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Picking up the pace

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Chapter 1

General introduction

Although humans are capable of incredible feats of performance, they are not in possession of an endless supply of energy (1). It is therefore key to adequately distribute one's efforts over an exercise task, a process which has been termed *'pacing'* (2). When too much effort is exerted early in the tasks' duration, the end-point of the exercise task might not be reached. Yet, exerting too little effort might cause there to be too much energy left in reserve after task completion. Both situations lead to sub-optimal performance. Consequently, the distribution of effort is essential to sports performance (2). In addition, to feel competent in one's performance, it is also important to reach the end of a race, match or game. Individuals who perceive themselves as not having adequate skills to compete are more likely to not enjoy participating in physical activity and drop out (3). This drop-out of sports and exercise is associated with greater health risks (4). Support of pacing could, therefore, not only help athletes in optimizing their performance but can also help a wider population in maintaining the feeling of enjoyment and inclusion in sports and exercise.

Pacing: an introduction.

The distribution of effort during exercise has been of interest to scientists for over a century. For example, in 1925 Hill demonstrated that the average velocity of athletes in competition decreased as the duration of the exercise event increased (5). Contemporary interest in the phenomenon was sparked in the 1990s by the work of Foster *et al.* (2). Through several laboratory and field studies, as well as an overview of the scientific literature, they demonstrated that athletes engaged in the distribution of effort during exercise, that this distribution varied between exercise tasks with different characteristics and that it impacted exercise task performance (2, 6, 7). Following this work, there was a considerable increase in the number of studies supporting these notions, specifically by denoting the observation of an increase in performance during the final section of an exercise task ('end-spurt') (8, 9). At the same time, modelling studies investigated the distribution of effort during exercise by studying the balance of power production from the aerobic and anaerobic energy systems and the relative power loss due to restrictive forces (10-12). Substantiated by laboratory experiments, these studies provided evidence for the biomechanical advantages of specific distributions of effort in tasks of a particular duration and with sport-specific features (13-16). The systematic analysis of the contribution of the energetic systems corroborated these findings (13, 17). In addition, it was demonstrated that a larger initial burst of power output accelerates the aerobic contribution and that differences in pacing primarily originate from the utilisation of energy stemming from the anaerobic system (17-19).

In tandem with the experimental work, an attempt was made to describe a definitive model that encapsulates the mechanisms behind the distribution of effort during exercise. In 1996, Ulmer proposed that the distribution of effort is regulated by a feedback system, in which afferent information from the muscles and other organs is received by a central controller in the brain, which regulates physical performance (20). Later, St Clair Gibson, Noakes and Lambert expanded on this concept by proposing that a central governor, located in a region of the subconscious brain, continuously monitors the physiological systems via feedforward and feedback loops (21, 22). Using the information provided by the peripheral systems, and the goal of the exercise task as a known variable, this central governor regulates the distribution of effort towards achieving the goal of the exercise task while guarding the internal homeostasis against catastrophic failure (1). Although crucial for the reintegration of the brain in models of fatigue, the central governor model has also received criticism. First, it was noted that catastrophic failures of homeostasis do occur during exercise (23). Second, the idea of a single intelligent regulatory governor within the mind is akin to a homunculus, thereby creating a situation of infinite regress (1). Third, the need to increase the complexity of the model to incorporate perceived exertion and motivational factors (24). Based on these criticisms, Marcora proposed an alternative model, suggesting that effort distribution is regulated by the conscious brain, and withdrawal from the exercise task occurs when the effort required to complete the task is equal to the maximum effort the individual is willing to exert to successfully complete the exercise task, or when the individual beliefs to have exerted their maximal effort and continuation of exercise is perceived to be impossible (24). Alternatively, Edwards and Polman (1) suggested that the brain as a whole works as a central governor which communicates via complex neural circuits. They have suggested that effort distribution is regulated by awareness, whereby at low levels of physical effort, control can be maintained at an automated sub-aware level of consciousness (1). Increasing afferent stimuli as a result of increasing physical effort lead to conscious awareness and accompanying regulation of effort expenditure in order to reach the goal of the exercise task.

