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REVIEW ARTICLE

Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review

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Abstract An athlete's pacing strategy is widely recognised as an essential determinant for performance during individual events. Previous research focussed 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. The PubMed, CINAHL and Web of Science electronic databases 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, 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

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.

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

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 [1]. This goal-directed regulation of 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].

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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) and biomechanical (conversion of metabolic data to mechanical power output; aerodynamics and frictional losses) components are crucial [3–6]. To optimise performance in endurance time-trial events for example, athletes should maximise their mechanical power output while minimising 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 pacing strategy is advised when exercise duration is over 2 min, 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 < 30 s, an all-out strategy is advised in order to use all 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 approximately 1–2 min [8, 9].

Without underestimating the insight these studies provide 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 individual time trials, where the effects of external influences are much less predominant compared with, for example, head-to-head competitions. From 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 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 one of the most important human–environment interactions 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 (Sect. 2). This will provide context and explanations about the development and current state of research into this 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 in regard to the effect of competitors on pacing behaviour is presented (Sect. 3). Finally, we consolidate the evidence presented to help illustrate 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 (Sect. 4).

2 The Regulation of Exercise Intensity

The regulatory mechanisms underpinning the decision-making processes involved in pacing are still strongly debated. The predominant theory in exercise physiology has, for a long time, been 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 homeostasis 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 change 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 with 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 a psychobiological model, whereby 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, whereby 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. However, whether this discussion is still helping us forward in the understanding of the regulatory mechanisms involved in pacing 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 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 while 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 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. Given the aforementioned theories and models, it is evident that 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, are of importance in the regulation of exercise intensity. However, there has been little consideration of human–environment interaction as part of these proposed pacing theories. As such, there is a need to consider and integrate the available evidence regarding human–environment interactions in pacing research to date.

3 The Role of Interpersonal Competition in Pacing Research

In order to explore the influence of an opponent on pacing regulation in sports where performance is expressed in time, the existing literature has been critically reviewed. The PubMed, CINAHL, and Web of Science electronic databases 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 studies were independently reviewed by each author to remove duplicate samples and to exclude papers that did not describe pacing or in which the design of the study could not be perceived as a competitive situation. 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 in which the design of the study could not be perceived as a competitive situation, leading to 75 included papers (see Table 1). A distinction was made between observational and experimental studies. The observational studies were examined to provide insight into the pacing decisions of athletes during real-life competitions, while the experimental studies were 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 with 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 with the predicted optimal pacing strategies in modelling studies [8, 37]. However, a faster 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 developing their pacing strategy towards that of elite skaters already from an earlier age (13–15 years), and even more clearly later on in their adolescence in 1500 m competitive races [42].

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 one finishes 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 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 [63–65] and short-track speed skating [66–68], spontaneous group synchronisation of movements seems to occur and pacing behaviour is adjusted drastically by the athletes [65, 69–71]. In addition, these adjustments become even more extreme during important events such as the Olympic Games and World Championships [43, 64]. Only in world record performances [72], or when an all-out strategy could be adopted from the beginning of the race, do athletes display pacing behaviour similar to time-trial sports [56, 67].

