Pacing decision-making in sport and exercise: The regulation of exercise intensity during competition

Marco J. Konings[1], Florentina J. Hettinga[1]

REVIEW ARTICLE

[1] Sport, Performance and Fatigue Research Unit, School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Colchester, Essex, United Kingdom.

Corresponding Author:
Florentina J. Hettinga, Ph.D.
Sport, Performance and Fatigue Research Unit
School for Sport, Rehabilitation and Exercise Sciences
University of Essex
Wivenhoe Park, Colchester CO4 3SQ, UK
E-mail: fjhett@essex.ac.uk

Running heading: The regulation of exercise intensity during competition

ABSTRACT

An athlete's pacing strategy is widely recognised as an essential determinant for performance during individual events. Previous research, focused on the importance of internal bodily state feedback, revealed optimal pacing strategies in time trial exercise and explored concepts such as teleoanticipation and template formation. Recently, human-environment interactions have additionally been emphasized as a crucial determinant for pacing, yet how they affect pacing is not well understood. Therefore, this literature review focussed on exploring one of the most important human-environment interactions in sport competitions: the interaction among competitors. The existing literature regarding the regulation of exercise intensity and the effect of competition on pacing and performance is critically reviewed in this paper. PubMed, CINAHL, and Web of Science were searched for studies about pacing in sports and (interpersonal) competition between January 2000 to October 2017 using the following combination of terms: 1. Sports AND 2. Pacing, resulting in 75 included papers. The behaviour of opponents was shown to be an essential determinant in the regulation of exercise intensity, based on both observational (N=59) and experimental (N=16) studies. However, the adjustment in the pacing response related to other competitors appears to depend on the competitive situation and the current internal state of the athlete. The findings of this review emphasize the importance of what is happening around the athlete 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 in sports and exercise.

KEY POINTS

1) The behaviour of an opponent is an essential determinant in pacing regulation, however, any adjustments in pacing responses appear to depend on the competitive situation and the current internal state of the athlete.

2) What is happening in the environment of the athlete during competitions is crucial for the outcome of the decision-making process involved in pacing.

3) The findings of this review highlight the necessity to incorporate human-environment interactions into any model that attempts to explain the regulation of exercise intensity.

1. Pacing and human-environment interactions

Athletes 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 [1]. This goal-directed regulation of the exercise intensity over an exercise bout is also known as 'pacing' [2]. Although pacing is not exclusive to sports and race performances, an athlete's pacing behaviour is widely recognised as an essential determinant for performance [1].

Based on the duration of an event, different pacing strategies appear to be optimal in time trial exercise. To determine the optimal pacing strategy for a time trial event, both physiological (aerobic and anaerobic metabolic energy production) as well as biomechanical (conversion of metabolic power output to mechanical power output; aerodynamics and frictional losses) components are crucial [3–6]. To optimize performance in endurance time trial events for example, athletes should maximize their mechanical power output while minimizing the power lost to overcome frictional forces. As aerodynamic frictional losses are non-linearly related to velocity, a different velocity distribution over the race will lead to differing aerodynamic losses, which is very relevant for optimal pacing [3,5]. Based on modelling studies incorporating this, an even-paced strategy is advised when exercise duration is over two minutes, thereby minimising the energy losses related to accelerating and decelerating from average velocity [2,3,5,7]. In contrast, 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 your available energy before the finish line is reached [2,6]. Finally, modelling studies revealed a positive pacing strategy (i.e. starting fast with a subsequently decreasing power output throughout the race) would lead to optimal performance in middle-distance time trial events lasting about 1-2 minutes [8,9].

Without underestimating the useful novel insights these studies provided into the regulation of exercise intensity, the decision-making process involved in pacing during competitive events is still not yet well understood. Part of this lack of understanding could be attributable to previous literature mostly focusing on explaining the regulation of exercise in self-paced time trials, where the effects of external influences are much less predominant compared to for example head-to-head competitions. In this perspective, the necessity to incorporate human-environment interactions into our thinking about the regulation of exercise intensity has been emphasised by several different research groups in the recent years [10–14]. This review aims to explore how human-environment interactions affect and can be incorporated into the decision-making process involved in pacing. This has been done by focussing on the most important human-environment interaction present in competitive sports: the interaction among competitors [12]. To do this, we will first critically review the existing models attempting to explain self-paced exercise regulation in section 2. This will provide context and explanations about where we are coming from as a research area and for possible inconsistencies in the regulation of pace during competition between theory and practice. Thereafter an overview of the existing experimental and observational literature regarding the effect of competitors on pacing behaviour is presented in Section 3. Finally, we will further elaborate in Section 4 about the similarities and differences between the two above-mentioned sections, and discuss how human-environment interactions in general, and the athlete-opponent interaction in particular, could be incorporated as a determinant in self-paced exercise regulation during competition in a way that is consistent with pacing literature.

2. The regulation of exercise intensity

The regulatory mechanisms behind the decision-making process involved in pacing are still strongly debated. The predominant theory in exercise physiology has been for a long time that performance is limited by metabolic changes in the exercising muscles, so called peripheral fatigue [15]. 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 [15,16]. However, in the late 1990s, the Hill model was extensively questioned, mainly because it did not allow a role for the brain in the regulation of exercise and protection of the homeostasis. It did not explain for example why people tended to finish with an end spurt during self-paced exercise [17].

As an alternative, Ulmer [18] 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 from exceeding metabolic limits, a central programmer was introduced 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) [17,19–24]. According to the CGM, homeostasis is protected under all conditions and behaviour will be changed when internal homeostasis is threatened [25]. 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, exercise regulation involves subconscious neural calculations in a "governor" region of the brain, which integrates afferent feedback and projects the sensation of fatigue to the conscious brain [21,24]. 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 [20,22]. An updated version added the rate of perceived exertion (RPE) template to the CGM in 2009, 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 [22]. Finally, the Integrative Governor Model was recently introduced as a further enhancement [26]. In this most recent model, it is suggested that competition between psychological and physiological homeostatic drives is central to exercise regulation and is based on governing principles, using complex algorithms and dynamic negative feedback activity [26].

Although the introduction of a central brain component in the regulation of the exercise intensity 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 [14]. Finally, based on the fact that catastrophic failures of homeostasis can and do occur [27], it can be argued that the central governor could at least be overridden [10]. Therefore, several alternative theories in regard to pacing regulation have been proposed. Marcora [28] introduced for example a psychobiological model, where exercise intensity is regulated by the conscious brain without the need to include an additional subconscious governor. The adopted exercise intensity is then the result of the effort required by the exercise and the maximum effort the athlete is willing to exert, or when athletes believe they are exerting a true maximal effort [28,29]. Alternatively, Edwards and Polman [1] consider the brain as a complex communication system in which pacing is regulated by consciousness and where 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 [1].

In this respect, the conscious-subconscious dichotomy has been predominant in the debate of how pace is regulated during exercise. Whether this discussion is still helping us forward in our understanding of the regulatory mechanisms involved in pacing, however, can be questioned [13]. Alternatively, Micklewright et al. [13] proposed to approach the mechanisms involved in the decision-making process of pacing as being intuitive or deliberative thinking processes [30,31]. 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 [30,31]. In a broader sense, we could then make the distinction between a pre-planned strategy and in-race adaptations. Concepts such as teleoanticipation and template formation are crucial for this pre-planned strategy and could be perceived as a mainly deliberative process [13]. In contrast, in-race adaptations in pacing behaviour are likely more intuitive responses driven by human-environment interactions [13].

