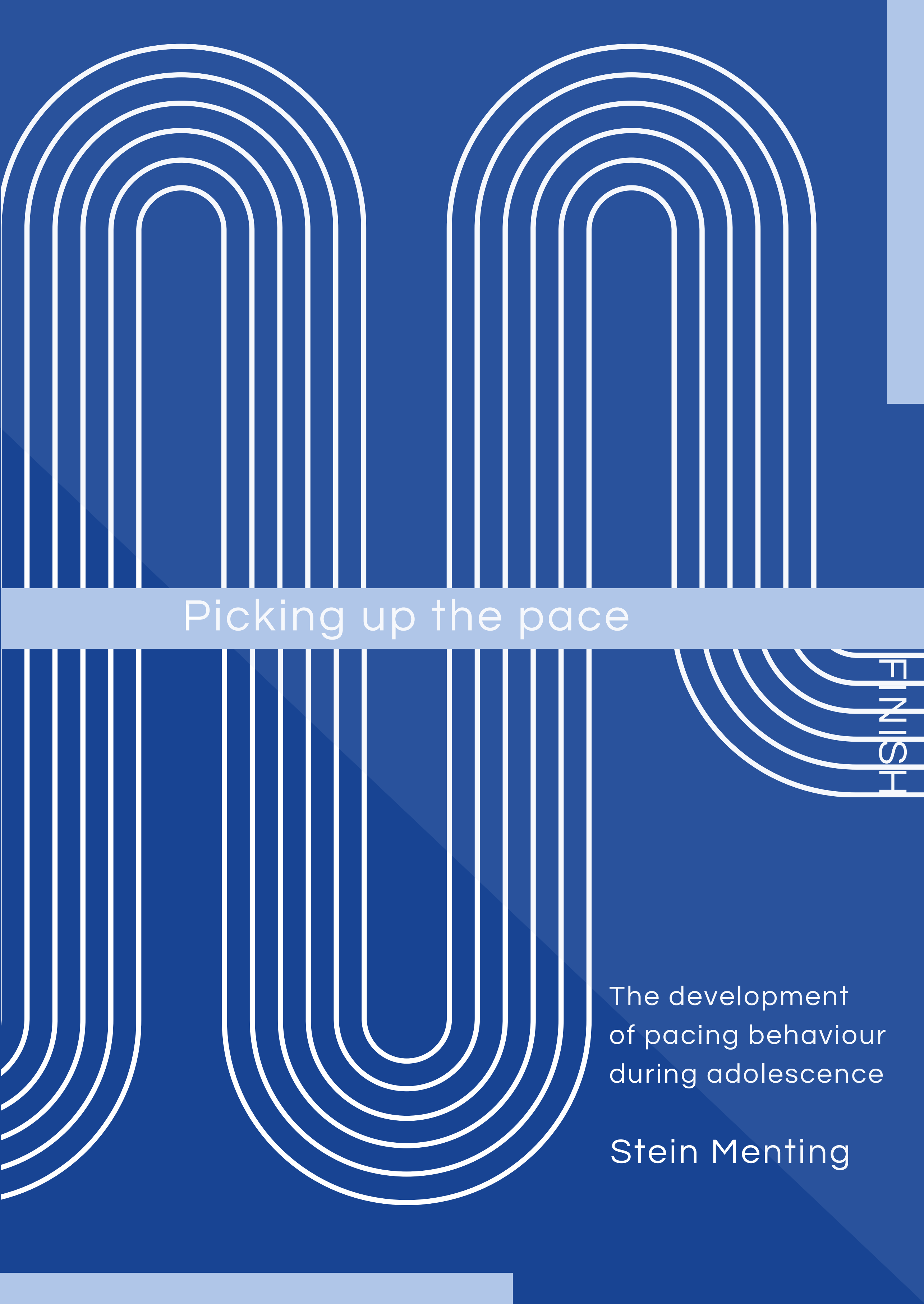

Picking up the pace

The development of pacing behaviour during adolescence

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Outline

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).

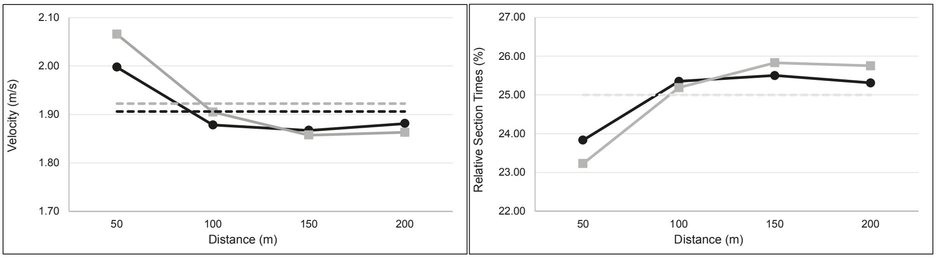

Figure 1. The pacing behaviour of two swimmers competing in the 200-meter freestyle at the Olympic games of 2021 quantified using both velocity and relative section times (data publicly available via swimrankings.net). The dotted lines represent mean velocity.

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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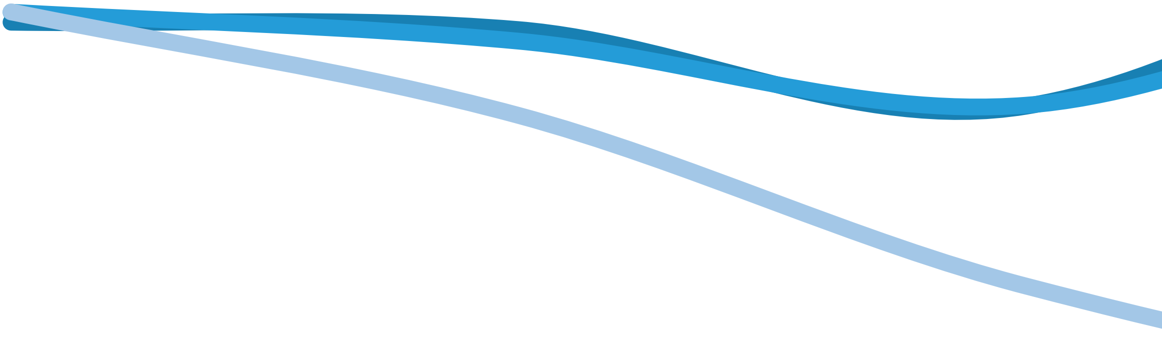

Chapter 2

Pacing behaviour in junior track athletics: middle-long distance running and race-walking

Adapted from:
Menting S.G.P., Hanley B., Elferink-Gemser M.T., Hettinga F.J. Pacing behaviour of middle-long distance running & race-walking athletes at the IAAF U18 and U20 World Championship finals. *European Journal of Sport Science. 2022;22(6):780-789.*

Abstract

Purpose: The current study analysed the pacing behaviour of athletes competing in the middle-long track event finals of the IAAF Under 18 and Under 20 World Championships between 2015 and 2018.