In the last decade, multiple authors steered away from the consciousness debate as it was argued that the focus on this one facet would provide little knowledge to advance our understanding of the mechanisms underlying the multidimensional pacing process (25). These authors argued that the distribution of effort during exercise should instead be approached as a decision-making process (25-27). Adopting this view, the distribution of effort results from individuals continuously deciding between decreasing, increasing or sustaining the level of effort (26). This decision is made with the aim of reaching the goal of the exercise task and is influenced by competing stimuli from a complex psychophysiological interaction between the musculoskeletal, cardiovascular, and nervous systems as well as the environment (27-29). Human decision-making is, however, not always rational due to the influence of various factors such as previous experience, risk perception and social context (25). It has been argued that individuals engage in two types of decision-making: 1) deliberative decision-making, which through relatively slow consideration, facilitates hypothetical, abstract and prospective thought yet requires considerable cognitive effort, and 2) intuitive decision-making, which requires less cognitive effort and through association facilitates fast decision-making in complex tasks based on only a limited number of informational stimuli (30, 31). Differentiating between these types of decision-making could provide greater insight into the role of cognitive functions, such as memory, attention allocation and hypothetical thought, in the distribution of effort

(25). In contrast to previous models, which had been based on the concept of information processing, Smits *et al.* argued for an ecological perspective on effort distribution. In this model, decision-making is considered to be the actualization of affordances, the directly perceptible possibilities for action in the environment that individuals perceive and may act upon (27). One's pacing behaviour thus results from the choice between multiple, simultaneously specified possibilities for action (i.e. affordance competition)(29). Hettinga and Konings further developed and expanded upon the ecological perspective on effort distribution through theoretical and empirical research into the role of competitors in effort distribution (29, 32). They argued that competitors provide unique social invitations for action (29). In other words, the presence of competitors influences both the availability and selection of possibilities for action, impacting the resulting behaviour. These claims were supported by observational field studies and experimental laboratory studies, which demonstrated that the presence and behaviour of the competitors impacted an individual's distribution of effort and exercise performance (33-36). The work of Smits, Hettinga and Konings reemphasised the importance of the interaction between the individual and the (social) environment within the process of effort distribution. These studies moved the field from mainly studying single individuals in time trial events towards the study of multiple individuals in competition (32). Adopting the view of the distribution of effort as a goal-directed decision-making process closely links it to the process of self-regulation (37, 38). Self-regulation is the extent to which individuals monitor and control their thoughts and actions in order to reach a specific future goal (39). More in detail, self-regulation of behaviour involves individuals cyclically engaging in the meta-cognitive processes of planning, self-monitoring and adaptation, as well as evaluating and reflecting upon their behaviour, in order to achieve a set goal (40). Elferink-Gemser and Hettinga proposed that this cyclical process also applies to the process of effort distribution (40). In this model, the pacing process is divided into three stages: i) before the task the individual reflects upon the task goal and plans their distribution of effort according to the expected task demands, ii) during the task the individual monitors and evaluates the incoming stimuli from both their own body and the environment, using this as a basis to decide whether to adapt their effort distribution, iii) after the task the individual reflects and evaluates upon their pacing behaviour as well as the resulting task performance, and uses this information in the reflection and planning of the next iteration of the task. The framework of pacing as a self-regulatory process also linked it to the prefrontal cortical processes of executive functioning, which are proposed to aid the self-regulatory process by retaining the exercise goal and pre-planned distribution of effort, inhibiting distractors and shifting towards more an appropriate effort distribution when it is available (38).

In line with the developments in the field, this thesis will adopt the following definitions: *Pacing* is the goal-directed, decision-making process regarding the self-regulation of effort distribution over an exercise task. The outcome of this process will be defined as the individuals' *pacing behaviour*.

Quantifying pacing behaviour

Investigating the factors influencing pacing behaviour creates the necessity for quantification. Although pacing has a valuable role in healthcare and rehabilitation settings (41, 42), the majority of literature investigating pacing behaviour is set in an (endurance) sports setting. The sports environment is ideally suited as a basis for experimental research, as it offers a standardized performance task in a consistent and controlled setting, measured by validated and accurate equipment (43). In sports literature, pacing behaviour is often quantified as a measure of effort (e.g. energy expenditure, power output, rate of perceived exertion) over segments of the exercise task (e.g. distance or time) (2). An example of quantification of pacing behaviour in a sports setting is the lap times in swimming: the time needed to complete each 50m section. Due to the restrictive properties of locomotion through water, swimmers use increased effort to reach a higher swimming velocity, resulting in a lower lap time (14, 44). Plotting the lap times over the distance provides a quantification of the pacing behaviour of that swimmer in that specific race. A comparison of the pacing behaviour of individuals with different performance levels can be achieved by the normalisation of the measure of effort. In the swimming example, each lap time can be recalculated into relative section times:

$$Relative\ section\ time\ (\%) = \left(\frac{Lap\ time}{Total\ race\ time}\right) * 100$$

A *lower* percentage constitutes less time spent in that particular section, which represents a relatively higher velocity (as exemplified in Figure 1).