Finally, two recent reviews attempted to incorporate decision-making theories into the regulation of exercise intensity, arguing pacing can be seen as the behavioural outcome of an underlying continuous decision-making process. Renfree et al. [11] 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 [11]. 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 [11]. In contrast, Smits et al. [10] 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 athlete for action [32,33]. 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 [34]. That is, a parallel preparation of several potential actions whilst collecting evidence for the selection between these potential actions while exposed to an array of biasing influences, such as rewards, costs or risks [6]

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. 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 have been pointed out for example. In Section 4, 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 experimental and observational literature regarding pacing regulation during competition will be presented.

3. The role of interpersonal competition in pacing research

In order to explore the influence of an opponent on pacing regulation in individual sports, 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 October 2017 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 707 papers. After reading the body of these remaining articles, 570 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 75 included papers (see Table 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 athletes during real-life competitions, while the experimental studies will be used to gain information regarding the underlying mechanisms via manipulations in well-controlled conditions.

3.1 Observational studies

The observational studies (N=59) 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, in 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.

3.1.1 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 [3,6,8,9,35–40]. Moreover, the differences in competitional data compared to model predictions that had been reported appeared to be related more to internal rather than external factors. Elite long track time trial speed skaters started relatively slow, for example, during 1500-m long track speed skating competitions compared to the predicted optimal pacing strategies in modelling studies [8,37]. However, an imposed fast start did not improve skating performance, probably due to the relatively high penalty of impairments in technique related to fatigue in speed skating [8,41]. 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 [42].

Table 1 Overview of the articles about pacing behaviour and competition included in this review.

Study	Sport	Distance	Sex	Study type	Type of Comp	Proficiency	No. of subjects
Konings et al., 2017	Short-track speed skating	500-m	Both	Obs	H-H	Elite	12550
		1000-m	Both	Obs	H-H	Elite	12143
		1500-m	Both	Obs	H-H	Elite	9402
Hanley, 2017	Cross-country running	~10-km	Both	Obs	H-H	Elite	199

Bossi et al., 2017	Cyclo-cross	~15-km ~30-km	Men Women	Obs Obs	H-H H-H	Elite Elite	174 179
Nikolaidis & Knechtle, 2017	Marathon running	42.1-km	Both	Obs	H-H	Recreational	451637
Lipińska & Hopkins, 2017	Swimming	400-m	Women	Obs	H-H	Elite	20
Rodriguez & Veiga, 2017	Swimming	10-km	Both	Obs	H-H	Elite	120
Sandford et al., 2017	Track running	800-m	Men	Obs	H-H	Elite	21
Konings et al., 2017	Cycling	4000-m	Men	Exp	TT	Trained	12
Wiersma et al., 2017	Long-track speed skating	1500-m	Men	Obs	TT	Talent	104
Konings et al., 2017	Short-track speed skating	500-m 1000-m 1500-m	Both Both Both	Obs Obs Obs	H-H H-H H-H	Elite Elite Elite	10483 9889 7890
Stone et al., 2017	Cycling	4000-m	Men	Exp	H-H	Trained	10
Losnegard et al., 2016	Cross-country skiing	10-km 15-km	Women Men	Obs Obs	TT TT	Elite Elite	14 22
Deaner & Lowen, 2016	Cross-country running	5000-m	Both	Obs	H-H	Trained	3948
Van Biesen et al., 2016	Track running	400-m 1500-m	Men Both	Obs Obs	H-H H-H	Elite Elite	47 28
Hanley, 2016	Road running	42.1-km	Both	Obs	H-H	Elite	1222
Renfree et al., 2016	Road running	100-km	Both	Obs	H-H	Elite	196
Jones et al., 2016	Cycling	16.1-km	Men	Exp	H-H	Trained	17
Lipińska et al., 2016	Swimming	800-m	Women	Obs	H-H	Elite	20
Lipińska et al., 2016	Swimming	1500-m	Men	Obs	H-H	Elite	24
Edwards et al. 2016	Rowing	6800-m	Men	Obs	H-H	Elite	228
Konings et al., 2016	Cycling	4000-m	Men	Exp	H-H	Trained	12
Taylor et al., 2016	Swimming	400-m	Both	Obs	H-H	Elite	1176
Noorbergen et al., 2016	Short-track speed skating	500-m 1000-m	Both Both	Obs Obs	H-H H-H	Elite Elite	1056 844
Konings et al., 2016	Short-track speed skating	1500-m	Both	Obs	H-H	Elite	510
Heidenfelder et al., 2016	Road cycling	4860-km	?	Obs	H-H	Trained	?
Carlsson et al., 2016	Skiing	90-km	Both	Obs	H-H	Trained	2400
Nikolaidis & Knechtle, 2016	Swimming	100-m 200-m 400-m 800-m	Both Both Both Both	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	Both	Obs	TT	Trained	501
Jones et al. 2016	Cycling	16.1-km	Men	Exp	H-H	Trained	20
Shei et al. 2016	Cycling	4000-m	Men	Exp	H-H	Trained	14
Wright, 2016	Para-cycling	500-m 1000-m	Women Men	Obs Obs	TT	Elite Elite	47 21
Williams et al., 2015	Cycling	16.1-km	Men	Exp	H-H	Trained	12
Williams et al., 2015	Cycling	16.1-km	Men	Exp	H-H	Trained	15
Tomazini et al., 2015	Running	3000-m	Men	Exp	H-H	Recreational	9
Kerhervé et al., 2015	Road running	106-km	Men	Obs	H-H	Trained	15
Hanley, 2015	Road running	21.1-km	Both	Obs	H-H	Elite	838
Knechtle et al., 2015	Road running	100-km	Men	Obs	H-H	Trained	1000
Mytton et al., 2015	Swimming Track running	400-m 1500-m	Men Men	Obs Obs	H-H H-H	Elite Elite	48 60
Deaner et al., 2015	Road running	42.1-km	Both	Obs	H-H	Amateur	91929
Moffatt et al., 2014	Track cycling	1000-m	Both	Obs	H-H	Elite	462
Renfree et al., 2014	Track running	800-m 1500-m	Both Both	Obs Obs	H-H H-H	Elite Elite	109 136
Esteve-Lanao et al., 2014	Cross country running	?	Men	Obs	H-H	Elite	768
Hanley, 2014	Cross-country running	12-km	Men	Obs	H-H	Elite	1273
Hoffman, 2014	Road running	161-km	Men	Obs	H-H	Elite	24
Santos-Lozano et al., 2014	Road running	42.1-km	Both	Exp	H-H	All	190228
Lambrick et al., 2013	Track running	800-m	Both	Exp	TT	Novices	13
Dwyer et al., 2013	Track cycling	Elimina-tion	Men	Obs	H-H	Elite	91
Hanley, 2013	Race walking	20-km 50-km	Both Men	Obs Obs	H-H H-H	Elite Elite	439 232
Renfree & St Clair Gibson, 2013	Road running	42.1-km	Women	Obs	H-H	Elite	60
Bath et al., 2012	Track running	5-km	Men	Exp	H-H	Trained	11
Thiel et al., 2012	Track running	800-m 1500-m 5-km 10-km	Both Both Both Both	Obs Obs Obs Obs	H-H H-H H-H H-H	Elite Elite Elite Elite	16 24 29 64
Stone et al. 2012	Cycling	4000-m	Men	Exp	H-H	Trained	9
Corbett et al., 2012	Cycling	2000-m	Men	Exp	H-H	Amateur	14
Mauger et al., 2012	Swimming	400-m	Both	Obs	H-H	Sub-elite	264

