championships. *Journal of Sports Sciences*, **32**(11), 1060–1065.

Hanley, B., Smith, L.C. and Bissas, A. (2011). Kinematic variations due to changes in pace during men's and women's 5 km road running. *International Journal of Sports Science and Coaching*, **6**(2), 243–252.

Hanon, C. and Gajer, B. (2009). Velocity and stride parameters of world-class 400-meter athletes compared with less experienced runners. *Journal of Strength and Conditioning Research*, **23**(2), 524–531.

Haug, W., Drinkwater, E., Mitchell, L. and Chapman, D. (2015). The relationship between start performance and race outcome in elite 500m short track speed skating. *International Journal of Sports Physiology and Performance*, **10**(7), 902-906.

Heidenfelder, A., Rosemann, T., Rüst, C.A. and Knechtle, B. (2016). Pacing strategies of ultracyclists in the "Race across America." *International Journal of Sports Physiology and Performance*, **11**(3), 319–327.

Hettinga, F.J., De Koning, J.J., Schmidt, L., Wind, N., Macintosh, B.R. and Foster, C. (2011). Optimal pacing strategy: from theoretical modelling to reality in 1500-m speed skating. *British Journal of Sports Medicine*, **45**(1), 30–35.

Hettinga, F.J., Konings, M.J., Al, M. and De Jong, R. (2016). Overtaking behavior in elite 1500m short track speed skating competitions. *Medicine and Science in Sports and Exercise*, **48**(5 Suppl 1), 330.

Hettinga, F.J., De Koning, J.J., Broersen, F.T., Van Geffen, P. and Foster, C. (2006). Pacing strategy and the occurence of fatigue in 4000-m cycling time trials. *Medicine and Science in Sports and Exercise*, **38**(8), 1484–1491.

Hettinga, F.J., De Koning, J.J., Hulleman, M. and Foster, C. (2012). Relative importance of pacing strategy and mean power output in 1500-m self-paced cycling. *British Journal of Sports Medicine*, **46**(1), 30–35.

Hettinga, F.J., De Koning, J.J. and Foster, C. (2009). VO2 response in supramaximal cycling time trial exercise of 750 to 4000 m. *Medicine and Science in Sports and Exercise*, **41**(1), 230–236.

Hettinga, F.J., Konings, M.J. and Pepping, G.-J. (2017). The science of racing against opponents: Affordance competition and the regulation of exercise intensity in head-to-head competition. *Frontiers in Physiology*, **8**, 118.

Hettinga, F.J., Schoenmakers, P.P.J.M. and Smit, A. (2015). The mechanical power output-velocity curves for Velotron ergometer cycling and track cycling, and the relevance for cycling performance and pacing research. *Congress of the International Society of Biomechanics. [abstract]*

Hill, A., Long, C. and Lupton, H. (1924). Muscular exercise, lactic acid, and the supply and utilisation of oxygen. *Proceedings of the Royal Society B: Biological Sciences*, **97**(681), 84–138.

Hoffman, M.D. (2014). Pacing by winners of a 161-km mountain ultramarathon. *International Journal of Sports Physiology and Performance*, **9**(6), 1054–1056.

Hopkins, W.G. (2006). A spreadsheet for combining outcomes from several subject groups. *Sportscience. Available at: http://www.sportsci.org/2006/wghcom.htm [Accessed August 25, 2016]*.

Hopkins, W.G. (2000). Log transformation for better fits. A new view of statistics. *Available at: http://www.sportsci.org/resource/stats/logtrans.html [Accessed August 25, 2016]*.

Hopkins, W.G., Marshall, S.W., Batterham, A.M. and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, **41**(1), 3–13.

Hopkins, W.G., Hawley, J.A. and Burke, L.M. (1999). Design and analysis of research on sport performance enhancement. *Medicine and Science in Sports and Exercise*, **31**(3), 472–485.

Hulleman, M., De Koning, J.J., Hettinga, F.J. and Foster, C. (2007). The effect of extrinsic motivation on cycle time trial performance. *Medicine and Science in Sports and Exercise*, **39**(4), 709–715.

Ingham, A.G., Levinger, G., Graves, J. and Peckham, V. (1974). The Ringelmann effect: Studies of group size and group performance. *Journal of Experimental Social Psychology*, **10**(4), 371–384.

Jeukendrup, A.E., Hesselink, M., Snyder, A.C., Kuipers, H. and Keizer, H. (1992). Physiological changes in male competitive cyclists after two weeks of intensified training. *International Journal of Sports Medicine*, **13**(7), 534–541.

Johnson, B., Joseph, T., Wright, G., Battista, R.A., Dodge, C., Balweg, A., De Koning, J.J. and Foster, C. (2009). Rapidity of responding to a hypoxic challenge during exercise. *European Journal of Applied Physiology*, **106**(4), 493–499.

Jones, A.M. and Whipp, B. (2002). Bioenergetic constraints on tactical decision making in middle distance running. *British Journal of Sports Medicine*, **36**, 102–104.