Methods: Official finish times, 1000-m split times and positioning data of 116 female and 153 male athletes, competing in the middle-long distance running (3000 m, 5000 m and 10,000 m) and race walking (5000 m and 10,000 m) events, were gathered. Repeated measures analysis of variance, with 1000-m speed as within-subjects factor and final ranking (medallist, Top 8 or Top 12, rest of the field) as between-subjects factor, was performed to compare the pacing behaviour between athletes. Positioning of the athletes was analysed by Kendall tau-b (T_b) correlation between the intermediate position and final position.

Results: Overall, medallists increased their speed throughout the race, with the exception of the 5000 m running event, in which a parabolic pacing behaviour was exhibited. The 1000-m segment in which a significant ($p > 0.05$) difference in speed was exhibited between differently ranked athletes coincided with a strong ($T_b > 0.7$) correlation between intermediate and final positioning. These combined results point towards a separation between the athletes during the race, as the Top 8 or Top 12 and the rest of the field are unable to match the speed of the medallists.

Conclusion: The distance, discipline, sex, age category and behaviour of competitors all influence the pacing behaviour of young track athletes during international level competition, emphasising the importance and complexity of developing adequate pacing behaviour in track athletes.

Keywords: pacing, performance, athletics, running, race walking, middle-long distance.

1. Introduction

The pathway to elite performance in track athletics requires athletes to master a wide range of aspects that characterise their sport (1), one of which is pacing. Pacing can be defined as the goal-oriented, self-regulated distribution of effort over an exercise task (2) and is described as the decision-making process regarding how an individual expends their energy (3). Within this decision-making process, athletes determine the optimal distribution of effort while taking into account a multitude of factors, such as tactical considerations, environmental features and the behaviour of other competitors (4, 5). The outcome of this decision-making process determines an individual's behaviour (i.e. pacing behaviour), which is can be quantified by expressing a measure of effort (power output or speed) over segments of the set exercise task (6). An athlete's pacing behaviour has been shown to be a decisive feature in athletic performance (5) and is influenced by a multitude of factors, including the nature of the task (7, 8), the characteristics of the athlete (9) and the competitive environment (5, 10). The impact of these factors on the pacing behaviour of elite athletes has been thoroughly studied. Within a discipline, the goal (e.g. qualifying for the next round or winning the final) and the importance of the event (e.g. a single world cup competition or the Olympic final) could influence the behaviour of athletes (11, 12). In championship track athletic races, athletes competing in short-distance events (100 m and 200 m) most frequently exhibit an '*all-out*' pacing behaviour, in which initial acceleration to near maximal speed is key (13). Conversely, in the middle-long distance track events (5000 m and 10,000 m), athletes generally exhibit a gradual increase in speed over the race (14). Additionally, the middle-long distance track athletes who achieved the highest final ranking (e.g. medallists) tend to pace their race differently from the rest of the field (14). It has been shown that medallists in middle-long distance track races separate themselves from the rest of the field due to their capability to maintain a constant speed or even to increase speed throughout the race (14, 15). Similar pacing behaviour was observed in championship race walking races (over 20-km and 50-km), however, race walkers also need to consider the option to walk in a pack, as it might reduce the chances of attracting the judges' attention (16). As for the characteristics of the athlete, previous research has established that the sex and expertise of an athlete influence the distribution of effort over a single race and consecutive races (15, 16).

Although the influence of pacing on elite athletic performance in adult athletes has been studied for over 30 years, the way athletes acquire their pacing behaviour has received less attention (17). This is remarkable as the literature indicates that pacing is not an innate ability, but develops relative to an athlete's (meta-) cognitive and physical attributes (18) as well as the experience an athlete has with an exercise task (19). Evidence suggests that athletes who develop their pacing behaviour at a younger age achieve better race results during adulthood (20). Moreover, it has been proposed that the failure to develop adequate pacing behaviour can lead to mismanagement of energy distribution that could result in increased injury and drop-out rates among young athletes (21). Around the age of 10, children are first observed to seemingly reserve their energy to achieve the set exercise goal. This behaviour further develops during adolescence (18). Studies in swimming and speed skating found that although pacing behaviour is primarily determined by the characteristics of the task and the characteristics of the athletes, there are distinct differences in pacing behaviour between adolescent and adult athletes (22-24). For example, although the general pacing behaviour in speed skating is determined by the distance and the discipline (long- or short-track), athletes' pacing behaviour develops to become more conservative (featuring a slower start and faster finish) throughout adolescence (20, 24). Additionally, the development of pacing behaviour towards that of adults seems to commence earlier in female athletes (23). Because of the complexity of pacing behaviour development during adolescence, as well as the previously mentioned advantages and risks, coaches are encouraged to monitor the pacing behaviour of developing athletes and compare it against established benchmarks (17). It seems evident that the impact of pacing behaviour development on the path to elite performance should not be underestimated, and insight therein might improve training programmes. Although numerous international-level youth sports events which feature reliable performance recording, such as the World Rowing Junior Championships and the World Junior Speed Skating Championships, have been organised for decades, the detailed data recorded during these events are not always publicly available. Even if there is publicly available data, the analysis of these data is complicated by the fact that youth athletes frequently do not compete in every edition of a championship (24). Nevertheless, the analysis of the distribution of effort (e.g. speed) over the duration of a race and the positioning of athletes within a race, based on publicly available data from international-level youth sports events, has allowed for some of the most rigorous studies on pacing behaviour development in adolescent athletes to date (20, 24). These studies form an excellent basis for the creation of informed practical guidelines for the development of pacing behaviour in young athletes (17). However, taking into account the fact that the characteristics of a sport have a large impact on the pacing behaviour of athletes (25), it cannot be taken for granted that the results found in one sport (e.g. speed skating) can be applied to another sport (e.g. track athletics) in an identical fashion. To assist future elite track athletes, it therefore seems essential to have access to research describing the pacing behaviour of young male and female international-level athletes competing in specific track athletic events. The current study aims to document the pacing behaviour of young high-standard middle-long distance track athletes during international-level championship finals. Previous studies in track athletics have shown that in adult athletes, the athletes who achieved the highest final ranking in the race (e.g., the medallists) determined the pace of the race, hereby influencing the behaviour of the rest of the field (14). It is therefore hypothesised that alongside the event characteristics (the combination of discipline, race distance and sex), the exhibited pacing behaviour will be linked to the final ranking of the competing athletes.