Hettinga et al., 2012	Cycling	1500-m	Men	Obs	TT	Trained	6
Hanley et al., 2011	Road running	5-km	Both	Obs	H-H	Sub-elite	20
Muehlbauer & Melges, 2011	Rowing	2000-m	Both	Obs	H-H	Elite	1682
Le Meur et al., 2011	Triathlon (running)	9.68-km	Both	Obs	H-H	Elite	12
Saraslanidis et al., 2011	Track running	400-m	Men	Obs	H-H	Amateur	8
Smith & Hopkins, 2011	Rowing	2000-m	Both	Obs	H-H	Elite	4234
Hettinga et al., 2011	Long-track speed skating	1500-m	Men	Obs	TT	Sub-elite	7
Brown et al., 2010	Rowing	2000-m	Both	Obs	TT	Sub-elite	507
Muehlbauer et al., 2010	Long-track speed skating	1000-m	Both	Obs	TT	Elite	65
Muehlbauer et al., 2010	Long-track speed skating	1500-m	Both	Obs	TT	Elite	114
Muehlbauer et al., 2010	Long-track speed skating	3-km	Women	Obs	TT	Elite	144
		5-km	Both	Obs	TT	Elite	226
		10-km	Men	Obs	TT	Elite	82
Peveler & Green, 2010	Cycling	20-km	Men	Exp	TT	Trained	8
Hanon & Gajer, 2009	Track running	400-m	Both	Obs	H-H	Elite	10
						Sub-elite	10
						Trained	10
Corbett, 2009	Track cycling	1-km	Men	Obs	TT	Elite	42
		3-km	Women	Obs	TT	Elite	68
		4-km	Men	Obs	TT	Elite	68
Hulleman et al., 2007	Cycling	1500-m	Men	Exp	TT	Trained	7
Tucker et al., 2006	Track running	800-m	Men	Obs	H-H	Elite	26
		5-km	Men	Obs	H-H	Elite	32
		10-km	Men	Obs	H-H	Elite	34
Garland, 2005	Rowing	2000-m	Both	Obs	H-H	Elite	1782
Lambert et al. 2004	Road running	100-km	Men	Obs	H-H	Elite	67
Jones & Whipp, 2002	Track running	800-m	Men	Obs	H-H	Elite	2
		5-km	Men	Obs	H-H	Elite	2

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

3.1.2 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 [12,43,44]. 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 [45].

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 [46–54], 400-m track running [55,56], and rowing [57–60], the adopted pacing behaviour is quite similar to the pacing strategies as predicted in modelling studies [8,9]. 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 [61], 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 [62], long-distance running [63,64] and short track speed skating [65–67], spontaneous group synchronization of movements seems to occur and pacing behaviour is adjusted drastically by the athletes [68–70]. In addition, these adjustments become even more extreme during important events such as the Olympic Games and World Championships [43,64]. Only when an all-out strategy could be adopted from the beginning of the race, all athletes displayed pacing behaviour similar to time trial sports [56,66].

Although head-to-head competitions without separate lanes seem 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, for example short track speed skating and cycling, are characterised by a slow, tactical development of the race [62,65,66]. That is, a strategy that will assist in saving energy via intelligent tactical positioning for the final acceleration at the end of a race. A remarkable exception to this perspective is the pacing profile during the elimination discipline in track cycling as a relatively fast start is adopted in these competitions [71]. 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 variability in lap speed increases significantly with a lower number of competitors [71]. In contrast, sport disciplines where the beneficial effect of drafting is much less predominant such as race walking or middle-and long-distance, 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 [43,64,72–77]. 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 [78–82]. Interestingly, the slowdown in speed seems to be higher for men compared to women [75,83,84], and in younger compared to older age-groups [85]. In this respect, initial pace has been associated recently with an individual's perception of risk [86], and might indicate an important mediating role of competition in risk perception. Moreover, the chosen initial pacing behaviour of elite athletes does seem to change over the seasons as shown in 800-m running [87] and short track speed skating [88]. In addition, stage of competition, the possibility of time fastest qualification, start position, altitude, and the number of competitors per race have been identified as influencing factors in the adopted pacing behaviour [88]. Finally, it has been highlighted in several studies that the appropriate strategy in competition is obviously related to other external aspects such as terrain [79,89–92], temperature [82,92], and humidity [82] rather than solely the other competitors.

3.2 Experimental studies

The experimental studies (N=16) that examined the influence of a competitor have mainly focussed on the performance effects rather than the changes in pacing. In general, an improved performance during competitive trials compared to individual or non-competitive trials has been found [93–106]. 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 [102]. Indeed, being aware of the deception did not alter the performance effect of an opponent compared to the deceived conditions [102,103]. Moreover, when participants were not deceived they were still able to establish an improvement in performance [94–96]. Interestingly, the prospect of a monetary incentive ($100) did not improve 1500-m cycling performance [97]. However, as the prior time trials in this particular study were already designed 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 performance improvement related to the presence of an opponent appears to remain quite stable, regardless of the level of performance [100,107] or the pacing profile of the opponent [95]. Yet a different level of performance of the opponent appeared to affect one’s self-efficacy to compete with their opponent [100]. Moreover, the improvement in performance achieved when riding against a virtual opponent has been related to a greater increased external distraction [98,108], increased anaerobic energy contribution [94,107], a more positive affect [100] and a greater decline in voluntary and evoked muscle force [96]. Yet despite a higher work rate, the presence of an opponent did not affect perceived exertion during the race compared to riding alone [96,98]. 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 [101]. Moreover, the perception of approaching or getting further behind your opponent might be a crucial variable [109]. That is, 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-m during the whole time trial [93]. 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 [93]. Regardless, 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 [110].

Despite the primary focus on the performance effects rather than the changes in pacing in the majority of studies, the pacing behaviour of the opponent has been shown to alter the initial pace of cyclists in laboratory-controlled conditions [95]. That is, a faster starting opponent evoked a faster initial pace compared a slower starting opponent, even in a situation where changing the pacing behavior based on the virtual opponent had neither a beneficial nor a detrimental effect for the exerciser [95]. Finally, although most pacing studies up until now mainly used experienced athletes, pacing behaviour of inexperienced athletes in a competitive environment has been studied once before [111]. Running performance decreased for inexperienced children (9-11 years old) during a competitive 800-m as they started significantly slower compared to individually completed trials [111].