Jones, H.S., Williams, E.L., Marchant, D.C., Sparks, S.A., Bridge, C.A., Midgley, A.W. and McNaughton, L.R. (2016a). Deception has no acute or residual effect on cycling time trial performance but negatively effects perceptual responses. *Journal of Science and Medicine in Sport*, **19**(9), 771–776.

Jones, H.S., Williams, E.L., Marchant, D.C., Sparks, S.A., Bridge, C.A., Midgley, A.W. and McNaughton, L.R. (2016b). Improvements in cycling time trial performance are not sustained following the acute provision of challenging and deceptive feedback. *Frontiers in Physiology*, **7**, 399.

Joseph, T., Johnson, B., Battista, R.A., Wright, G., Dodge, C., Porcari, J.P., De Koning, J.J. and Foster, C. (2008). Perception of fatigue during simulated competition. *Medicine and Science in Sports and Exercise*, **40**(2), 381–386.

Kahneman, D. (2011). Thinking, Fast and Slow. *New York, United States: Farrar, Straus and Giroux Inc.*

Karageorghis, C.I., Priest, D-L. (2012). Music in the exercise domain: a review and synthesis. *International Review of Sport and Exercise Psychology*. **5**, 44–84.

Kerhervé, H.A., Cole-Hunter, T., Wiegand, A.N. and Solomon, C. (2016). Pacing during an ultramarathon running event in hilly terrain. *PeerJ*, **4**, e2591.

Kerhervé, H.A., Millet, G.Y. and Solomon, C. (2015). The Dynamics of Speed Selection and psycho-physiological load during a mountain ultramarathon. *PLoS ONE*, **10**(12), e0145482.

Knechtle, B., Rosemann, T., Zingg, M.A., Stiefel, M. and Rüst, C.A. (2015). Pacing strategy in male elite and age group 100 km ultra-marathoners. *Open Access Journal of Sports Medicine*, **6**, 71–80.

Konings, M.J., Noorbergen, O.S., Parry, D., Elferink-Gemser, M.T. and Hettinga, F.J. (2016). Pacing behaviour and tactical positioning in 1500 m short-track speed skating. *International Journal of Sports Physiology and Performance*, **11**(1), 122–129.

Konings, M.J., Elferink-Gemser, M.T., Stoter, I.K., Van der Meer, D., Otten, E. and Hettinga, F.J. (2015). Performance characteristics of long-track speed skaters: A literature review. *Sports Medicine*, **45**(4), 505–516.

Lambert, E. V, St Clair Gibson, A. and Noakes, T.D. (2005). Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. *British Journal of Sports Medicine*, **39**(1), 52–62.

Lambert, M.I., Dugas, J.P., Kirkman, M.C., Mokone, G. and Waldeck, M.R. (2004). Changes in running speeds in a 100 km ultra-marathon race. *Journal of Sports Science and Medicine*, **3**(3), 167–73.

Lambrick, D., Rowlands, A., Rowland, T. and Eston, R. (2013). Pacing strategies of inexperienced children during repeated 800 m individual time-trials and simulated competition. *Pediatric Exercise Science*, **25**(2), 198–211.

Lima-Silva, A.E., Silva-Cavalcante, M.D., Pires, F.O., Bertuzzi, R.C., Oliveira, R., Bishop, D.J. (2012). Listening to music in the first, but not the last 1.5 km of a 5-km running trial alters pacing strategy and improves performance. *International Journal of Sports Medicine.* **33**, 813–8.

Lipińska, P., Allen, S.V. and Hopkins, W.G. (2016a). Modeling parameters that characterize pacing of elite female 800-m freestyle swimmers. *European Journal of Sport Science*, **16**(3), 287–292.

Lipińska, P., Allen, S.V and Hopkins, W.G. (2016b). Relationships between pacing parameters and performance of elite male 1500-m swimmers. *International Journal of Sports Physiology and Performance*, **11**(2), 159–163.

Lohse, K.R. and Sherwood, D.E. (2011). Defining the focus of attention: Effects of attention on perceived exertion and fatigue. *Frontiers in Psychology*, **2**. DOI: 10.3389/fpsyg.2011.00332

Lombardo, T.J. (1987). The reciprocity of perceiver and environment: The evolution of James J. Gibson's ecological psychology, *Hillsdale: Erlbaum.*

MacIntosh, B.R. and Shahi, M.R.S. (2011). A peripheral governor regulates muscle contraction. *Applied Physiology, Nutrition, and Metabolism*, **36**(1), 1–11.

Mador, M. and Acevedo, F. (1991). Effect of respiratory muscle fatigue on subsequent exercise performance. *Journal of Applied Physiology*, **70**(5), 2059–2065.

Malcata, R.M. and Hopkins, W.G. (2014). Variability of competitive performance of elite athletes: a systematic review. *Sports Medicine*, **44**(12), 1763–1774.

Marcora, S.M. (2010). Counterpoint: Afferent feedback from fatigued locomotor muscles is not an important determinant of endurance exercise performance. *Journal of Applied Physiology*, **108**(2), 454–456.

Marcora, S.M. (2008). Do we really need a central governor to explain brain regulation of exercise performance? *European Journal of Applied Physiology*, **104**(5), 929–931.