2. Methods

Official finish times, 1000-m split times and positional data were gathered from men and women competing in the finals of the middle-long distance running (3000 m, 5000 m and 10,000 m) and race-walking (5000 m and 10,000 m) finals at the International Association of Athletics Federations (IAAF) Under 18 and Under 20 World Championships between 2015 and 2018. The collected data comprises all currently publicly available data of athletes competing at the Under 18 and Under 20 World Championships. Additional data collection included the date of the competition, the date of birth of competing athletes and the temperature during the competition. The temperature during the finals was 21.2 ± 3.7° C (14-25° C). All data were obtained from the open-access website of the IAAF (since renamed World Athletics) (http://www.iaaf.org/results) (26). The study was approved by the local ethics committee and is in accordance with the Declaration of Helsinki. The split times were electronically recorded using transponders fit into the bibs worn by the athletes. Finish times were recorded using electronic timing devices with an accuracy of a thousandth of a second, as required by the IAAF. Overall, a total of 116 female and 153 male athletes' performances were analysed.

2.1. Data analyses

The current study was designed as observational research. All collected data were categorised by discipline (race walking, running), distance (3000 m, 5000 m and 10,000 m) and sex (female, male). Data of the male 10,000 m race walking event from both U18 and U20 championships were available, therefore, an additional split in age category (U18 & U20) was made for this event. Next, the data were categorised by final ranking: medallists, Top 8 (3000 m & 5000 m) or Top 12 (10,000 m), and the rest of the field. The 1000-m split times were converted to speed to provide a better visual comparison between disciplines and distances. The age of the athletes (Table 1) was calculated by comparing the date of competition with the date of birth of the athlete.

2.2. Statistical analysis

Data were analysed per discipline, distance, and sex. To analyse the difference in pacing behaviour by ranking, a repeated measures analysis of variance was performed, with the 1000-m speed as a within-subjects factor and the final ranking (medallists, Top 8 or Top 12, rest of the field) as a between-subjects factor. A significant ($p < 0.05$) within-between interaction effect indicates a difference in pacing behaviour between the groups of athletes with differing final rankings. In the analysis of the male 10,000 m race walking events, age category (U18 & U20) was included as an additional between-subjects factor, allowing for an examination of the effect of age category on pacing behaviour. For all repeated measures analyses of variance, the effect sizes were calculated using Cohen's *f*, categorised as small ($f < 0.1$), medium ($f < 0.3$), and large ($f < 0.5$). If a significant difference in pacing behaviour between ranked athletes was found, a multiple comparison post hoc analysis, including Tukey correction, was performed to identify the difference in speed between differently ranked athletes in each 1000-m segment of the race. The effect sizes for the differences in speed between ranked athletes were calculated using Cohen's *d* and categorised as either trivial ($d < 0.20$), small (0.21-0.60), moderate (0.61-1.20), large (1.21-2.00) or very large (2.01-4.00) (27). To analyse the impact of positioning during the race, the relationship between the position at 1000-m segments and the final position of the athlete (first, second, third, etc.) was analysed by means of a Kendall's Tau-b (T_b) correlation. A positive correlation would indicate that an athlete positioned in the front of the race at a specific 1000-m segment, was also among the first to finish. Correlations were perceived as not present/low ($T_b < 0.50$), moderate ($0.50 \leq T_b < 0.70$), or high ($T_b \geq 0.70$), as used in previous research (23, 28).

3. Results

The finish times of the athletes in all events, categorised for final ranking, can be found in Table 1. In the male 10,000 m race walking event, a significant interaction effect between age category (U18 vs U20), final ranking and speed at 1000-m segments, indicating a difference in pacing behaviour between age categories, was found ($F_{8.93, 388.45} = 2.14$, $p \leq 0.01$, large). The U18 and U20 male 10,000 m race walking events shall therefore be considered as separate events. A significant interaction effect, indicating a difference in pacing behaviour between athletes categorised by final ranking, was found in all events (Table 1). The speed per 1000-m segment for the male and female running events can be found in Figure 1. The speed per 1000-m segment for the male and female race walking events can be found in Figure 2. The positioning data, describing the correlation between the intermediate position at 1000 m segments and the final position, of all events can be found in Figure 3.

Table 1. Means (± SD) for age (years) and finish time (min:s) as well as the outcome of the statistical tests for a difference in pacing behaviour between the athletes with differing final rankings (medallists, Top 8/12, rest of the field), per discipline, distance and sex.

Discipline	Distance (m)	Sex	Age category	Age	Finish time (min:s)			Pacing behaviour (split times * final ranking)
					Medallists	Top 8 / Top 12	Rest of the field	
Run	3000	Male	U18	16.7 (± 0.7)	07:49.0 (± 00:01.2)	08:20.1 (± 00:15.1)	08:57.4 (± 00:23.8)	$F_{4,18} = 9.96$ $p \leq 0.001$, large.
		Female	U18	16.8 (± 0.6)	09:25.9 (± 00:02.2)	09:47.3 (± 00:13.2)	10:45.6 (± 00:55.6)	$F_{4,20} = 9.73$ $p \leq 0.001$, large.
	5000	Male	U20	17.6 (± 1.0)	13:20.5 (± 00:00.3)	13:40.8 (± 00:25.4)	14:46.7 (± 00:34.3)	$F_{2.89, 24.56} = 9.65$ $p \leq 0.001$, large.
		Female	U20	18.5 (± 0.9)	15:31.9 (± 00:01.8)	15:50.5 (± 00:06.1)	16:35.6 (± 00:24.4)	$F_{4.13, 22.70} = 13.49$ $p \leq 0.001$, large.
	10,000	Male	U20	18.8 (± 0.6)	27:36.6 (± 00:14.04)	29:29.9 (± 00:56.2)	31:28.5 (± 00:40.8)	$F_{6.67, 83.36} = 9.23$ $p \leq 0.001$, large.
Race Walk	5000	Female	U18	17.0 (± 0.5)	22:39:2 (± 00:06.65)	23:24.5 (± 00:21.7)	25:13.9 (± 00:58.6)	$F_{6.62, 175.52} = 17.06$ $p \leq 0.001$, large.
	10,000	Male	U18	16.8 (± 0.5)	41:59.1 (± 00:43.5)	43:51.0 (± 01:09.0)	47.18.7 (± 01:43.3)	$F_{8.72, 248.61} = 4.16$ $p \leq 0.001$, large.
			U20	18.6 (± 0.6)	42:26.7 (± 02:00.9)	43:43.4 (± 01:12.8)	47.22.9 (± 03:32.8)	$F_{6.55, 98.25} = 9.67$ $p \leq 0.001$, large.
		Female	U18	18.4 (± 0.6)	44:17.0 (± 00:02.83)	45:48.6 (± 00:37.9)	50:15.5 (± 01:58.2)	$F_{5.88, 88.23} = 8.98$ $p \leq 0.001$, large.