4. Discussion

A better understanding of how athletes respond to their opponents could assist coaches and athletes to optimally prepare for the tactical decision-making involved in athletic competitions [10,11]. In this respect, technological developments and improved accessibility of online data regarding sport competitions have led to an exponential increase in the recent years of the number of observational pacing studies. These studies have described the pacing behaviour of athletes in a competitive setting over a broad range of sports. Nevertheless, the opportunities that are present to examine athlete-environment interactions and pacing using observational data have not yet been fully elucidated. Pacing behaviour could be significantly affected, for example, by tactical considerations or the rules of the sport. 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 theoretical most optimal pacing strategy [12,65]. Observational studies involving large datasets could help us in providing appropriate indicators or methods to assess tactics more objectively. Notable examples have been the work of Hanley [63,76] and Vleck et al. [112], in which pacing decisions in (half) marathon and triathlon races have been related to packing behaviour. In addition, in rowing [113], track cycling [62], cyclo-cross [114] and short track speed skating [65–67] first attempts have been made to incorporate tactical positioning when exploring pacing behaviour.

Most of the cited experimental studies used a virtual opponent in order to examine something else (i.e. the effect of deception). Regardless, the situation of a time trial against a virtual opponent while monitoring pacing behaviour provided several novel insights into how athletes 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 [94–96,98,100,104,105]. In addition, a virtual opponent has been shown to alter psychological responses [100], and the performance improvement when riding against an opponent appeared to be related to a greater anaerobic contribution [94,107]. Recently, Konings et al. [96] added to this by showing that riding a time trial in the presence of a virtual opponent improved performance, altered pacing behaviour and led to a greater decline in neuromuscular function, without changing perceived level of exertion [96]. In this respect, it has been suggested that the improved performance and deterred perceived exertion in the presence of an opponent is possibly related to motivational aspects [115] and/or attentional strategies [98,116]. Finally, experimental evidence suggests that an opponent may act as an invitation for action, as different pacing behaviour of an opponent evoked a different behavioural response in terms of pacing, even in laboratory-controlled conditions [95]. That is, a faster starting opponent evoked a faster initial pace compared to a slower starting opponent [95]. 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. In a similar way, coaches may have to be aware of the effects of competitive elements during training sessions designed to be of a relative low-intensity.

In the 1980s, researchers attempted to explain how athletes regulated their exercise intensity during competition [3,5,117–120]. Modelling studies revealed optimal pacing strategies related to the duration of an event based on aerodynamics and power losses [3–6,8,9,121–123]. The findings from these modelling studies 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 [4,8,9]. In this perspective, 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 [12]. As demonstrated in this review, findings as reported in time trial exercise cannot be 1:1 translated to actual real-life competitions, in which athletes clearly demonstrated 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 [12]. These findings support the idea that human-environment interactions indeed need to incorporated in models that attempt to explain the regulation of exercise intensity.

To incorporate human-environment interactions into pacing regulation, an important question that needs to be considered 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 [124]. Perception is determined via the construction of an internal representation of reality in our mind based on previous experiences and stored information [124]. However, the constructivist approach faces several limitations. It cannot explain, for example, 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 [125,126]. 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 above for the constructivist approach towards perception can be applied to concepts such as template formation, and heuristics or algorithms used for decision-making, as proposed in the several existing theories regarding the regulation of self-paced exercise intensity. The concept of a template is used, for example, in several pacing models [22,127]. The robustness of these proposed (RPE) templates in time trial exercise at maximal effort is remarkable [128]. 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 [96]. 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 athlete and opponent was already sufficient to take people off their RPE template as used in the other time trials [129].

In contrast to the constructivist approach, the ecological approach argues a direct rather than indirect perception-action coupling [32,33]. Instead of creating an internal representation of reality in our mind, individuals perceive direct action possibilities in their environment, so-called affordances [32,33]. Footballs for example, could be perceived as objects that can be kicked or thrown. In addition, one does not per se have to understand “what” something is, in order to decide “how” to use it. Even if one has never seen a football before, one could still perceive the action possibility to kick it. In a sport setting, many of these perceptual affordances are likely to be present and could potentially affect the outcome of the decision-making process involved in the regulation of the exercise intensity during competitions [10]. In this respect, this ecological approach seems to provide an opportunity to incorporate human-environment interactions and tactical decision-making onto the regulation of exercise intensity [10,12]. Several variables have been identified in this review that could potentially be seen as invitations for action or could affect the action selection based on all multiple affordance presented towards the athlete during competition, such as the behaviour of opponents, the possibility of fastest time qualification, the rules of the event, the number of competitors or the stage of competition [88]. In addition, previous research had shown already that an ecological concept such as optical flow does affect exercise regulation [130,131]. Finally, ecological dynamics have shown to be useful in the understanding of cooperative athlete interactions in team sports [132–134].

Yet also this ecological approach towards pacing is not without any flaws. There is undeniably a strong anticipatory, strategic component in pacing regulation [17,18]. 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, athletes may be able to learn based on previous experiences which action possibilities and/or information (both interoceptive and exteroceptive) presented towards the athlete are useful and/or should be acted upon in each particular situation [10,135]. Indeed, previous experience has been shown multiple times to be crucial for optimal pacing regulation [22,111,136–138], and different information-seeking behaviour is reported in experienced cyclists compared to novices [139].

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 [140]. In a longitudinal study for example, elite long track speed skaters distinguished themselves from non-elite skaters throughout their adolescence by a faster development of their pacing strategy towards the pacing strategies as used in elite 1500-m speed skating competitions [42]. Furthermore, athletes with an intellectual impairment appeared to have difficulties to efficiently self-regulate their pace [61,141], 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, 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 [10]. The affordance presented by the environment to the athlete will always be there to be perceived [126], providing the opportunity to incorporate human-environment interactions and tactical decision-making onto the regulation of exercise intensity [10,12]. However, which affordances the athlete selects to realize among the variety of affordances that are presented simultaneously and continuously, will also be based on the athlete's motivation, previous experience, the internal state of the athlete and/or the perceived level of exertion [10]. In addition, Pijpers et al. [135] showed that the internal state of an athlete 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 to the athlete, rather than on the perception of the affordance itself.

The virtual opponents used in previous research have typically been 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 [142]. 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; [142]. 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 [143]. Moreover, a negative momentum resulted in a rapid decline in exerted efforts of the rowing team, whereas a more appropriate regulation of exercise intensity was found during the positive momentum [143]. 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. In this respect, good examples of experimental studies that manipulated the lead or chase position are Peveler and Green [110] in cycling and Bath et al. [93] in running.

Finally, 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 [144–146]. In fact, understanding the interaction between external cues and the internal bodily state may even be the key for pushing the limits of human performance. Presenting external cues, such as a virtual avatar of an opponent as shown in this review, may assist in accessing a part of the exercise reserve that is not possible in "normal" conditions [94,96,107]. 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, and could be crucial in pushing the limits of human performance.