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 an

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

Study	Sport	Distance	Sex	Type of competition	Proficiency	No. of subjects
Observational studies						
Running						
Hanley [79]	Cross-country running	∼ 10 km	Both	H-H	Elite	199
Nikolaidis and Knechtle [91]	Marathon running	42.1 km	Both	H-H	Recreational	451,637
Sandford et al. [93]	Track running	800 m	Men	H-H	Elite	21
Bossi et al. [86]	Road running	24 h	Both	TT	Trained	501
Deaner and Lowen [90]	Cross-country running	5000 m	Both	H-H	Trained	3948
		400 m	Men	H-H	Elite	47
Van Biesen et al. [61]	Track running	1500 m	Both	H-H	Elite	28
Hanley [78]	Road running	42.1 km	Both	H-H	Elite	1222
Renfree et al. [85]	Road running	100 km	Both	H-H	Elite	196
Kerhervé et al. [97]	Road running	173 km	?	H-H	Trained	10
Tan et al. [87]	Road running	101 km	?	H-H	Trained	120
		161 km	?	H-H	Trained	47
Kerhervé et al. [96]	Road running	106 km	Men	H-H	Trained	15
Hanley [63]	Road running	21.1 km	Both	H-H	Elite	838
Knechtle et al. [95]	Road running	100 km	Men	H-H	Trained	1000
Mytton et al. [48]	Swimming Track running	400 m	Men	H-H	Elite	48
		1500 m	Men	H-H	Elite	60
Deaner et al. [77]	Road running	42.1 km	Both	H-H	Amateur	91,929
Renfree et al. [44]	Track running	800 m	Both	H-H	Elite	109
		1500 m	Both	H-H	Elite	136
Esteve-Lanao et al. [81]	Cross-country running	?	Men	H-H	Elite	768
Hanley [76]	Cross-country running	12 km	Men	H-H	Elite	1273
Hoffman [84]	Road running	161 km	Men	H-H	Elite	24
Santos-Lozano et al. [88]	Road running	42.1 km	Both	H-H	All	190,228
		20 km	Both	H-H	Elite	439
Hanley [75]	Race walking	50 km	Men	H-H	Elite	232
Renfree and St Clair Gibson [64]	Road running	42.1 km	Women	H-H	Elite	60
Thiel et al. [43]	Track running	800 m	Both	H-H	Elite	16
		1500 m	Both	H-H	Elite	24
		5 km	Both	H-H	Elite	29
		10 km	Both	H-H	Elite	64
Hanley et al. [74]	Road running	5 km	Both	H-H	Sub-elite	20
Le Meur et al. [82]	Triathlon (running)	9.68 km	Both	H-H	Elite	12
Saraslanidis et al. [55]	Track running	400 m	Men	H-H	Amateur	8
Hanon and Gajer [56]	Track running	400 m	Both	H-H	Elite	10
					Sub-elite	10
					Trained	10
Tucker et al. [72]	Track running	800 m	Men	H-H	Elite	26
		5 km	Men	H-H	Elite	32
		10 km	Men	H-H	Elite	34
Lambert et al. [83]	Road running	100 km	Men	H-H	Elite	67
Jones and Whipp [45]	Track running	800 m	Men	H-H	Elite	2
		5 km	Men	H-H	Elite	2
Cycling						
Bossi et al. [119]	Cyclo-cross	∼ 15 km	Men	H-H	Elite	174
		∼ 30 km	Women	H-H	Elite	179
Heidenfelder et al. [98]	Road cycling	4860 km	?	H-H	Trained	?

Table 1 continued

Study Observational studies	Sport	Distance	Sex	Type of competition	Proficiency	No. of subjects
Wright [40]	Para-cycling	500 m	Women	TT	Elite	47
		1000 m	Men		Elite	21
Moffatt et al. [62]	Track cycling	1000 m	Both	H-H	Elite	462
Dwyer et al. [73]	Track cycling	Elimination	Men	H-H	Elite	91
Hettinga et al. [9]	Cycling	1500 m	Men	TT	Trained	6
Corbett [39]	Track cycling	1 km	Men	TT	Elite	42
		3 km	Women	TT	Elite	68
		4 km	Men	TT	Elite	68
Speed skating						
Konings et al. [94]	Short-track speed skating	500 m	Both	H-H	Elite	12,550
		1000 m	Both	H-H	Elite	12,143
		1500 m	Both	H-H	Elite	9402
Wiersma et al. [42]	Long-track speed skating	1500 m	Men	TT	Talent	104
Konings et al. [68]	Short-track speed skating	500 m	Both	H-H	Elite	10,483
		1000 m	Both	H-H	Elite	9889
		1500 m	Both	H-H	Elite	7890
		500 m	Both	H-H	Elite	1056
Noorbergen et al. [67]	Short-track speed skating	1000 m	Both	H-H	Elite	844
Konings et al. [66]	Short-track speed skating	1500 m	Both	H-H	Elite	510
Hettinga et al. [8]	Long-track speed skating	1500 m	Men	TT	Sub-elite	7
Muehlbauer et al. [36]	Long-track speed skating	3 km	Women	TT	Elite	144
		5 km	Both	TT	Elite	226
		10 km	Men	TT	Elite	82
Muehlbauer et al. [37]	Long-track speed skating	1500 m	Both	TT	Elite	114
Muehlbauer et al. [38]	Long-track speed skating	1000 m	Both	TT	Elite	65
Swimming						
Lipińska and Hopkins [53]	Swimming	400 m	Women	H-H	Elite	20
Rodriguez and Veiga [54]	Open-water swimming	10 km	Both	H-H	Elite	120
Nikolaidis and Knechtle [52]	Swimming	100 m	Both	H-H	Elite	1602
		200 m	Both	H-H	Elite	1228
		400 m	Both	H-H	Elite	772
		800 m	Both	H-H	Elite	880
Lipińska et al. [49]	Swimming	800 m	Women	H-H	Elite	20
Lipińska et al. [50]	Swimming	1500 m	Men	H-H	Elite	24
Taylor et al. [51]	Swimming	400 m	Both	H-H	Elite	1176
Mauger et al. [46]	Swimming	400 m	Both	H-H	Sub-elite	264
Rowing						
Edwards et al. [118]	Rowing	6800 m	Men	H-H	Elite	228
Muehlbauer and Melges [58]	Rowing	2000 m	Both	H-H	Elite	1682
Smith and Hopkins [59]	Rowing	2000 m	Both	H-H	Elite	4234
Brown et al. [57]	Rowing	2000 m	Both	TT	Sub-elite	507
Garland [60]	Rowing	2000 m	Both	H-H	Elite	1782
Other						
Losnegard et al. [80]	Cross-country skiing	10 km	Women	TT	Elite	14
		15 km	Men	TT	Elite	22
Carlsson et al. [89]	Skiing	90 km	Both	H-H	Trained	2400