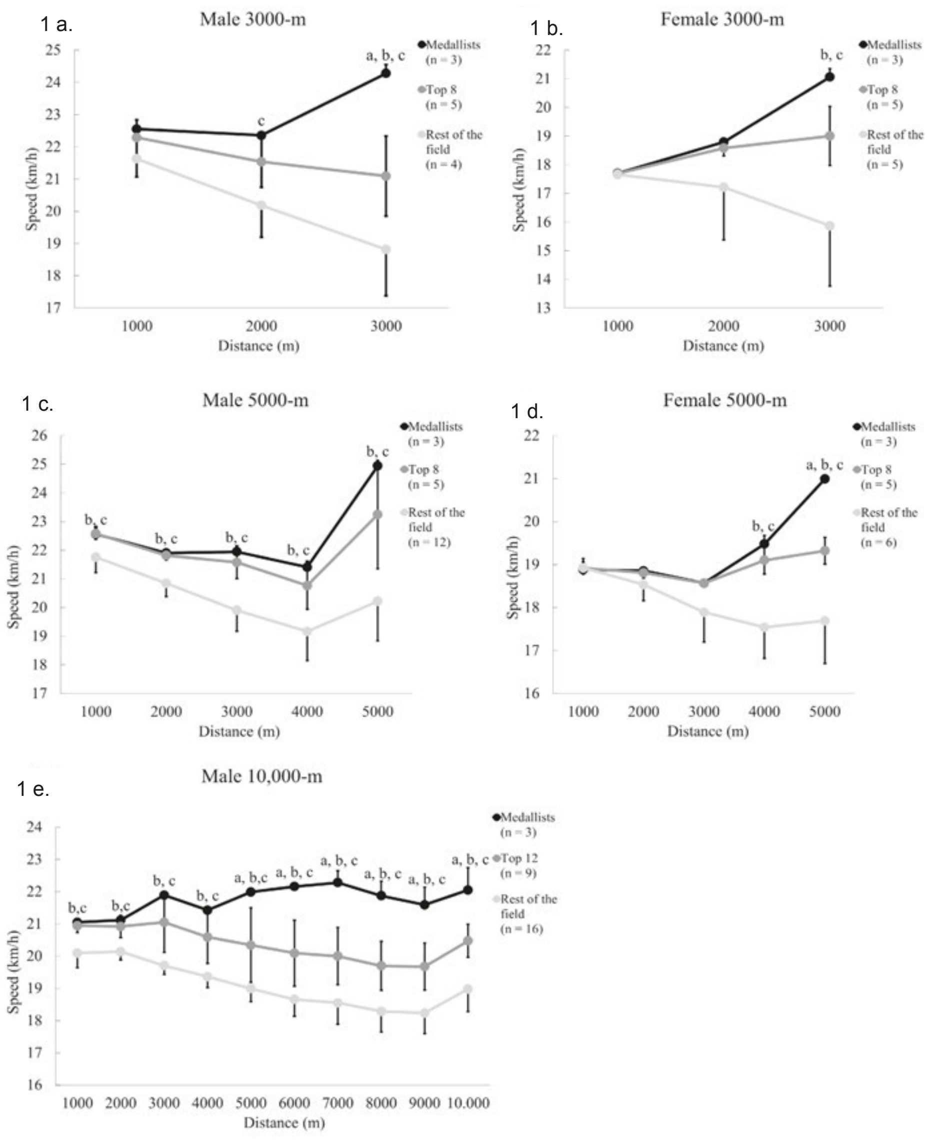

Figure 1. Mean (SD) 1000-m segment speed of athletes during 3000 m, 5000 m and 10,000 m running events. Significant differences ($p < 0.05$, $d \geq 0.61$) between athletes with different final rankings are annotated as: a = difference between medallists and Top 8 (5000 m) or Top 12 (10,000 m), b = difference between Top 8 (5000 m) or Top 12 (10,000 m) and the rest of the field, c = difference between medallists and the rest of the field.

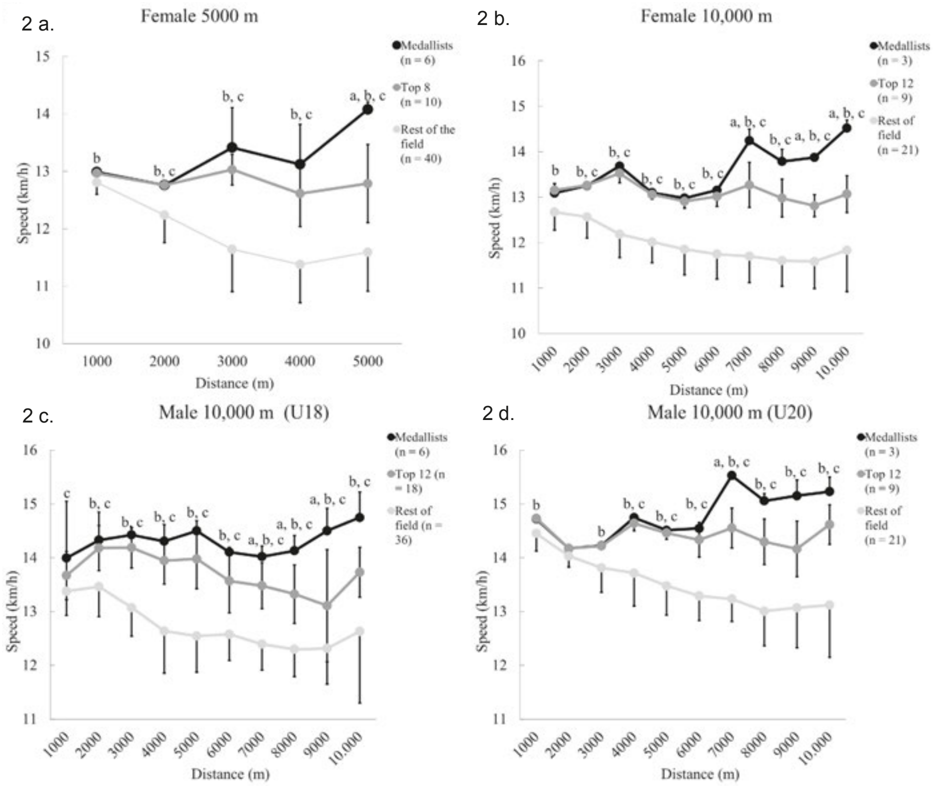

Figure 2. Mean (SD) 1000 m segment speed of athletes during 5000 m and 10,000 m race walk events. Significant differences ($p < 0.05$, $d \geq 0.61$) between athletes with different final rankings are annotated as: a = difference between medallists and Top 8 (5000 m) or Top 12 (10,000 m), b = difference between Top 8 (5000 m) or Top 12 (10,000 m) and the rest of the field, c = difference between medallists and the rest of the field.