5. Conclusion

The regulation of the exercise intensity is an essential determinant for optimal performance in competitive sports. Previous research revealed the optimal pacing strategies in time trial exercise, the importance of feedback regarding the internal bodily state, and focused on concepts such as teleoanticipation [18] and template formation [127]. The importance of in-race adaptations to this planned pacing strategy in response to whatever is happening in the external world around the athlete, however, has been recently highlighted [10,13]. The present review 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, based on both observational and experimental studies. The present literature review showed that athletes adopted different pacing profiles during head-to-head competitions compared to the theoretical optimal strategies. A behavioural response to adjust the initial pace based on the behaviour of other competitors was revealed. However, the pacing adjustments related to other competitors appear to depend upon the competitive situation and the current internal state of the athlete. Furthermore, an improved time trial performance when riding against a virtual opponent was found. Based on the observational and experimental studies, 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 that exercise intensity is regulated based on afferent and efferent information in an anticipatory way that does not exceed the limits of the body [10]. That is, affordances presented by the environment to the athlete will always be there to be perceived [126], providing the opportunity to incorporate human-environment interactions and tactical decision-making into the regulation of exercise intensity [10,12]. However, which affordances the athlete selects to realise among the variety of affordances that are presented simultaneously and continuously, will also be based on the athlete's motivation, previous experience, the internal state of the athlete and/or the perceived level of exertion. The present findings of this review emphasise the importance of what is happening around the athlete 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.

Conflict of Interest: Marco J. Konings, and Florentina J. Hettinga declare that they have no conflict of interest.

References

1. Edwards AM, Polman RC. Pacing and awareness: Brain regulation of physical activity. Sport. Med. 2013;43:1057–64.

2. Abbiss CR, Laursen PB. Describing and understanding pacing strategies during athletic competition. Sport. Med. 2008;38:239–52.

3. van Ingen Schenau GJ, Cavanagh P. Power equations in endurance sports. J. Biomech. 1990;23:865–81.

4. De Koning JJ, Foster C, Lampen J, Hettinga FJ, Bobbert MF. Experimental evaluation of the power balance model of speed skating. J. Appl. Physiol. 2005;98:227–33.

5. Van Ingen Schenau GJ, De Koning JJ, De Groot G. A simulation of speed skating performances based on a power equation. Med. Sci. Sports Exerc. 1990;22:718–28.

6. De Koning JJ, De Groot G, Van Ingen Schenau GJ. A power equation for the sprint in speed skating. J. Biomech. 1992;25:573–80.

7. Hettinga FJ, De Koning JJ, Broersen FT, Van Geffen P, Foster C. Pacing strategy and the occurence of fatigue in 4000-m cycling time trials. Med. Sci. Sports Exerc. 2006;38:1484–91.

8. Hettinga FJ, De Koning JJ, Schmidt L, Wind N, Macintosh BR, Foster C. Optimal pacing strategy: from theoretical modelling to reality in 1500-m speed skating. Br. J. Sports Med. 2011;45:30–5.

9. Hettinga FJ, De Koning JJ, Hulleman M, Foster C. Relative importance of pacing strategy and mean power output in 1500-m self-paced cycling. Br. J. Sports Med. 2012;46:30–5.

10. Smits BL, Pepping G-J, Hettinga FJ. Pacing and decision making in sport and exercise: the roles of perception and action in the regulation of exercise intensity. Sport. Med. 2014;44:763–75.

11. Renfree A, Martin L, Micklewright D, St Clair Gibson A. Application of decision-making theory to the regulation of muscular work rate during self-paced competitive endurance activity. Sport. Med. 2014;44:147–58.

12. Hettinga FJ, Konings MJ, Pepping G-J. The science of racing against opponents: Affordance competition and the regulation of exercise intensity in head-to-head competition. Front. Physiol. 2017;8:118.

13. Micklewright D, Kegerreis S, Raglin J, Hettinga FJ. Will the Conscious–Subconscious Pacing Quagmire Help Elucidate the Mechanisms of Self-Paced Exercise? New Opportunities in Dual Process Theory and Process Tracing Methods. Sport. Med. 2017;47:1231–9.

14. Venhorst A, Micklewright D, Noakes TD. Towards a three-dimensional framework of centrally regulated and goal-directed exercise behaviour: a narrative review. Br. J. Sports Med. 2017;1–12.

15. Hill A, Long C, Lupton H. Muscular exercise, lactic acid, and the supply and utilisation of oxygen. Proc. R. Soc. B Biol. Sci. 1924;97:84–138.

16. Hill A, Lupton H. Muscular Exercise, Lactic Acid, and the Supply and Utilization of Oxygen. QJM. Oxford University Press; 1923;os-16:135–71.

17. Noakes TD. Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scand. J. Med. Sci. Sport. 2000;10:123–45.

18. Ulmer H. Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. Experientia. 1996;52:416–20.

19. Noakes TD, St Clair Gibson A. Logical limitations to the “catastrophe” models of fatigue during exercise in humans. Br. J. Sports Med. 2004;38:648–9.

20. Noakes TD, St Clair Gibson A, Lambert E V. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. Br. J. Sports Med. 2005;39:120–4.

21. Lambert E V, St Clair Gibson A, Noakes TD. Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. Br. J. Sports Med. 2005;39:52–62.

22. Tucker R. The anticipatory regulation of performance: the physiological basis for pacing strategies and the

development of a perception-based model for exercise performance. Br. J. Sports Med. 2009;43:392–400.

23. Noakes TD. Time to move beyond a brainless exercise physiology: the evidence for complex regulation of human exercise performance. Appl. Physiol. Nutr. Metab. 2011;36:23–35.

24. St Clair Gibson A, Noakes TD. Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. Br. J. Sports Med. 2004;38:797–806.

25. Tucker R, Bester A, Lambert E V, Noakes TD, Vaughan C, St Clair Gibson A. Non-random fluctuations in power output during self-paced exercise. Br. J. Sports Med. 2006;40:912–7.

26. St Clair Gibson A, Swart J, Tucker R. 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. Eur. J. Sport Sci. 2017;1–12.

27. Esteve-Lanao J, Lucía A, Foster C. How do humans control physiological strain during strenuous endurance exercise? PLoS One. 2008;3:e2943.

28. Marcora SM. Do we really need a central governor to explain brain regulation of exercise performance? Eur. J. Appl. Physiol. 2008;104:929–31.

29. Marcora SM. Counterpoint: Afferent Feedback From Fatigued Locomotor Muscles Is Not An Important Determinant Of Endurance Exercise Performance. J. Appl. Physiol. 2010;108:454–6.

30. Tversky A, Kahneman D. Judgment under Uncertainty: Heuristics and Biases. Science (80-.). 1974;185:1124–31.

31. Kahneman D. Thinking, Fast and Slow. New York, United States: Farrar, Straus & Giroux Inc; 2011.

32. Gibson JJ. The Senses Considered as Perceptual Systems. Boston: Houghton Mifflin; 1966.

33. Gibson JJ. A Theory of Direct Visual Perception. In: Royce J, Rozenboom W, editors. Psychol. Knowing. New York: Gordon & Breach; 1972.

34. Smith J, Pepping G-J. Effects of Affordance Perception on the Initiation and Actualization of Action. Ecol. Psychol. 2010;22:119–49.

35. Foster C, De Koning JJ, Hettinga FJ, Lampen J, Dodge C, Bobbert MF, et al. Effect of competitive distance on energy expenditure during simulated competition. Int. J. Sports Med. 2004;25:198–204.

36. Muehlbauer T, Panzer S, Schindler C. Pacing pattern and speed skating performance in competitive long-distance events. J. Strength Cond. Res. 2010;24:114–9.

37. Muehlbauer T, Schindler C, Panzer S. Pacing and performance in competitive middle-distance speed skating. Res. Q. Exerc. Sport. 2010;81:1–6.