Table 1 continued

Study Experimental studies	Sport	Distance	Sex	Type of competition	Proficiency	No. of subjects
Cycling						
Konings et al. [102]	Cycling	4000 m	Men	TT	Trained	12
Stone et al. [113]	Cycling	4000 m	Men	H-H	Trained	10
Jones et al. [108]	Cycling	16.1 km	Men	H-H	Trained	17
Konings et al. [101]	Cycling	4000 m	Men	H-H	Trained	12
Jones et al. [107]	Cycling	16.1 km	Men	H-H	Trained	20
Shei et al. 2016 [109]	Cycling	4000 m	Men	H-H	Trained	14
Williams et al. [106]	Cycling	16.1 km	Men	H-H	Trained	12
Williams et al. [104]	Cycling	16.1 km	Men	H-H	Trained	15
Stone et al. [105]	Cycling	4000 m	Men	H-H	Trained	9
Corbett et al. [100]	Cycling	2000 m	Men	H-H	Amateur	14
Peveler and Green [116]	Cycling	20 km	Men	TT	Trained	8
Hulleman et al. [103]	Cycling	1500 m	Men	TT	Trained	7
Running						
Tomazini et al. [110]	Running	3000 m	Men	H-H	Recreational	9
Lambrick et al. [117]	Track running	800 m	Both	TT	Novices	13
Bath et al. [99]	Track running	5 km	Men	H-H	Trained	11

H-H head-to-head competitions, *TT* time-trial competitions, *?* indicates data not available

opponent, for example short-track speed skating and cycling, are characterised by a slow, tactical development of the race [62, 66, 67]. 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 [73]. 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 [73]. 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, 74–82]. In fact, even in ultra-running events, winners distinguish themselves by preventing a significant slowdown in the second half of the race compared with their less-successful counterparts [83–88]. Interestingly, the slowdown in speed seems to be higher for men compared with women [77, 89, 90], and in younger compared with older age groups [91]. In this respect, initial pace has been associated recently with an individual's perception of risk [92], 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 [93] and short-track speed skating [94]. 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 [94]. Finally, it has been highlighted in several studies that the appropriate strategy in competition is obviously related to other external aspects such as terrain [84, 95–98], temperature [87, 98] and humidity [87] rather than solely the presence of 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 with individual or non-competitive trials has been found [99–112]. 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 [108]. Indeed, being aware of the deception did not alter the performance effect of an opponent compared with the deceived conditions [108, 109]. Moreover, when participants were not deceived, they were still able to establish an improvement in performance [100–102]. Interestingly, the prospect of a monetary incentive ($100) did not improve 1500 m cycling performance, possibly because the ‘competitor’ (i.e. best previous performance so far) was not visible during the trial [103].

The performance improvement related to the presence of an opponent appears to remain quite stable, regardless of the level of performance [106, 113] or the pacing profile of the opponent [101]. Yet a different level of performance of the opponent appeared to affect one’s self-efficacy to compete with their opponent [106]. Moreover, the improvement in performance achieved when riding against a virtual opponent has been related to a greater increased external distraction [104, 114], increased anaerobic energy contribution [100, 113], a more positive affect [106] and a greater decline in voluntary and evoked muscle force [102]. However, despite a higher work rate, the presence of an opponent did not affect perceived exertion during the race compared with riding alone [102, 104]. 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 [107]. Moreover, the perception of approaching or getting further behind an opponent might be a crucial variable [115]. 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 [99]. 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 [99]. Regardless, starting 1 min 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 [116].