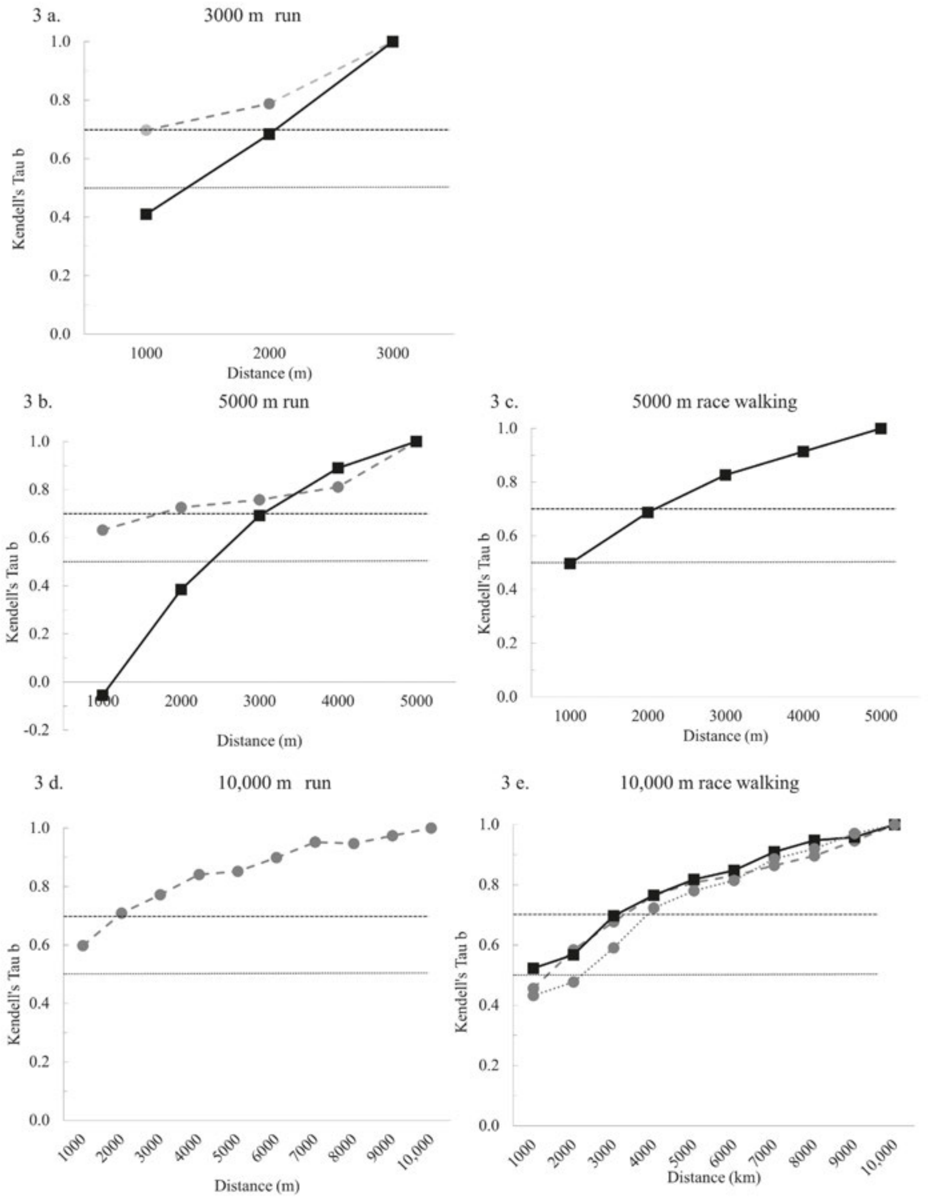

Figure 3. Correlation between the position at 1000 m segments and the final ranking. Black squares indicating females and grey circles indicating males. In the 10,000 m race walking event, U18 males are indicated with a fine dotted line and U20 males with a broad dotted line. The two horizontal lines indicate a Kendell's Tau b correlation of 0.5 (moderate) and 0.7 (high), respectively.

4. Discussion

Pacing behaviour is an important element in the development of athletes (17). To guide future athletes in developing adequate pacing behaviour, a better understanding of the pacing behaviour of young athletes is needed (17). As pacing behaviour is impacted by the characteristics of the sport performed, race distance and sex of the athletes, these factors should all be taken into account. The aim of the current study was to document the pacing behaviour of young international-level track athletes during middle-long distance events. Differences in pacing behaviour were evident between the differently ranked athletes in all analysed events. As hypothesised, higher ranking athletes (medallists and Top 8 or Top 12) generally exhibited a pacing behaviour characterised by an increasing speed, whereas the rest of the field exhibited a decrease in speed over the course of the race. Overall, the pacing behaviour of medallists was characterised by an increase in speed over the course of the race. The exception to this was the 5000 m running event, in which a more parabolic pacing behaviour was exhibited, characterised by a decrease in speed from the start of the race and an increase in speed at the end of the race. The pacing behaviour of the athletes in the Top 8 or Top 12 generally matched the behaviour of the medallists, with differences in speed occurring later in the race. By this point, the athletes in the Top 8 or Top 12 failed to match the speed exhibited by the medallists. The group of athletes making up the rest of the field exhibited a pacing behaviour characterised by a decrease in speed throughout the race, failing to match the speed of the medallists early on. A similar pattern of pacing behaviour was previously found in adult athletes competing in the 5000 m and 10,000 m running events, whereby the medallists and top eight finishing athletes increased speed during the race, the top 16 athletes demonstrated a constant pace, and the lower-finishing rest of the field showed a decrease in speed over the course of the race (15). The positioning data provide further insight into the pacing behaviour of the athletes. In all included events, it is evident that the 1000-m segment at which a difference in speed between differently ranked athletes occurs is coinciding with the segment in which there is a strong correlation between the intermediate position and final position. This finding provides further evidence that the non-medallists, especially the Top 8 or Top 12 group, match the speed of the medallists for some time, during this time the groups of differently ranked athletes exhibit a similar speed and there is a low or medium correlation between intermediate and final positioning. However, eventually, the non-medallists are not able to match the speed of the medallists any more, an event marked by a difference in speed between the groups and a high correlation between intermediate and final positioning. The moment in the race at which the speed profiles of medallists start to follow a different trajectory from those of other competitors has previously been termed the separation point (14). An explanation for the separation of higher-ranked athletes from lower-ranked athletes during a race could be found in differences in the physiological capabilities of the athletes or factors influencing the decision-making making process of effort regulation during competition. It is possible that the physiological capabilities determining performance in track athletics (such as oxidative capacity) of medallists exceed those of other competitors. This would mean that by keeping up with higher-ranking athletes, the lower-ranking athletes are performing at an unsustainable level of effort (15). Continuous work at the upper limit of an athlete's physiological capacity is unsustainable and fatigue will increase rapidly, forcing a decrease in power output in order to prevent lasting damage to the homeostasis (29). If the goal of the race was purely to cross the given distance in the shortest time, as is seen in time trial sports, performing for a prolonged duration at the upper limit of an athlete's performance capacity in the initial section of an exercise task (with a total duration lasting over 120 seconds) generally leads to sub-optimal performance (7). However, as middle-long distance track athletics is a head-to-head competition, the goal is to finish before the other athletes in the race, altering the decision-making process regarding the distribution of effort (5, 11). Being in the presence of a direct opponent affords the athlete beneficial effects influencing motivation and opportunities for drafting (30). Furthermore, in the discipline of race walking, walking in a pack could reduce the chances of attracting the judges' attention (16). Although it has been shown that adult athletes are able to use the presence of an opponent to improve their sports performance (31), similar results have thus far not been shown in younger individuals (32, 33). It has been proposed that younger individuals are still gathering the necessary experience and developing the required (meta-)cognitive skillset needed to optimally integrate environmental factors (such as opponents) in their pacing behaviour (23, 32). It could therefore be difficult for younger athletes to optimally navigate the complex decision-making making process regarding effort distribution during competition.