38. Muehlbauer T, Schindler C, Panzer S. Pacing and sprint performance in speed skating during a competitive season. Int. J. Sports Physiol. Perform. 2010;5:165–76.

39. Corbett J. An analysis of the pacing strategies adopted by elite athletes during track cycling. Int. J. Sports Physiol. Perform. 2009;4:195–205.

40. Wright R. Positive Pacing Strategies Are Utilized by Elite Male and Female Para-cyclists in Short Time Trials in the Velodrome. Front. Physiol. 2016;6:425.

41. Stoter IK, MacIntosh BR, Fletcher JR, Pootz S, Zijdewind I, Hettinga FJ. Pacing Strategy, Muscle Fatigue and Technique in 1500m Speed Skating and Cycling Time-Trials. Int. J. Sports Physiol. Perform. 2016;11:337–43.

42. Wiersma R, Stoter IK, Visscher C, Hettinga FJ, Elferink-Gemser MT. Development of 1500m Pacing Behavior in Junior Speed Skaters: A Longitudinal Study. Int. J. Sports Physiol. Perform. 2017;1–20.

43. Thiel C, Foster C, Banzer W, De Koning JJ. Pacing in Olympic track races: Competitive tactics versus best performance strategy. J. Sports Sci. 2012;30:1107–15.

44. Renfree A, Mytton GJ, Skorski S, St Clair Gibson A. Tactical considerations in the middle-distance running events at the 2012 olympic games: A case study. Int. J. Sports Physiol. Perform. 2014;9:362–4.

45. Jones AM, Whipp B. Bioenergetic constraints on tactical decision making in middle distance running. Br. J. Sports Med. 2002;36:102–4.

46. Mauger AR, Neuloh J, Castle PC. Analysis of pacing strategy selection in elite 400-m freestyle swimming. Med. Sci. Sports Exerc. 2012;44:2205–12.

47. Skorski S, Faude O, Abbiss CR, Caviezel S, Wengert N, Meyer T. Influence of pacing manipulation on performance of juniors in simulated 400 m swim competition. Int. J. Sports Physiol. Perform. 2014;8:817–24.

48. Mytton GJ, Archer DT, Turner LA, Skorski S, Thompson KG, St Clair Gibson A. Increased variability of lap speeds differentiate medallists and non-medallists in middle distance running and swimming events. Int. J. Sports Physiol. Perform. 2015;10:369–73.

49. Lipińska P, Allen S V, Hopkins WG. Modeling parameters that characterize pacing of elite female 800-m freestyle swimmers. Eur. J. Sport Sci. 2016;16:287–92.

50. Lipińska P, Allen S V, Hopkins WG. Relationships between Pacing Parameters and Performance of Elite Male 1500-m Swimmers. Int. J. Sports Physiol. Perform. 2016;11:159–63.

51. Taylor JB, Santi G, Mellalieu SD. Freestyle race pacing strategies (400 m) of elite able-bodied swimmers and swimmers with disability at major international championships. J. Sports Sci. 2016;34:1913–20.

52. Nikolaidis PT, Knechtle B. Pacing in age-group freestyle swimmers at The XV FINA World Masters Championships in Montreal 2014. J. Sports Sci. 2017;35:1165–72.

53. Lipinska P, Hopkins WG. Pacing profiles and competitive performance of elite female 400-m freestyle swimmers. J. Strength Cond. Res. 2017;

54. Rodriguez L, Veiga S. Effect of the Pacing Strategies on the Open Water 10km World Swimming Championships Performances. Int. J. Sports Physiol. Perform. 2017;1–19.

55. Saraslanidis PJ, Panoutsakopoulos V, Tsalis GA, Kyprianou E. The effect of different first 200-m pacing strategies on blood lactate and biomechanical parameters of the 400-m sprint. Eur. J. Appl. Physiol. 2011;111:1579–90.

56. Hanon C, Gajer B. Velocity and stride parameters of world-class 400-meter athletes compared with less experienced runners. J. Strength Cond. Res. 2009;23:524–31.

57. Brown MR, Delau S, Desgorces FD. Effort regulation in rowing races depends on performance level and exercise mode. J. Sci. Med. Sport. 2010;13:613–7.

58. Muehlbauer T, Melges T. Pacing patterns in competitive rowing adopted in different race categories. J. Strength Cond. Res. 2011;25:1293–8.

59. Smith TB, Hopkins WG. Variability and predictability of finals times of elite rowers. Med. Sci. Sports Exerc. 2011;43:2155–60.

60. Garland SW. An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. Br. J. Sports Med. 2005;39:39–42.

61. Van Biesen D, Hettinga FJ, McCulloch K, Vanlandewijck YC. Pacing Profiles in Competitive Track Races: Regulation of Exercise Intensity Is Related to Cognitive Ability. Front. Physiol. 2016;7:624.

62. Moffatt J, Scarf P, Passfield L, McHale IG, Zhang K. To lead or not to lead: analysis of the sprint in track cycling. J. Quant. Anal. Sport. 2014;10:161–72.

63. Hanley B. Pacing profiles and pack running at the IAAF World Half Marathon Championships. J. Sports Sci. 2015;33:1189–95.

64. Renfree A, St Clair Gibson A. Influence of different performance levels on pacing strategy during the Women's World Championship marathon race. Int. J. Sports Physiol. Perform. 2013;8:279–85.

65. Konings MJ, Noorbergen OS, Parry D, Hettinga FJ. Pacing behaviour and tactical positioning in 1500 m short-track speed skating. Int. J. Sports Physiol. Perform. 2016;11:122–9.

66. Noorbergen OS, Konings MJ, Elferink-Gemser MT, Micklewright D, Hettinga FJ. Pacing and tactical positioning in 500 and 1000m short-track speed skating. Int. J. Sports Physiol. Perform. 2016;11:742–8.

67. Konings MJ, Hettinga FJ. Objectifying tactics: Athlete and race variability in elite short-track speed skating. Int. J. Sports Physiol. Perform. 2017;

68. Codrons E, Bernardi NF, Vandoni M, Bernardi L. Spontaneous group synchronization of movements and respiratory rhythms. PLoS One. 2014;9:e107538.

69. Renfree A, Crivoi do Carmo E, Martin L, Peters DM. The Influence of Collective Behavior on Pacing in Endurance Competitions. Front. Physiol. Frontiers; 2015;6.

70. Ackland GJ, Butler D. Pack formation in cycling and orienteering. Nature. 2001;413:127–127.

71. Dwyer DB, Ofoghi B, Huntsman E, Rossitto D, McMahon C, Zeleznikow J. The elimination race in track cycling: patterns and predictors of performance. J. Sci. Cycl. 2013;2:6–12.

72. Hanley B, Smith LC, Bissas A. Kinematic variations due to changes in pace during men's and women's 5 km road running. Int. J. Sport. Sci. Coach. 2011;6:243–52.

73. Hanley B. An analysis of pacing profiles of world-class racewalkers. Int. J. Sports Physiol. Perform. 2013;8:435–41.

74. Hanley B. Senior men's pacing profiles at the IAAF World Cross Country Championships. J. Sports Sci. 2014;32:1060–5.

75. Deaner RO, Carter RE, Joyner MJ, Hunter SK. Men are more likely than women to slow in the marathon. Med. Sci. Sports Exerc. 2015;47:607–16.