Marcora, S.M. and Bosio, A. (2007). Effect of exercise-induced muscle damage on endurance running performance in humans. *Scandinavian Journal of Medicine and Science in Sports*, **17**(6), 662–671.

Marcora, S.M., Bosio, A. and De Morree, H.M. (2008). Locomotor muscle fatigue increases cardiorespiratory responses and reduces performance during intense cycling exercise independently from metabolic stress. *American Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, **294**(3), R874–R883.

Marcora, S.M. and Staiano, W. (2010). The limit to exercise tolerance in humans: mind over muscle? *European Journal of Applied Physiology*, **109**, 763–770.

Mauger, A.R., Jones, A.M. and Williams, C.A. (2009). Influence of feedback and prior experience on pacing during a 4-km cycle time trial. *Medicine and Science in Sports and Exercise*, **41**(2), 451–458.

Mauger, A.R., Neuloh, J. and Castle, P.C. (2012). Analysis of pacing strategy selection in elite 400-m freestyle swimming. *Medicine and Science in Sports and Exercise*, **44**(11), 2205–2212.

Maw, S., Proctor, L., Vredenburg, J. and Ehlers, P. (2006). Influence of starting position on finishing position in World Cup 500 m short track speed skating. *Journal of Sports Sciences*, **24**(12), 1239–1246.

McCormick, A., Meijen, C. and Marcora, S.M. (2015). Psychological determinants of whole-body endurance performance. *Sports Medicine*, **45**(7), 997–1015.

Meerhoff, L., De Poel, H.J. and Button, C. (2014). How visual information influences coordination dynamics when following the leader. *Neuroscience Letters*, **582**, 12–15.

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J. and Urhausen, A. (2013). Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of *Sports Medicine* (ACSM). *European Journal of Sport Science*, **13**(1), 1–24.

Merton, P. (1954). Voluntary strength and fatigue. *Journal of Physiology*, **123**(3), 553–564.

Micklewright, D., Angus, S.D., Suddaby, J., St Clair Gibson, A., Sandercock, G. and Chinnasamy, C. (2012). Pacing strategy in schoolchildren differs with age and cognitive development. *Medicine and Science in Sports and Exercise*, **44**(2), 362–369.

Micklewright, D., Papadopoulou, E., Swart, J. and Noakes, T.D. (2010). Previous experience influences pacing during 20 km time trial cycling. *British Journal of Sports Medicine*, **44**(13), 952–960.

Micklewright, D., Parry, D., Robinson, T., Deacon, G., Renfree, A., St Clair Gibson, A. and Matthews, W.J. (2015). Risk perception influences athletic pacing strategy. *Medicine and Science in Sports and Exercise*, **47**(5), 1026–1037.

Micklewright, D., Kegerreis, S., Raglin, J. and Hettinga, F.J. (2017). Will the conscious–subconscious pacing quagmire help elucidate the mechanisms of self-paced exercise? new opportunities in dual process theory and process tracing methods. *Sports Medicine*, **47**(7), 1231–1239.

Moffatt, J., Scarf, P., Passfield, L., McHale, I.G. and Zhang, K. (2014). To lead or not to lead: analysis of the sprint in track cycling. *Journal of Quantitative Analysis in Sports*, **10**(2), 161–172.

Muehlbauer, T. and Melges, T. (2011). Pacing patterns in competitive rowing adopted in different race categories. *Journal of Strength and Conditioning Research*, **25**(5), 1293–1298.

Muehlbauer, T., Panzer, S. and Schindler, C. (2010a). Pacing pattern and speed skating performance in competitive long-distance events. *Journal of Strength and Conditioning Research*, **24**(1), 114–119.

Muehlbauer, T. and Schindler, C. (2011). Relationship between starting and finishing position in short track speed skating races. *European Journal of Sport Science*, **11**(4), 225–230.

Muehlbauer, T., Schindler, C. and Panzer, S. (2010b). Pacing and performance in competitive middle-distance speed skating. Research Quarterly for Exercise and Sport, **81**(1), 1–6.

Muehlbauer, T., Schindler, C. and Panzer, S. (2010c). Pacing and sprint performance in speed skating during a competitive season. *International Journal of Sports Physiology and Performance*, **5**(2), 165–176.

Mytton, G.J., Archer, D.T., Turner, L.A., Skorski, S., Renfree, A., Thompson, K.G. and St Clair Gibson, A. (2015). Increased variability of lap speeds differentiate medallists and non-medallists in middle distance running and swimming events. *International Journal of Sports Physiology and Performance,* **10**(3), 369–373.

Nikolaidis, P.T. and Knechtle, B. (2017). Pacing in age-group freestyle swimmers at The XV FINA World Masters Championships in Montreal 2014. *Journal of Sports Sciences*, **35**(12), 1165–1172.

Noakes, T.D. (2012). Fatigue is a Brain-Derived Emotion that Regulates the Exercise Behavior to Ensure the Protection of Whole Body Homeostasis. *Frontiers in Physiology*, **3**, 82.