The inclusion of similar events in male and female athletes in the current study provides the opportunity to compare the pacing behaviour between sexes. Comparing the pacing behaviour exhibited by male and female athletes in the 3000 m and 5000 m running events, it was evident that the separation point between the differently ranked athletes occurred earlier on in the male event, compared to the female event. At first glance, these findings seem to contradict a previous study in elite adults athletes which concluded that, in the 5000 m events, female medallists separate themselves at an earlier stage of the race, between 2000 and 3000 m, and male medallists differentiate themselves from the rest of the field after 4000 m (14). However, it has previously been suggested that the development of pacing behaviour differs between male and female athletes (23, 34), with girls experiencing growth spurt-related physical changes and development of the prefrontal cortical functioning at an earlier age (35, 36). The change in cognitive development and maturation of the musculoskeletal system could be the reason for the difference in pacing behaviour exhibited by male and female athletes in the observed races (23, 37), however, more extensive research is needed.

Notwithstanding the fact that this study is a response to the need for more sport-specific literature on the pacing behaviour of young athletes (17, 37), some limitations should be addressed. Although this study includes all currently available data of youth athletes performing at international underage championships, only data on athletes performing in a limited number of races (all finals of a championship) were available. The use of a limited number of races provides the disadvantage of not having the possibility to account for inter-race variability, which decreases the generalisation of the findings. However, the examination of a small number of races, including singles races, has previously been shown to provide valuable new insights into the behaviour of athletes in endurance athletic events (38, 39). In this trend, the current study provides novel insights into the behaviour of young (U18 and U20) middle-long distance track athletes. It should nevertheless be mentioned that the use of larger datasets, including data from more athletes, over more years, and from different stages of competition (e.g. heats and semi-finals), has provided valuable information regarding the pacing behaviour of athletes in other sports such as short-track speed skating (11, 24). Access to data from a larger number of athletes, made publicly available by the IAAF or collected with the permission of the athletes, would provide the opportunity to expand on the novel findings of the current study. Secondly, the resolution of the publicly available data from athletes performing in the IAAF Under 18 and Under 20 World Championships was low when compared to data used in previous studies (14, 40). Using data with a higher resolution will allow for a more detailed description of the variation in speed over the course of the race, and therefore a more detailed description of an athlete's pacing behaviour (40). The gathering of higher-resolution data has previously been achieved through a collaboration with official timing companies linked to athletic events or the use of video recording (14, 41). Lastly, to properly study the development of pacing behaviour during adolescence, a longitudinal design, following athletes throughout adolescence and controlling for each athlete's sport-specific experience, is desirable (24, 42). Future research, featuring a longitudinal design, higher resolution data from a larger number of athletes and the inclusion of different stages of competition should be conducted to further our understanding of the development of young track athletes.

5. Conclusion

The current study analysed the pacing behaviour of athletes performing in international U18 and U20 middle-long distance track athletic finals. The pacing behaviour of these athletes is linked to the athletes' final ranking in the race. The highest-ranking athletes (the medallists) increased their speed throughout the race. Over the course of the race, the other athletes failed to match the speed of the medallists, likely causing a separation between the higher and lower-ranking athletes. The distance at which athletes exhibit a failure to match the speed of the medallists differentiates the Top 8 or Top 12 athletes (late separation from medallists) and the rest of the field (early separation from medallists). The differences in pacing behaviour between young track athletes of different sexes competing in the same event, fit the current general knowledge regarding the pacing behaviour development of youth athletes. However, more extensive longitudinal research is needed to provide further details on the development of pacing behaviour in track athletics.

6. Declaration of interest statement

The authors do not have any conflict of interest. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors received no specific funding for this work.

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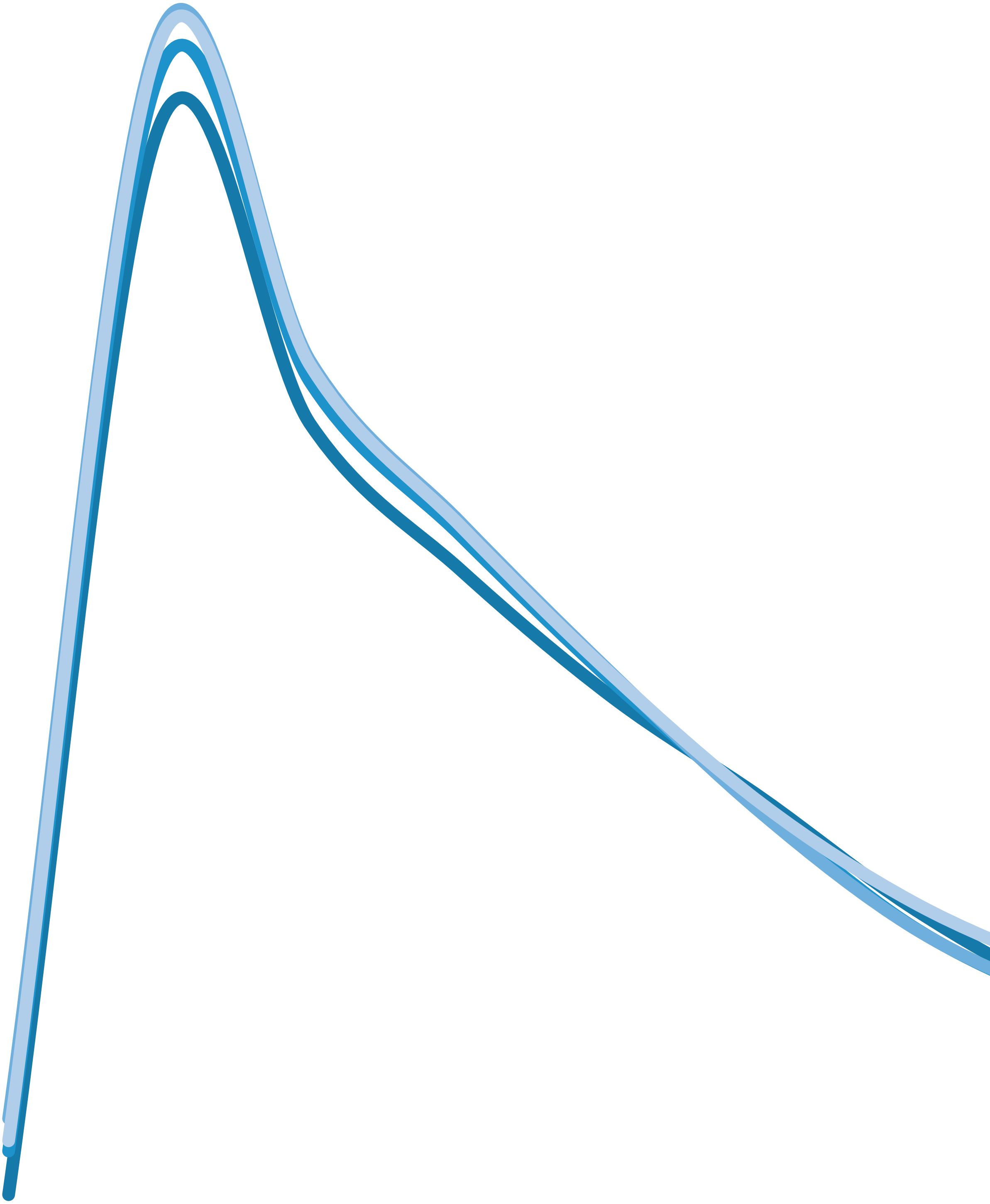