76. Hanley B. Pacing, packing and sex-based differences in Olympic and IAAF World Championship marathons. J. Sports Sci. 2016;34:1675–81.

77. Hanley B. Pacing profiles of senior men and women at the 2017 IAAF World Cross Country Championships. J. Sports Sci. 2017;1–5.

78. Lambert MI, Dugas JP, Kirkman MC, Mokone GG, Waldeck MR. Changes in Running Speeds in a 100 KM Ultra-Marathon Race. J. Sport. Sci. Med. 2004;3:167–73.

79. Hoffman MD. Pacing by Winners of a 161-km Mountain Ultramarathon. Int. J. Sports Physiol. Perform. 2014;9:1054–6.

80. Renfree A, Crivoi do Carmo E, Martin L. The influence of performance level, age and gender on pacing strategy during a 100-km ultramarathon. Eur. J. Sport Sci. 2016;16:409–15.

81. Bossi AH, Matta GG, Millet GY, Lima P, Pertence LC, de Lima JP, et al. Pacing Strategy During 24-hour Ultramarathon-Distance Running. Int. J. Sports Physiol. Perform. 2017;12:590–6.

82. Tan P, Tan FH, Bosch AN. Similarities and Differences in Pacing Patterns in a 161-km and 101-km Ultra-Distance Road Race. J. Strength Cond. Res. 2016;30:2145–55.

83. Carlsson M, Assarsson H, Carlsson T. The influence of sex, age, and race experience on pacing profiles during the 90 km Vasaloppet ski race. Open Access J. Sport. Med. 2016;7:11–9.

84. Deaner RO, Lowen A. Males and Females Pace Differently in High School Cross-Country Races. J. Strength Cond. Res. 2016;30:2991–7.

85. Nikolaidis PT, Knechtle B. Effect of age and performance on pacing of marathon runners. Open Access J. Sport. Med. 2017;8:171–80.

86. Micklewright D, Parry D, Robinson T, Deacon G, Renfree A, St Clair Gibson A, et al. Risk perception influences athletic pacing strategy. Med. Sci. Sports Exerc. 2015;47:1026–37.

87. Sandford GN, Pearson S, Allen S V, Malcata RM, Kilding AE, Ross A, et al. Tactical Behaviours in Men's 800m Olympic and World Championship Medallists: A Changing of the Guard. Int. J. Sports Physiol. Perform. 2017;1–13.

88. Konings MJ, Hettinga FJ. The impact of different competitive environments on pacing and performance. Int. J. Sports Physiol. Perform. 2017;Epub ahead of print.

89. Knechtle B, Rosemann T, Zingg MA, Stiefel M, Rüst CA. Pacing strategy in male elite and age group 100

km ultra-marathoners. Open Access J. Sport. Med. 2015;6:71–80.

90. Kerhervé HA, Millet GY, Solomon C. The Dynamics of Speed Selection and Psycho-Physiological Load during a Mountain Ultramarathon. PLoS One. 2015;10:e0145482.

91. Kerhervé HA, Cole-Hunter T, Wiegand AN, Solomon C. Pacing during an ultramarathon running event in hilly terrain. PeerJ. 2016;4:e2591.

92. Heidenfelder A, Rosemann T, Rüst CA, Knechtle B. Pacing Strategies of Ultracyclists in the "Race across AMerica." Int. J. Sports Physiol. Perform. 2016;11:319–27.

93. Bath D, Turner LA, Bosch AN, Tucker R, Lambert E V, Thompson KG, et al. The effect of a second runner on pacing strategy and RPE during a running time trial. Int. J. Sports Physiol. Perform. 2012;7:26–32.

94. Corbett J, Barwood MJ, Ouzounoglou A, Thelwell R, Dicks M. Influence of competition on performance and pacing during cycling exercise. Med. Sci. Sports Exerc. 2012;44:509–15.

95. Konings MJ, Schoenmakers PP, Walker A, Hettinga FJ. The behavior of an opponent alters pacing decisions in 4-km cycling time trials. Physiol. Behav. 2016;158:1–5.

96. Konings MJ, Parkinson J, Zijdewind I, Hettinga FJ. Racing an opponent alters pacing, performance and muscle force decline, but not RPE. Int. J. Sports Physiol. Perform. 2017;Epub ahead of print.

97. Hulleman M, De Koning JJ, Hettinga FJ, Foster C. The effect of extrinsic motivation on cycle time trial performance. Med. Sci. Sports Exerc. 2007;39:709–15.

98. Williams EL, Jones HS, Sparks SA, Marchant DC, Midgley AW, McNaughton LR. Competitor presence reduces internal attentional focus and improves 16.1km cycling time trial performance. J. Sci. Med. Sport. 2015;18:486–91.

99. Stone MR, Thomas K, Wilkinson M, Jones AM, St Clair Gibson A, Thompson KG. Effects of deception on exercise performance: Implications for determinants of fatigue in humans. Med. Sci. Sports Exerc. 2012;44:534–41.

100. Williams EL, Jones HS, Sparks SA, Midgley AW, Marchant DC, Bridge CA, et al. Altered Psychological Responses to Different Magnitudes of Deception during Cycling. Med. Sci. Sports Exerc. 2015;47:2423–30.

101. Jones HS, Williams EL, Marchant DC, Sparks SA, Bridge CA, Midgley AW, et al. Deception has no acute or residual effect on cycling time trial performance but negatively effects perceptual responses. J. Sci. Med. Sport. 2016;19:771–6.

102. Jones HS, Williams EL, Marchant DC, Sparks SA, Bridge CA, Midgley AW, et al. Improvements in Cycling Time Trial Performance Are Not Sustained Following the Acute Provision of Challenging and Deceptive Feedback. Front. Physiol. Frontiers; 2016;7:399.

103. Shei R-J, Thompson KG, Chapman R, Raglin J, Mickleborough T. Using deception to establish a reproducible improvement in 4-Km cycling time trial performance. Int. J. Sports Med. 2016;37:341–6.

104. Tomazini F, Pasqua LA, Damasceno M V, Silva-Cavalcante MD, De Oliveira FR, Lima-Silva AE, et al. Head-to-head running race simulation alters pacing strategy, performance, and mood state. Physiol. Behav. 2015;149:39–44.

105. Wilmore J. Influence of motivation on physical work capacity and performance. J. Appl. Physiol. 1968;24:459–63.

106. Bond CF, Titus LJ. Social facilitation: A meta-analysis of 241 studies. Psychol. Bull. 1983;94:265–92.

107. Stone MR, Thomas K, Wilkinson M, Stevenson E, St Clair Gibson A, Jones AM, et al. Exploring the performance reserve: Effect of different magnitudes of power output deception on 4,000 m cycling time-trial performance. PLoS One. 2017;12:e0173120.

108. Whitehead AE, Jones HS, Williams EL, Dowling C, Morley D, Taylor JA, et al. Changes in cognition over a 16.1 km cycling time trial using Think Aloud protocol: Preliminary evidence. Int. J. Sport Exerc. Psychol. 2017;15:1–9.

109. Meerhoff L, De Poel HJ, Button C. How visual information influences coordination dynamics when

following the leader. Neurosci. Lett. Elsevier Ireland Ltd; 2014;582:12–5.