Noakes, T.D. (2000). Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. *Scandinavian Journal of Medicine and Science in Sports*, **10**(3), 123–145.

Noakes, T.D. (2011). Time to move beyond a brainless exercise physiology: the evidence for complex regulation of human exercise performance. *Applied Physiology, Nutrition, and Metabolism*, **36**(1), 23–35.

Noakes, T.D. and St Clair Gibson, A. (2004). Logical limitations to the "catastrophe" models of fatigue during exercise in humans. *British Journal of Sports Medicine*, **38**, 648–649.

Noakes, T.D., St Clair Gibson, A. and Lambert, E.V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine*, **39**(2), 120–124.

Noorbergen, O.S., Konings, M.J., Micklewright, D., Elferink-Gemser, M.T., Hettinga, F.J. (2016). Pacing and tactical positioning in 500 and 1000m short-track speed skating. *International Journal of Sports Physiology and Performance*, **11**(6), 742–748.

Noordhof, D.A., Mulder, R.C.M., De Koning, J.J. and Hopkins, W.G. (2016). Race factors affecting performance times in elite long-track speed skating. *International Journal of Sports Physiology and Performance*, **11**(4), 535–542.

Parry, D., Chinnasamy, C. and Micklewright, D. (2012). Optic flow influences perceived exertion during cycling. *Journal of Sport and Exercise Psychology*, **34**(4), 444–56.

Parry, D. and Micklewright, D. (2014). Optic flow influences perceived exertion and distance estimation but not running pace. *Medicine and Science in Sports and Exercise*, **46**(8), 1658–1665.

Paton, C.D. and Hopkins, W.G. (2006). Variation in performance of elite cyclists from race to race. *European Journal of Sport Science*, **6**(1), 25–31.

Périard, J.D. and Racinais, S. (2016). Performance and pacing during cycle exercise in hyperthermic and hypoxic conditions. *Medicine and Science in Sports and Exercise*, **48**(5), 845–853.

Peveler, W.W. and Green, M. (2010). The effect of extrinsic factors on simulated 20-km time-trial performance. *Journal of Strength and Conditioning Research*, **24**(12), 3265–3269.

Pijpers, R., Oudejans, R.R. and Bakker, F.C. (2007). Changes in the perception of action possibilities while climbing to fatigue on a climbing wall. *Journal of Sports Sciences*, **25**(1), 97–110.

Renfree, A., Martin, L., Micklewright, D. and St Clair Gibson, A. (2014a). Application of decision-making theory to the regulation of muscular work rate during self-paced competitive endurance activity. *Sports Medicine*, **44**(2), 147–158.

Renfree, A., Mytton, G.J., Skorski, S. and St Clair Gibson, A. (2014b). Tactical considerations in the middle-distance running events at the 2012 olympic games: A case study. *International Journal of Sports Physiology and Performance*, **9**(2), 362–364.

Renfree, A., Crivoi do Carmo, E., Martin, L. and Peters, D.M. (2015). The influence of collective behavior on pacing in endurance competitions. *Frontiers in Physiology*, **6**. DOI: 10.3389/fphys.2015.00373

Renfree, A., Crivoi do Carmo, E. and Martin, L. (2016). The influence of performance level, age and gender on pacing strategy during a 100-km ultramarathon. *European Journal of Sport Science*, **16**(4), 409–415.

Renfree, A. and St Clair Gibson, A. (2013). Influence of different performance levels on pacing strategy during the Women's World Championship marathon race. *International Journal of Sports Physiology and Performance*, **8**(3), 279–285.

Ringelmann, M. (1913). Recherches sur les moteurs animes: Travail de l'homme [Research on animate sources of power: The work of man]. *Annales de l'lnstitut National Agronomique, 2nd series*, **12**, 1–40.

Roelands, B., De Koning, J.J., Foster, C., Hettinga, F.J. and Meeusen, R. (2013). Neurophysiological determinants of theoretical concepts and mechanisms involved in pacing. *Sports Medicine*, **43**(5), 301–311.

Romer, L.M. and Polkey, M.I. (2008). Exercise-induced respiratory muscle fatigue: implications for performance. *Journal of Applied Physiology*, **104**(3), 879–888.

Del Rosso, S., Barros, E., Tonello, L., Oliveira-Silva, I., Behm, D.G., Foster, C. and Boullosa, D.A. (2016). Can pacing be regulated by post-activation potentiation? Insights from a self-paced 30 km trial in half-marathon runners. *PloS ONE*, **11**(3), p.e0150679.

Rundell, K. (1996). Effects of drafting during short-track speed skating. *Medicine and Science in Sports and Exercise*, **28**(6), 765–771.

Saraslanidis, P.J., Panoutsakopoulos, V., Tsalis, G.A. and Kyprianou, E. (2011). The effect of different first 200-m pacing strategies on blood lactate and biomechanical parameters of the 400-m sprint. *European Journal of Applied Physiology*, **111**(8), 1579–1590.