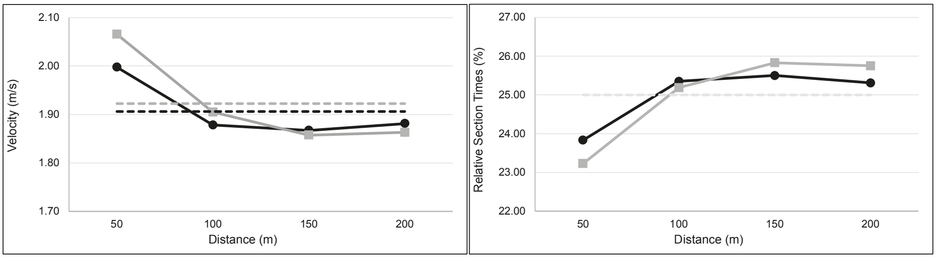

Figure 1. The pacing behaviour of two swimmers competing in the 200-meter freestyle at the Olympic games of 2021 quantified using both velocity and relative section times (data publicly available via swimrankings.net). The dotted lines represent mean velocity.

Factors influencing pacing behaviour

Due to the complex integration of the psychophysiological systems at work, there are a large number of factors that have an impact on an individual's pacing behaviour (28). Newell's constraints lead approach dictates that pacing behaviour, as any other human behaviour, would be affected by constraining factors that can be grouped into three categories: the task, the environment and the individual (45). Using both quantitative modelling and well-controlled laboratory experiments, Foster, de Koning and Hettinga extensively studied the effect of different constraints on pacing behaviour (2, 12-15). It was demonstrated that the duration of the task is a key determinant of an individual's pacing behaviour (2, 13). In general, exercise performance will be optimal when the maximal amount of available energy is used to reach the exercise goal ("nothing left in the tank"). Individuals performing short exercise tasks (<80 seconds) were predicted to benefit from an *all-out* pacing behaviour, in which an individual tries to achieve a maximal acceleration during the start of the exercise and subsequently attempts to minimize the decrease of power output for the duration of the exercise task (12, 13). During longer exercise tasks (>120 seconds) a balance needs to be found between maximizing power output and minimizing power loss, in which velocity scales non-linearly (12). Therefore, an even pacing behaviour in which acceleration and deceleration are minimized is predicted to lead to optimal performance (12, 13). Events lasting 80-120 seconds are of particular interest, as individuals need to balance contributions from both the anaerobic and aerobic systems to optimize performance (2, 13, 15, 16). Studies have reported that in these tasks a balanced combination of a high power output at the start followed by a relatively even distribution of power results in the best performance (16). In practice, individuals performing exercise tasks over 80 seconds tend to exhibit increased levels of effort during the initial and final sections of the exercise task (13, 46). This *parabolic* pacing behaviour is theorized to be caused by the uncertainty within the decision-making process, resulting from changes in the levels of motivation, the perceived effort needed to complete the task, and the necessity to avoid catastrophic harm to homeostasis (21, 24, 46). Additional to the duration of the task, the sport-specific features of the task influence the pacing behaviour (14). For example, swimmers, speed skaters and runners might demonstrate a slightly different pacing behaviour in a task of similar duration (2).

The second group of constraints originates from the environment. In sports, the goal of the exercise task is often closely associated with the presence of, and interaction with, other individuals (29). Improvements in time-capturing equipment and an increase in publicly available data of high-level sports events have allowed for a more extensive study of the interpersonal interactions of competitors on an individual's effort distribution (32). Using this type of field data it was demonstrated that in middle-long distance running and race-walking events, athletes would waive the adoption of a theoretically more optimal even pace to keep up with the race leaders (47). Eventually, the lower-finishing athletes would be unable to keep up with the medallists, who often exhibited a capability to increase their speed at the final section of the race (47). In short-track speed skating, individuals also distributed their effort based on the behaviour of the other competitors (35). In the highly interactive environment of this sport, athletes conserved their energy during the opening phases of the race to position themselves towards a winning position in the final sections (33). These results from observatory studies are corroborated by controlled laboratory studies which reported that the presence of a (virtual) opponent caused cyclists to adopt a faster pace at the initial section of a 4-km trial, resulting in increased task performance and a larger decline in post-exercise neuromuscular function at a similar rate of perceived exertion (34, 36).