Chapter 3

Pacing behaviour of adolescent athletes: analysing 1500-m short-track speed skating

Adapted from:
Menting S.G.P., Konings M.J., Elferink-Gemser M.T., Hettinga F.J. Pacing Behavior of Elite Youth Athletes: Analyzing 1500-m Short-Track Speed Skating. *International Journal of Sports Physiology and Performance. 2019;14(2):222-231.*

Abstract

Purpose: To gain insight into the development of pacing behaviour of adolescent athletes in 1500-m short-track speed skating competition.

Methods: Lap times and positioning of international-level short-track skaters during the seasons 2011/2012 - 2015/2016 were analysed (n=9715). The participants were grouped into age groups; under 17 (U17), under 19 (U19), under 21 (U21) and adult. The difference between age groups, sexes and the stages of competition within each age group were analysed through a MANOVA ($p<0.05$) of the relative section times (lap time as a percentage of total race time) per lap and by analysing Kendall's tau-b correlations between intermediate positioning and final ranking.

Results: The velocity distribution over the race differed between all age groups, explicitly during the first four laps (U17: 7.68±0.80%, U19: 7.77±0.81%, U21: 7.82±0.81%, adult: 7.80±0.82%) and laps 12, 13 and 14 (U17: 6.92±0.14%, U19: 6.83±0.13%, U21: 6.79±0.14%, adult: 6.69±0.12%). In all age groups, a difference in velocity distribution was found between the sexes and between finalists and non-finalists. Positioning data demonstrated that younger skaters showed a higher correlation between intermediate position and final ranking in laps 10, 11 and 12 compared to adults.

Conclusions: Younger short-track speed skaters demonstrated a less conservative pacing behaviour, compared to adults. The pacing behaviour of younger skaters, expressed in relative section times and positioning, changed throughout adolescence and came to resemble that of adults. These findings support the notion that pacing behaviour, including adequately responding to environmental cues in competition, could be seen as a self-regulatory skill that is under development throughout adolescence.

Keywords: pacing strategy, head-to-head competition, performance analysis, adolescence, self-regulation

1. Introduction

The distribution of energy over a race (i.e. pacing) has proven to be a decisive factor in athlete performance in both time trials (1, 2) and head-to-head competitions (3-5). Several modelling and experimental studies have found that there is a multitude of factors that influence the pacing process, which include: the duration of the event (6), perceived level of fatigue throughout the race (7), previously fatiguing exercise (qualification before a final) (8), the competitive environment (5, 8), and specific demands of a sport (9). The outcome of the goal-directed decision-making process involved in pacing is defined as pacing behaviour (10, 11).

In this context, it is known that previous experience plays a crucial role in the development of adequate pacing behaviour (10, 12-17). In fact, pacing has recently been argued to be a self-regulatory skill (13). As a result, the physical changes (18) as well as cognitive changes (19, 20) that athletes experience during adolescence, can be expected to have an effect on the pacing behaviour of younger athletes (13). Surprisingly, however, research into pacing behaviour in adolescent athletes is scarce (13-15). The only longitudinal research on the development of pacing behaviour in talented adolescent athletes was a recent study observing long-track speed skaters performing a 1500-m race. This study concluded that as athletes go through adolescence, their pacing behaviour develops more towards that of adult athletes (21). The more successful skaters differentiated themselves by an early adaptation of the lap time pattern similar to that of elite adult long-track speed skaters (21). However, this study is performed in a time-trial type sport in which the winner of the event is the athlete with the fastest completion time (5, 22). Long-track and short-track speed skating are, besides minor physiological differences, rather similar sport disciplines (23). However, where long-track speed skating is a typical time-trial sport, short-track speed skating features head-to-head races in a highly interactive competitive environment with up to nine athletes in one race (4, 24). With the presence of (multiple) opponents, additional environmental factors need to be incorporated into the goal-directed decision-making process, related to avoiding collisions, drafting, motivation and the behaviour and expectations of opponents (4, 24). Therefore, to perform successfully, athletes will need to balance the optimal energetic distribution while taking into account the cues supplied by the environment (8). Previous research into pacing behaviour in short-track speed skating has focussed on elite adult skaters (4, 24). It was found that elite short-track speed skaters performing a 1000-m and 1500-m race tend to save energy in the initial phase by adjusting their pacing behaviour to that of other competitors (8, 24, 25). The saved energy is later used in an ‘end-spurt’ to position the skater in the foremost position in the final phase of the race, increasing their chances of winning (4). The saving of energy for an end-spurt at the final stages of the race has been shown to be an effective mechanism to increase performance in a variety of sports disciplines (4, 26). As recent research emphasised the importance of environmental cues in optimizing pacing behaviour (5, 10), it would be interesting to study the pacing behaviour of adolescent athletes in a head-to-head competition type sport, involving direct competition against multiple opponents where relative rankings are the main determinant of winning.

The aim of the present study was to answer the question: what is the pacing behaviour of adolescent athletes in the head-to-head type sport of short-track speed skating? Information on the pacing behaviour of international-level adolescent and adult short-track speed skaters, performing in 1500-m competitions, was gathered and analysed. To achieve a better understanding of the pacing behaviour of short-track speed skaters, two types of analysis were used. First, the intermediate lap times and finishing times of races were examined to analyse the velocity distribution over a race. Secondly, the positioning of the skaters throughout the race was explored. The positioning of the skater offers different possibilities during the race (e.g. drafting, overtaking and motivational influence), these possibilities influence the decision-making process involved in pacing throughout the race. In line with the previous study into the pacing behaviour of adolescent long-track speed skaters (21), it was hypothesized that the pacing behaviour of younger skaters would deviate from that of adult skaters in key moments such as the start and finish of the race. Additionally, it was hypothesized that with age, the pacing behaviour would come to resemble that of adult skaters. Previous research revealed that pacing behaviour is influenced by the stage of competition (27) and sex (28). In order to provide a complete insight into the pacing behaviour of adolescent short-track speed skaters, the pacing behaviour of the different sexes and stages of competition was analysed.