Schallig, W., Veneman, T., Noordhof, D.A., Porcari, J.P., De Koning, J.J. and Foster, C. (2017). The role of the rating of perceived exertion template in pacing. *International Journal of Sports Physiology and Performance*, 1–22. DOI: 10.1123/ijspp.2016-0813

Schiphof-Godart, L., Konings, M.J. and Hettinga, F.J. (2017). The effect of trait characteristics and received feedback on pacing regulation during competition. *[In preparation]*.

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, **82**(4), 225–260.

Schoenmakers, P.P.J.M., Hettinga, F.J. and Smit, A. (2015). The mechanical power output velocity curves for Velotron ergometer cycling and the relevance for cycling performance and pacing research [abstract]. In: *Book of Abstract European College of Sport Science 2015, Malmö, Sweden*, **20**, .

Shei, R.-J., Thompson, K.G., Chapman, R., Raglin, J. and Mickleborough, T. (2016). Using deception to establish a reproducible improvement in 4-km cycling time trial performance. *International Journal of Sports Medicine*, **37**(5), 341–346.

Sidhu, S.K., Weavil, J.C., Mangum, T.S., Jessop, J.E., Richardson, R.S., Morgan, D.E. and Amann, M. (2017). Group III/IV locomotor muscle afferents alter motor cortical and corticospinal excitability and promote central fatigue during cycling exercise. *Clinical Neurophysiology*, **128**(1), 44–55.

Skorski, S., Hammes, D., Schwindling, S., Veith, S., Pfeiffer, M., Ferrauti, A., Kellmann, M. and Meyer, T. (2015). Effects of training-induced fatigue on pacing patterns in 40-km cycling time trials. *Medicine and Science in Sports and Exercise*, **47**(3), 593–600.

Skorski, S., Faude, O., Abbiss, C.R., Caviezel, S., Wengert, N. and Meyer, T. (2014). Influence of pacing manipulation on performance of juniors in simulated 400 m swim competition. *International Journal of Sports Physiology and Performance*, **8**(5), 817–824.

Skurvydas, A, Dudoniene, V., Kalvenas, A. and Zuoza, A. (2002). Skeletal muscle fatigue in long-distance runners, sprinters and untrained men after repeated drop jumps performed at maximal intensity. *Scandinavian Journal of Medicine and Science in Sports*, **12**(1), 34–39.

Skurvydas, A., Jascaninas, J. and Zachovajevas, P. (2000). Changes in height of jump, maximal voluntary contraction force and low-frequency fatigue after 100 intermittent or continuous jumps with maximal intensity. *Acta Physiologica Scandinavica*, **169**(1), 55–62.

Smith, J. and Pepping, G.-J. (2010). Effects of affordance perception on the initiation and actualization of action. *Ecological Psychology*, **22**(2), 119–149.

Smith, T.B. and Hopkins, W.G. (2011). Variability and predictability of finals times of elite rowers. *Medicine and Science in Sports and Exercise*, **43**(11), 2155–2160.

Smits, B.L., Pepping, G.-J. and Hettinga, F.J. (2014). Pacing and decision making in sport and exercise: the roles of perception and action in the regulation of exercise intensity. *Sports Medicine*, **44**(6), 763–775.

Spencer, M., Losnegard, T., Hallén, J. and Hopkins, W.G. (2014). Variability and predictability of performance times of elite cross-country skiers. *International Journal of Sports Physiology and Performance*, **9**(1), 5–11.

St Clair Gibson, A., Lambert, E.V., Rauch, L.H., Tucker, R., Baden, D.A., Foster, C. and Noakes, T.D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Medicine*, **36**(8), 705–722.

St Clair Gibson, A., Swart, J. and Tucker, R. (2017). The interaction of psychological and physiological homeostatic drives and role of general control principles in the regulation of physiological systems, exercise and the fatigue process – The Integrative Governor theory. *European Journal of Sport Science*, 1–12. DOI: 10.1080/17461391.2017.1321688

Stone, M.R., Thomas, K., Wilkinson, M., Jones, A.M., St Clair Gibson, A. and Thompson, K.G. (2012). Effects of deception on exercise performance: Implications for determinants of fatigue in humans. *Medicine and Science in Sports and Exercise*, **44**(3), 534–541.

Stone, M.R., Thomas, K., Wilkinson, M., Stevenson, E., St Clair Gibson, A., Jones, A.M. and Thompson, K.G. (2017). Exploring the performance reserve: Effect of different magnitudes of power output deception on 4,000 m cycling time-trial performance. *PloS one*, **12**(3), e0173120.

Stoter, I.K., MacIntosh, B.R., Fletcher, J.R., Pootz, S., Zijdewind, I. and Hettinga, F.J. (2016). Pacing strategy, muscle fatigue and technique in 1500m speed skating and cycling time-trials. *International Journal of Sports Physiology and Performance*, **11**(3), 337-343.

Swart, J., Lamberts, R.P., Lambert, M.I., Lambert, E.V., Woolrich, R., Johnston, S. and Noakes, T.D. (2009). Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. *British Journal of Sports Medicine*, **43**, 775–782.

Taguchi, T., Sato, J. and Mizumura, K. (2005). Augmented mechanical response of muscle thin-fiber sensory receptors recorded from rat muscle-nerve preparations in vitro after eccentric contraction. *Journal of Neurophysiology*, **94**(4), 2822–2831.