Finally, pacing behaviour is influenced by constraints originating from the individuals themselves. Each individual possesses different physiological and psychological characteristics which determine their performance capabilities (1). The culmination of variances in individual performance characteristics results in the observation that different individuals present an assortment of different pacing behaviours in set tasks within well-controlled environments (48). Furthermore, it should be noted that all models describing the distribution of effort have a commonality, which is the importance of prior experience. Ulmer emphasized the role of motor learning in his framework (20), the models based on information processing stress the ability to gather information from memory (49), and those grounded in the ecological approach suggest that affordances available to the individual are influenced by the history of similar situations (27). Elferink-Gemser and Hettinga stress the cyclical nature of pacing when viewed as a self-regulatory process, given that reflection and evaluation of previous tasks form the basis for the planning of the next iteration of a task (40). Furthermore, experimental laboratory studies have demonstrated that individuals' experience in previous iterations of a task influences their distribution of effort (49, 50). The effect of experience on (skilled) behaviour has been termed as *acquisition* or *learning* (51). Given the above, it could be stated that the capability to self-regulate the distribution of one's efforts over an exercise task is not an innate ability but rather has to be acquired through practice and experience (52).

The development of pacing behaviour

The majority of research into the factors influencing pacing behaviour is done in adult athletes (40, 52). However, from anecdotal evidence, we know that children generally face difficulties in pacing exercise tasks. A familiar sight on a school sports day is that of young children starting a race rapidly, to be followed by the same children quitting the race early because they are fatigued. The impact of age on (skilled) behaviour in children and adolescents is referred to as *development* (51). Scientific research into pacing behaviour development has been scarce (40, 52). Micklewright *et al.* cross-sectionally compared the distribution of velocity in a running task (~4 min) between groups of male and female schoolchildren of differing ages (53). The youngest two groups (5.6 ± 0.5 and 8.7 ± 0.5 years old) adopted an all-out pacing behaviour, in which velocity decreased over the duration of the task. Conversely, the two groups of older children (11.8 ± 0.4 and 14.0 ± 0.0 years old) adopted a lower velocity at the start of the task, but exhibited an increase in velocity at the final 20% of the race, adopting a more even pacing behaviour. The authors concluded that the goal-directed conservation of effort is a capability that develops during childhood. Subsequently, Wiersma *et al.* observed the pacing behaviour of a group of talented male speed skaters performing a 1500m race at the age of 15, 17 and 19 (±0.6) years old (54). As the speed skaters got older, they adopted a relatively slower start, a faster middle section and a slower finish. It was concluded by the authors that during adolescence, the pacing behaviour of junior speed skaters develops towards the behaviour demonstrated by adult speed skaters. Furthermore, there is evidence to suggest that the age of an individual does not only impact pacing behaviour directly but also interacts with the influence other constraints (task characteristics and the environment) have on pacing behaviour. For example, in adult athletes, the presence of competitors generally results in an alteration of pacing behaviour and a performance improvement (32). Yet, Lambrick *et al.* reported that when children were asked to perform a 800m running task, the presence of competitors had a negative impact on performance (55).

A development of pacing behaviour during childhood and adolescence would logically fit the existing knowledge from the fields of psychology and physiology. The pacing process is a psychophysiological interaction between the musculoskeletal, cardiovascular and nervous systems (28). Although these systems are relatively stable during adulthood, they are linked to processes of growth and maturation distinctive of childhood and adolescence. Indeed, the age period features a multitude of sex-specific, hormonally-induced, maturation processes of the musculoskeletal and cardiovascular systems, most of which play a key role during exercise (56). In parallel to the maturation of the body, the reorganisation of the neural circuitry of the higher brain centres spans the period between 10 and 24 years of age (57, 58). The key role of cognition in pacing behaviour has previously been established in studies comparing people with and without an intellectual impairment (59). Furthermore, Micklewright *et al.* demonstrated that the pacing behaviour differs between schoolchildren when grouped by Piaget's stages of cognitive development (53). Although this study provided initial evidence for the role of cognition in the development of pacing behaviour, it did not specify the cognitive functions underpinning this development. In an attempt to further specify the link between cognition and pacing behaviour development, it should be noted that the capability for self-regulation emerges during late childhood and adolescence (60). Individuals at this age start to engage in the meta-cognitive processes of planning, self-monitoring and adaptation in order to reach the set goal (61). Through self-reflection and evaluation of previous experiences, individuals start to determine what behaviour best fits the demands of a task (62). In addition, the age period is also associated with the development of executive functions, which are believed to sub-serve self-regulation by maintaining and updating information (i.e. working memory), retaining this information in the presence of distractions (i.e. inhibition) and shifting back and forth between multiple strategies (i.e. cognitive shifting) (63, 64). Recognizing the similarities between the cognitive functions facilitating self-regulation and pacing, Elferink-Gemser and Hettinga theorized that it is the emergence of these specific cognitive functions which underpins the development of pacing behaviour (40).