110. Peveler WW, Green M. The effect of extrinsic factors on simulated 20-km time trial performance. J. Strength Cond. Res. 2010;24:3265–9.

111. Lambrick D, Rowlands A, Rowland T, Eston R. Pacing strategies of inexperienced children during repeated 800 m individual time-trials and simulated competition. Pediatr. Exerc. Sci. 2013;25:198–211.

112. Vleck VE, Bentley DJ, Millet GP, Bürgi A. Pacing during an elite Olympic distance triathlon: Comparison between male and female competitors. J. Sci. Med. Sport. 2008;11:424–32.

113. Edwards AM, Guy JH, Hettinga FJ. Oxford and Cambridge Boat Race: Performance, Pacing and Tactics Between 1890 and 2014. Sport. Med. 2016;46:1553–62.

114. Bossi AH, O'Grady C, Ebreo R, Passfield L, Hopker JG. Pacing Strategy and Tactical Positioning During Cyclo-Cross Races. Int. J. Sports Physiol. Perform. 2017;1–23.

115. McCormick A, Meijen C, Marcora SM. Psychological Determinants of Whole-Body Endurance Performance. Sport. Med. 2015;45:997–1015.

116. Brick NE, Campbell MJ, Metcalfe RS, Mair JL, MacIntyre TE. Altering Pace Control and Pace Regulation: Attentional Focus Effects during Running. Med. Sci. Sports Exerc. 2016;48:879–86.

117. Van Ingen Schenau GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. Med. Sci. Sports Exerc. 1980;12:257–61.

118. Van Ingen Schenau GJ. The influence of air friction in speed skating. J. Biomech. 1982;15:449–58.

119. Van Ingen Schenau GJ, De Groot G, Hollander AP. Some technical, physiological and anthropometrical aspects of speed skating. Eur. J. Appl. Physiol. Occup. Physiol. 1983;50:343–54.

120. Van Ingen Schenau GJ, De Groot G. On the origin of differences in performance level between elite male and female speed skaters. Hum. Mov. Sci. 1983;2:151–9.

121. De Koning JJ, Foster C, Lucía A, Bobbert MF, Hettinga FJ, Porcari JP. Using modeling to understand how athletes in different disciplines solve the same problem: Swimming versus running versus speed skating. Int. J. Sports Physiol. Perform. 2011;6:276–80.

122. Foster C, De Koning JJ, Hettinga FJ, Lampen J, La Clair KL, Dodge C, et al. Pattern of energy expenditure during simulated competition. Med. Sci. Sports Exerc. 2003;35:826–31.

123. De Koning JJ, Bobbert MF, Foster C. Determination of optimal pacing strategy in track cycling with an energy flow model. J. Sci. Med. Sport. 1999;2:266–77.

124. Gregory R. Concepts and Mechanisms of Perception. London: Duckworth; 1974.

125. Lombardo TJ. The reciprocity of perceiver and environment: The evolution of James J. Gibson's ecological psychology. Hillsdale: Erlbaum; 1987.

126. Gibson JJ. The ecological approach to visual perception. J. Broadcast. Boston: Houghton Mifflin; 1979.

127. Foster C, Hendrickson K, Peyer K, Reiner B, De Koning JJ, Lucía A, et al. Pattern of developing the performance template. Br. J. Sports Med. 2009;43:765–9.

128. Schallig W, Veneman T, Noordhof DA, Porcari JP, De Koning JJ, Foster C. The role of the rating of perceived exertion template in pacing. Int. J. Sports Physiol. Perform. 2017;1–22.

129. Konings MJ, Foulsham T, Micklewright D, Hettinga FJ. The athlete-opponent relationship alters pacing decisions and information-seeking behaviour in 4-km cycling time trials. 22nd Annu. Congr. Eur. Coll. Sport Sci. B. Abstr. Essen, Germany; 2017. p. 227.

130. Parry D, Chinnasamy C, Micklewright D. Optic flow influences perceived exertion during cycling. J. Sport Exerc. Psychol. 2012;34:444–56.

131. Parry D, Micklewright D. Optic flow influences perceived exertion and distance estimation but not running pace. Med. Sci. Sports Exerc. 2014;46:1658–65.

132. Vilar L, Araújo D, Davids K, Button C. The Role of Ecological Dynamics in Analysing Performance in Team Sports. Sport. Med. 2012;42:1–10.

133. Silva P, Garganta J, Araújo D, Davids K, Aguiar P. Shared Knowledge or Shared Affordances? Insights from an Ecological Dynamics Approach to Team Coordination in Sports. Sport. Med. 2013;43:765–72.

134. Passos P, Araújo D, Davids K. Competitiveness and the Process of Co-adaptation in Team Sport Performance. Front. Psychol. 2016;7:1562.

135. Pijpers R, Oudejans RR, Bakker FC. Changes in the perception of action possibilities while climbing to fatigue on a climbing wall. J. Sports Sci. 2007;25:97–110.

136. Micklewright D, Papadopoulou E, Swart J, Noakes TD. Previous experience influences pacing during 20 km time trial cycling. Br. J. Sports Med. 2010;44:952–60.

137. Mauger AR, Jones AM, Williams CA. Influence of feedback and prior experience on pacing during a 4-km cycle time trial. Med. Sci. Sports Exerc. 2009;41:451–8.

138. Micklewright D, Angus SD, Suddaby J, St Clair Gibson A, Sandercock G, Chinnasamy C. Pacing Strategy in Schoolchildren Differs with Age and Cognitive Development. Med. Sci. Sports Exerc. 2012;44:362–9.

139. Boya M, Foulsham T, Hettinga FJ, Parry D, Williams EL, Jones HS, et al. Information Acquisition Differences between Experienced and Novice Time Trial Cyclists. Med. Sci. Sports Exerc. 2017;49:1884–98.

140. Elferink-Gemser MT, Hettinga FJ. Pacing and Self-regulation: Important Skills for Talent Development in Endurance Sports. Int. J. Sports Physiol. Perform. 2017;12:831–5.

141. Van Biesen D, Hettinga FJ, McCulloch K, Vanlandewijck YC. Pacing Ability in Elite Runners with Intellectual Impairment. Med. Sci. Sports Exerc. 2017;49:588–94.

142. Den Hartigh RJ, van der Sluijs J, Zaal FT, Gernigon C. Psychological Momentum Shapes Athletes' Affordances. Congr. French Soc. Sport Psychol. Montpellier, France; 2017.

143. Den Hartigh RJ, Gernigon C, Van Yperen NW, Marin L, Van Geert PL. How Psychological and Behavioral Team States Change during Positive and Negative Momentum. PLoS One. 2014;9:e97887.

144. Karageorghis CI, Priest D-L. Music in the exercise domain: a review and synthesis (Part I). Int. Rev. Sport Exerc. Psychol. 2012;5:44–66.

145. Karageorghis CI, Priest D-L. Music in the exercise domain: a review and synthesis (Part II). Int. J. Sport Exerc. Psychol. 2012;5:67–84.

146. Lima-Silva AE, Silva-Cavalcante MD, Pires FO, Bertuzzi RC, Oliveira R, Bishop DJ. 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. Int. J. Sports Med. 2012;33:813–8.