Tan, P., Tan, F.H. and Bosch, A.N. (2016). Similarities and differences in pacing patterns in a 161-km and 101-km ultra-distance road race. *Journal of Strength and Conditioning Research*, **30**(8), 2145–2155.

Taylor, J.B., Santi, G. and Mellalieu, S.D. (2016). Freestyle race pacing strategies (400 m) of elite able-bodied swimmers and swimmers with disability at major international championships. *Journal of Sports Sciences*, **34**(20), 1913–1920.

Thiel, C., Foster, C., Banzer, W. and De Koning, J.J. (2012). Pacing in Olympic track races: Competitive tactics versus best performance strategy. *Journal of Sports Sciences*, **30**(11), 1107–1115.

Thomas, K., Goodall, S., Stone, M.R., Howatson, G., St Clair Gibson, A. and Ansley, L. (2015). Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine and Science in Sports and Exercise*, **47**(3), 537–546.

Thomas, K., Elmeua, M., Howatson, G. and Goodall, S. (2016). Intensity-dependent contribution of neuromuscular fatigue after constant-load cycling. *Medicine and Science in Sports and Exercise*, **48**(9), 1751–1760.

Tomazini, F., Pasqua, L.A., Damasceno, M.V., Silva-Cavalcante, M.D., De Oliveira, F.R., Lima-Silva, A.E. and Bertuzzi, R.C. (2015). Head-to-head running race simulation alters pacing strategy, performance, and mood state. *Physiology and Behavior*, **149**, 39–44.

Tucker, R., Kayser, B., Rae, E., Rauch, L.H., Bosch, A.N. and Noakes, T.D. (2007). Hyperoxia improves 20 km cycling time trial performance by increasing muscle activation levels while perceived exertion stays the same. *European Journal of Applied Physiology*, **101**(6), 771–781.

Tucker, R., Lambert, M.I., Noakes, T.D. (2006) An analysis of pacing strategies during men's world-record performances in track athletics. *International Journal of Sports Physiology and Performance,* **1**(3), 233-245.

Tucker, R., Bester, A., Lambert, E.V., Noakes, T.D., Vaughan, C. and St Clair Gibson, A. (2006). Non-random fluctuations in power output during self-paced exercise. *British Journal of Sports Medicine*, **40**, 912–917.

Tucker, R. (2009). The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. *British Journal of Sports Medicine*, **43**(6), 392–400.

Tversky, A. and Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases. *Science*, **185**(4157), 1124–1131.

Twist, C. and Eston, R. (2009). The effect of exercise-induced muscle damage on perceived exertion and cycling endurance performance. *European Journal of Applied Physiology*, **105**(4), 559–567.

Ulmer, H. (1996). Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. *Experientia*, **52**(5), 416–420.

Van Biesen, D., Hettinga, F.J., McCulloch, K., and Vanlandewijck, Y.C. (2016a). Pacing profiles in competitive track races: Regulation of exercise Intensity is related to cognitive ability. *Frontiers in Physiology*, **7**, 624.

Van Biesen, D., McCulloch, K., Lenaerts, L., Mactavish, J., Vanlandewijck, Y.C. (2016b). Cognitive Profile of Young Well-Trained athletes with Intellectual Impairments, *Research In Developmental Disabilities*, **53**, 377-390.

Van Biesen, D., Hettinga, F.J., McCulloch, K., and Vanlandewijck, Y.C. (2017). Pacing ability in elite runners with intellectual impairment. *Medicine and Science in Sports and Exercise,* **49**(3), 588–594.

Van Biesen, D., Jacobs, L., McCulloch, K., Janssens, L., Vanlandewijck, Y.C. (2018). Cognitive-motor dual-task ability of athletes with and without intellectual impairment, *Journal of Sports Sciences,* **36**(5), 513-521.

Van Ingen Schenau, G.J. (1980). Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. *Medicine and Science in Sports and Exercise*, **12**(4), 257–261.

Van Ingen Schenau, G.J. (1982). The influence of air friction in speed skating. *Journal of Biomechanics*, **15**(6), 449–458.

van Ingen Schenau, G.J. and Cavanagh, P. (1990). Power equations in endurance sports. *Journal of Biomechanics*, **23**(9), 865–881.

Van Ingen Schenau, G.J. and De Groot, G. (1983). On the origin of differences in performance level between elite male and female speed skaters. *Human Movement Science*, **2**, 151–159.

Van Ingen Schenau, G.J., De Groot, G. and Hollander, A.P. (1983). Some technical, physiological and anthropometrical aspects of speed skating. *European Journal of Applied Physiology and Occupational Physiology*, **50**(3), 343–354.

Van Ingen Schenau, G.J., De Koning, J.J. and De Groot, G. (1990). A simulation of speed skating performances based on a power equation. *Medicine and Science in Sports and Exercise*, **22**(5), 718–728.