Thesis rationale

The goal-directed, decision-making process regarding the self-regulation of effort distribution over an exercise task plays a key role in sports performance and engagement in physical activity (1). Optimizing their pacing behaviour can help athletes increase their performance (12). In the general population, and even more in some clinical populations (41), improvement of the self-regulation of effort distribution can help manage fatigue, increase the feeling of competence and reduce drop-out from sports and exercise (42). Contrary, a repeated inaccuracy in the distribution effort during a multitude of exercise tasks over the longer term could lead to overexertion, which could result in overtraining, burn-out and injury (65). It would therefore be beneficial to create interventions and policies that stimulate and optimize the acquisition and development of pacing behaviour.

Unfortunately, there exists only a very limited amount of research on the development pacing behaviour. A larger quantity and broader scope of evidence are needed in order to make informed statements about the general existence of pacing behaviour development, the characteristics of this development, as well as the implications on exercise task performance. An important point of notice is the fact that the relation between the individual factor of age and the other factors influencing pacing behaviour, task characteristics and the environment, are still unidentified. In other words, it is unknown whether or not the development of pacing behaviour exists uniformly across exercise tasks with different constraints originating from the task characteristics and the environment. Furthermore, cognitive development and the gathering of exercise experience have been theorized as factors underpinning pacing behaviour development (40). Yet, there is currently limited experimental research into the specific nature of the link between age, (meta-) cognitive functions and pacing behaviour development. Untangling the processes of acquisition (i.e. the effect of experience) and development (i.e. the effect of age), as well as exploring the (meta-) cognitive functions influencing pacing behaviour, could aid in the design of interventions aimed at positively influencing pacing behaviour in various populations.

Thesis objective and outline

This thesis aimed to investigate what characterizes the development of pacing behaviour during adolescence and study the factors underpinning this development.

The included chapters feature a mix of methodologies, including; systematic literature reviews, laboratory studies and analysis of public databases of athlete competition data. The lack of studies into pacing behaviour development has been pointed out before (40, 52). To attain a better understanding of the pacing behaviour of adolescents, several studies previously performed in adults (33, 34, 47) were repeated in adolescents. Chapter 2 explores the pacing behaviour of adolescent athletes performing in middle-long distance running and race-walking events. In Chapter 3, large databases of public data were used to cross-sectionally investigate the difference in pacing behaviour in short-track speed skating between age groups. Chapter 4 gives a detailed insight into the pacing behaviour of novice adolescents performing a 2-km cycling trial in a controlled laboratory environment, and investigates the effect of task repetition and the presence of opponents. The findings of these chapters were put into a broader context in Chapter 5, in which the literature regarding the acquisition and development of pacing behaviour was systematically reviewed.

Taking the views of Chapter 5 on board, the development of pacing behaviour, and the effect of the (social) environment on this development, were explored in more rigorous longitudinal studies in multiple sports. Short-track speed skating and swimming were chosen as these represent sports on different ends of the spectrum of competitor interaction. Short-track speed skating features a highly interactive environment, whereas this is much more limited in swimming due to the lane-based set-up. Chapter 6 continued the work of Chapter 4 by studying the development of pacing behaviour in short-track speed skaters using multilevel modelling to analyse longitudinal data. Although a large amount of high-quality research on pacing behaviour in short-track speed skating has previously been published (33, 35), less is known about pacing behaviour in swimming. For this reason, in Chapter 7 the literature on pacing behaviour in swimming is systematically reviewed, with specific attention to adolescent swimmers. Chapter 8 explored the development of the pacing behaviour of adolescent swimmers, attempted to disentangle the effects of age and experience, and investigated whether performance level in adulthood is related to pacing behaviour development during adolescence.

Building on the findings of the observational studies, a series of experimental studies set in a controlled laboratory environment further explored the factors underpinning pacing behaviour development. Chapter 9 investigated the role of the (meta-) cognitive functions of planning, self-monitoring and adaptation during submaximal and maximal exercise tasks. In Chapter 10, the use of reflection upon previous pacing behaviour to inform the planning of future exercise tasks and the engagement with stimuli from the environment (e.g. competitors) was investigated. This was done by studying the pacing behaviour of adults and adolescents performing multiple repeated 4-km cycling time trials in three different conditions on the time-trial to head-to-head spectrum. Finally, Chapter 11 provides a general discussion of the findings in this thesis, including practical applications and future directions.

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