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 [101]. That is, a faster starting opponent evoked a faster initial pace compared with a slower starting opponent, even in a situation where changing the pacing behavior based on the virtual opponent had neither a beneficial nor detrimental effect for the exerciser [101]. Finally, although most pacing studies to date mainly used experienced athletes, pacing behaviour of inexperienced athletes in a competitive environment has been studied once before [117]. Running performance decreased for inexperienced children (9–11 years of age) during a competitive 800 m race as they started significantly slower compared with individually completed trials [117].

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 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 their opponents affecting winning chances, rather than adopting the theoretically optimal pacing strategy [12, 66]. Observational studies involving large datasets could help provide appropriate indicators or methods to assess tactics more objectively. Notable examples have been the work of Hanley [63, 78] and Vleck et al. [65], in which pacing decisions in half marathon, marathon and triathlon races have been related to packing behaviour. In addition, in rowing [118], track cycling [62], cyclo-cross [119] and short-track speed skating [66–68], 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 [100–102, 104, 106, 110, 111]. In addition, a virtual opponent has been shown to alter psychological responses [106], and the performance improvement when riding against an opponent appeared to be related to a greater anaerobic contribution [100, 113]. Recently, Konings et al. [102] 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 [102]. 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 [120] and/or attentional strategies [104, 121]. 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 [101]. That is, a faster starting opponent evoked a faster initial pace compared with a slower starting opponent [101]. 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, 122–125]. Modelling studies revealed optimal pacing strategies related to the duration of an event based on aerodynamics and power losses [3–6, 8, 9, 126–128]. The findings from these modelling studies have been confirmed in experimental and observational studies focusing on time-trial exercise, bringing forward 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 directly translated to actual competitions, in which athletes clearly demonstrated different pacing profiles compared with 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 in general, and the influence of an opponent in particular, 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 [129]. Perception is determined via the construction of an internal representation of reality in one's mind based on previous experiences and stored information [129]. 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 [130, 131]. 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, 132]. The robustness of these proposed (RPE) templates in time-trial exercise at maximal effort is remarkable [133]. 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 [102]. 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 on 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 let cyclists shift from their RPE template as used in the other time trials [134].

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 one's 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 into 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 [94]. In addition, previous research has already shown that an ecological concept such as optical flow does affect exercise regulation [135, 136]. Finally, ecological dynamics have shown to be useful in the understanding of cooperative athlete interactions in team sports [137–139].

However, this ecological approach towards pacing is not without any flaws. There is undeniably a strong anticipatory, strategic component in pacing regulation [17, 18]. Nonetheless, it seems possible to incorporate the anticipatory, strategic component into the ecological approach towards exercise regulation, without the need for 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 on in each particular situation [10, 140]. Indeed, previous experience has been shown multiple times to be crucial for optimal pacing regulation [22, 117, 141–143], and different information-seeking behaviour is reported in experienced cyclists compared with novices [144].

In this perspective, it has recently been proposed that pacing could be perceived as a self-regulatory skill of learning that needs to be developed over the years [145]. In a longitudinal study for example, elite long-track speed skaters distinguished themselves from non-elite skaters throughout their adolescence by 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 in efficiently self-regulating their pace [61, 146], 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 [131], 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 [10, 140]. In this perspective, opponents present a multitude of affordances that influence motivation, attentional focus, the ability to tolerate fatigue and pain, perceived exertion, positioning, drafting, falls risk and/or packing behaviour. To understand the effect of opponents on the regulation of exercise intensity, it is therefore advised to consider opponents in the context of the affordances that they provide and the changes they invite in the ongoing behaviour of athletes [12].

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 [147]. 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 a competitor catching up) [147]. 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 a competitor catching up) led to stronger negative changes [148]. 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 [148]. Future research is advised to explore different competitive scenarios and their effect on pacing, and in particular to explore 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 [116] in cycling, and Bath et al. [99] in running.

Finally, although this review specifically focused on the effect of competitors on pacing, it can be argued that similar effects are expected to be found for other external cues. Motivational and stimulating music for example has been shown to enhance affect and reduce ratings of perceived exertion [149–151]. 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 [100, 102, 113]. 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.

5 Conclusion

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 and the importance of feedback regarding the internal bodily state, and focused on concepts such as teleoanticipation [18] and template formation [132]. However, the importance of in-race adaptations to this planned pacing strategy in response to whatever is happening in the external world around the athlete has recently been 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 with 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 on 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 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 [131], 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.

Compliance with Ethical Standrads

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

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