Venhorst, A., Micklewright, D. and Noakes, T.D. (2017). Towards a three-dimensional framework of centrally regulated and goal-directed exercise behaviour: a narrative review. *British Journal of Sports Medicine*, 1–12. DOI: 10.1136/bjsports-2016-096907

Weavil, J.C., Sidhu, S.K., Mangum, T.S., Richardson, R.S. and Amann, M. (2016). Fatigue diminishes motoneuronal excitability during cycling exercise. *Journal of Neurophysiology*, **116**(4), 1743–1751.

Whitehead, A.E., Jones, H.S., Williams, E.L., Dowling, C., Morley, D., Taylor, J.A. and Polman, R.C. (2017). Changes in cognition over a 16.1 km cycling time trial using Think Aloud protocol: Preliminary evidence. *International Journal of Sport and Exercise Psychology*, **15**, 1–9. DOI: 10.1080/1612197X.2017.1292302

Wiersma, R., Stoter, I.K., Visscher, C., Hettinga, F.J. and Elferink-Gemser, M.T. (2017). Development of 1500m Pacing Behavior in Junior Speed Skaters: A Longitudinal Study. *International Journal of Sports Physiology and Performance*, 1–20. DOI: 10.1123/ijspp.2016-0517

Williams, E.L., Jones, H.S., Sparks, S.A., Midgley, A.W., Marchant, D.C., Bridge, C.A. and McNaughton, L.R. (2015a). Altered psychological responses to different magnitudes of deception during cycling. *Medicine and Science in Sports and Exercise*, **47**(11), 2423–2430.

Williams, E.L., Jones, H.S., Sparks, S.A., Marchant, D.C., Midgley, A.W. and McNaughton, L.R. (2015b). Competitor presence reduces internal attentional focus and improves 16.1km cycling time trial performance. *Journal of Science and Medicine in Sport*, **18**(4), 486–491.

Wilmore, J. (1968). Influence of motivation on physical work capacity and performance. *Journal of Applied Physiology*, **24**(4), 459–463.

Winchester, R., Turner, L.A., Thomas, K., Ansley, L., Thompson, K.G., Micklewright, D., St. Clair Gibson, A. (2012). Observer effects on the rating of perceived exertion and affect during exercise in recreationally active males. *Perceptual and Motor Skills*, **115**(1), 213-227.

Withagen, R., De Poel, H.J., Araújo, D. and Pepping, G-J. (2012). Affordances can invite behavior: Reconsidering the relationship between affordances and agency. *New Ideas in Psychology*, **30**(2), 250–258.

Wright, R. (2016). Positive Pacing Strategies Are Utilized by Elite Male and Female Para-cyclists in Short Time Trials in the Velodrome. *Frontiers in Physiology*, **6**, 425.

Zajonc, R.B. (1965). Social facilitation, *Science*, **149**(3681), 269-274.

Appendix

List of Publications

International publications (peer-reviewed scientific journals)

Konings MJ, Hettinga FJ. (2018) Preceding Race Efforts Affect Pacing and Short-Track Speed Skating Performance. *International Journal of Sport Physiology and Performance.* 1-23. DOI: 10.1123/ijspp.2017-0637. [Epub ahead of print].

Konings MJ, Hettinga FJ. (2017) The impact of different competitive environments on pacing and performance. *International Journal of Sport Physiology and Performance.* 1-21. DOI: 10.1123/ijspp.2017-0407. [Epub ahead of print].

Konings MJ, Parkinson J, Zijdewind I, Hettinga FJ. (2017) Racing an Opponent Alters Pacing, Performance and Muscle Force Decline, But Not RPE. *International Journal of Sport Physiology and Performance.* 1-24. DOI: 10.1123/ijspp.2017-0220. [Epub ahead of print].

Konings MJ, Hettinga FJ. (2017) Objectifying Tactics: Athlete and Race Variability in Elite Short-Track Speed Skating. *International Journal of Sport Physiology and Performance.* 1-20. DOI: 10.1123/ijspp.2016-0779. [Epub ahead of print].

Hettinga FJ, ***Konings MJ***, Pepping G-J. (2017) The Science of Racing against Opponents: Affordance Competition and the Regulation of Exercise Intensity in Head-to-Head Competition. *Frontiers in Physiology.* **8**, 118. DOI: 10.3389/fphys.2017.00118.

Hettinga FJ, ***Konings MJ***, Cooper CE. (2016). Differences in Muscle Oxygenation, Perceived Fatigue and Recovery between Long-Track and Short-Track Speed Skating. *Frontiers in Physiology.* **7**, 619. DOI: 10.3389/fphys.2016.00619

Konings MJ, Schoenmakers PPJM, Walker AJ, Hettinga FJ. (2016) The behaviour of an opponent alters pacing decisions in 4-km cycling time trials. *Physiology & Behavior.* **158**, 1-5.

Noorbergen OS, ***Konings MJ***, Micklewright D, Elferink-Gemser MT, Hettinga FJ. (2016) Pacing Behaviour and Tactical Positioning in 500m and 1000m Short-Track Speed Skating. *International Journal of Sport Physiology and Performance.* **11**(6): 742-748.

Konings MJ, Noorbergen OS, Parry D, Hettinga FJ. (2016) Pacing Behaviour and Tactical Positioning in 1500 m Short-Track Speed Skating. *International Journal of Sport Physiology and Performance.* **11**(1), 122-129

Konings MJ, Elferink-Gemser MT, Stoter IK, Van der Meer D, Otten E, Hettinga FJ. (2015) Performance Characteristics of Long-Track Speed Skaters: A Literature Review. *Sports Medicine*. **45**(4): 505-516.

International Conferences

Konings MJ, Hettinga FJ. (2017) How does fatigue impact on pacing when riding against an opponent? [abstract]. Abstract is presented at the Movementis conference, University of Oxford, UK

Schiphof-Godart L, ***Konings MJ***, Hettinga FJ. (2017) Effect of opponent on performance might be influenced by athletes' risk perception and perfectionism [abstract]. Abstract is presented at the Movementis conference, University of Oxford, UK

Konings MJ, Foulsham T, Micklewright D, Hettinga FJ. (2017) The athlete-opponent relationship alters pacing decisions and information-seeking behaviour in 4-km cycling time trials [abstract]. *Book of Abstracts of the 22nd annual congress of the European College of Sport Science 2-5th July ECSS Essen 2017.* Abstract is presented at the European College of Sport Science congress 2017, Essen, Germany

Schiphof-Godart L, ***Konings MJ***, Hettinga FJ. (2017) Socially prescribed perfectionism might predict enhanced performance when racing against an opponent. *Medicine and Science in Sports and Exercise,* **49**(5 Suppl 1): 531 [Abstract]. Abstract is presented at the ACSM Annual Meeting 2017, Denver, USA

Parkinson J, ***Konings MJ***, Hettinga FJ. (2016) Sex differences in overtaking frequency in male and female elite speed skater 500m and 1000m race winners [abstract]. *Journal of Sport Sciences 34(sup1): i-s85*. Abstract is presented at the BASES Conference 2016, Nottingham, UK

Chinery K, ***Konings MJ***, Hettinga FJ. (2016) Pacing behaviour in talented 1500m short-track speed skaters [abstract]. *Journal of Sport Sciences 34(sup1): i-s85*. Abstract is presented at the BASES Conference 2016, Nottingham, UK

Konings MJ, Parkinson J, Micklewright D, Zijdewind I, Hettinga FJ. (2016) The willingness to tolerate higher levels of peripheral fatigue might explain the improved performance during head-to-head cycling competitions [abstract]. *Book of Abstracts of the 21st annual congress of the European College of Sport Science 2-5th July ECSS Vienna 2016*, **21**, 334. Abstract is presented at the European College of Sport Science congress 2016, Vienna, Austria

Al M, ***Konings MJ***, De Jong R, Hettinga FJ. (2016) Overtaking behaviour in elite and sub-elite 1500m short track speed skaters. [abstract]. *Book of Abstracts of the 21st annual congress of the European College of Sport Science 2-5th July ECSS Vienna*

2016, **21**, 115-116. Abstract is presented at the European College of Sport Science congress 2016, Vienna, Austria.

De Jong R, ***Konings MJ***, Al M, Hettinga FJ. (2016) The positioning behind one's forerunner in the final stages of the race distinguishes elite and sub-elite short track speed skaters. [abstract]. *Book of Abstracts of the 21st annual congress of the European College of Sport Science 2-5th July ECSS Vienna 2016,* **21**, 116. Abstract is presented at the European College of Sport Science congress 2016, Vienna, Austria.

Hettinga FJ. ***Konings MJ***, Al M, De Jong R (2016) Overtaking Behavior in Elite 1500m Short Track Speed Skating Competitions. *Medicine and Science in Sports and Exercise,* **48**(5 Suppl 1): 330 [Abstract]. Abstract is presented at the ACSM Annual Meeting 2016, Boston, USA

Konings MJ, Hettinga FJ. (2015) Between- and within-race variance in elite short-track speed skating: a new approach to analyse group behaviour during competition [abstract]. *Journal of Sport Sciences* **33**(Suppl 1): 76-77. Abstract is presented at the BASES Conference 2015, St. George's Park, UK

Konings MJ, Schoenmakers PPJM, Hettinga FJ. (2015) Competing Against a Controlled Opponent: Pacing Behaviour in 4-km Cycling Time-Trials [abstract]. Abstract presented at the Endurance Research Conference 2015, University of Kent, UK

Konings MJ, Schoenmakers PPJM, Hettinga FJ. (2015) The number of competitors affects pacing and performance in short-track speed skating competitions [abstract]. *Book of Abstracts of the 20th annual congress of the European College of Sport Science 2-5th July ECSS Malmö 2015*, **20**, 117. Abstract is presented at European College of Sport Science congress 2015, Malmö, Sweden

Konings MJ, Noorbergen OS, Elferink-Gemser MT, Hettinga FJ. (2014) Pacing in a broader sense: tactics in short track speed skating [abstract]. *Book of Abstracts of the 19th annual congress of the European College of Sport Science 2-5th July ECSS Amsterdam 2014*, **19**, 153. Abstract is presented at European College of Sport Science congress, Amsterdam