2. Methods

2.1. Participants and events

To analyse the pacing behaviour of short-track skaters, an observational research design was used. Finish and lap times, as well as start, intermediate and finish positions, were gathered from 1500-m races (13.5 laps of 111.12m) performed during Short-track Skating World Cups, the European Championships, World Championships and World Junior Short-track Speed Skating Championships during the seasons 2010/2011 until 2015/16. Each competitive event consisted of qualification stages in which skaters could directly qualify for the next stage by finishing in either first or second place. Additionally, skaters could qualify for the next stage indirectly by setting the fastest time in the competition round or through advance by jury decision. Recordings of lap and final times were done electronically with an accuracy of at least one-hundredth of a second, as is demanded by the International Skating Union. The position of the skaters was coded 1 (skater in first position) up to 9 (skater in ninth position). As the data were publicly available on the International Skating Union website (http://www.sportresult.com/federations/ISU/ShortTrack/) no written consent was given by the skaters. The study was approved by the local ethical committee and is in accordance with the Declaration of Helsinki (2013).

A total of 14,783 skating performances (spanning 2197 races) were analysed. Falls and/or disqualifications could affect the lap times and positioning of the skaters and of other competitors, which could lead to a misinterpretation of the results. Therefore, skating performances with falls, disqualifications or missing data were excluded from the analysis. Additionally, outliers, defined as lap times that exceeded the mean ± two times the standard deviation, were excluded. After these exclusions, 9715 performances of 1500-m races (65.71%) were included.

2.2. Statistical analyses

2.2.1. Lap times

To compare pacing behaviour independent of skating performance, the lap times were converted into relative section times (RST) by expressing the lap time as a percentage of the total race time. Whereas a difference in absolute velocity would indicate a difference in performance, a difference in RST denotes a difference in the distribution of velocity, indicating a difference in pacing behaviour. The method of normalizing lap times to study pacing behaviour is common practice in studies with a similar design (21, 29). The skaters were categorized into age groups based on the skater's year of birth and the year in which the analysed race was performed. Skaters younger than 17 were placed in the group under 17 (U17), skaters who were 17 and 18 years old were placed in the group under 19 (U19), skaters who were 19 or 20 years old were placed in the group under 21 (U21), skaters who were older than 20 years old were placed in the group adult. The races were divided by the stage of competition, categorizing them as either finals (finals, semi-finals, and quarter-finals) or non-finals (preliminaries, heats, repeated heats and repeated semi-finals). Quantile-quantile plots were checked to assure the assumption of normality. A multivariate analysis of variance (MANOVA) ($p<0.05$) was used to search for a difference in the distribution of velocity between the age groups, sexes and stages of competition. The RST of the 14 laps were used as the dependent variables and age group (U17, U19, U21 and adult), sex (male, female) and stage of competition (final, non-final) were used as independent variables. A significant difference ($p<0.05$) between the age groups pointed to a difference in the distribution of velocity between age groups. If a significant difference was found, a Bonferroni post hoc analysis would identify in which specific laps of the race the difference in velocity distribution between age groups presented itself.

A significant ($p<0.05$) interaction effect between age group and sex, or age groups and stage of competition, indicated a difference between the sexes or the stages of competition within individual age groups. For example: a difference in velocity distribution between males and females within the U17 age group. If such a significant interaction effect were found, an additional MANOVA, which used the RST data of an individual age group as the dependent variable and, sex (male, female) or stage of competition (final, non-final) as the independent variables, was performed to explore in which specific lap there was a difference between the sexes or the stages of competition within each age group.

2.2.2. Positioning

To examine the positioning behaviour of the skaters during the race, the relation between start/intermediate rankings and final rankings was analysed using Kendall's Tau-b correlations. Positive correlations would indicate that the highest-ranked skater in that particular lap was also ranked highest at the end of the race. In contrast, negative correlations would indicate a high-ranking skater in that particular intermediate lap is related to a low ranking at the end of the race, and vice versa. Through this analysis, it is possible to examine the changes in positioning that influence the outcome of the race. The positioning data of the different age groups were compared as well as the data of all individual age groups divided by sex and stage of competition. Positive and negative correlations were perceived as not present/low ($r < 0.50$), moderate ($0.50 \leq r < 0.70$), or high ($r \geq 0.70$)(4, 24).

3. Results

3.1. RST analyses

Analysing the RST data revealed a significant effect for the age group ($F_{42} = 10.48$, $p < 0.001$), which indicated a significant difference in pacing behaviour between the different age groups. The mean (SD) of the RST and the outcome of the post hoc analyses, indicating the differences in velocity distribution between age groups, are presented in Figure 1. Younger skaters display a lower RST in the initial four laps (mean RST over laps one, two, three and four for age groups U17: 7.68±0.80%, U19: 7.77±0.81%, U21: 7.82±0.81%, and adult: 7.80±0.82%). On the other hand, the younger skaters display a higher RST in the final three laps (mean RST over laps 12, 13 and 14, for age groups U17: 6.92±0.14%, U19: 6.83±0.13%, U21: 6.79±0.14%, and adult: 6.69±0.12%).

A significant interaction effect was found for age group and sex ($F_{42} = 2.98$, $p < 0.001$), indicating a difference between the sexes in different age groups. The mean (SD) of the RST of male and female skaters in the individual age groups were presented in Figure 2. The additional MANOVAs revealed a significant difference in the distribution of velocity between the sexes in age groups U17 ($F_{13} = 2.37$, $p < 0.01$), U19 ($F_{14} = 2.33$, $p < 0.01$), U21 ($F_{14} = 4.05$, $p < 0.001$) and adult ($F_{14} = 27.26$, $p < 0.001$). The laps wherein a significant difference between sexes was found are indicated in figure 2. Furthermore, a significant interaction effect for age group and stage of competition was found ($F_{42} = 3.92$, $p < 0.001$), indicating a difference in pacing behaviour between the finals and non-finals in different age groups. The mean (SD) of the RST of finalists and non-finalists in each age group is presented in Figure 3. The additional MANOVAs reflected a significant difference in the distribution of velocity between the finalists and non-finalists in age groups U17 ($F_{13} = 2.65$, $p < 0.01$), U19 ($F_{14} = 10.03$, $p < 0.001$), U21 ($F_{14} = 10.29$, $p < 0.001$) and adult ($F_{14} = 36.22$, $p < 0.001$). The specific laps in which a difference between finalists and non-finalists was found are indicated in Figure 3.

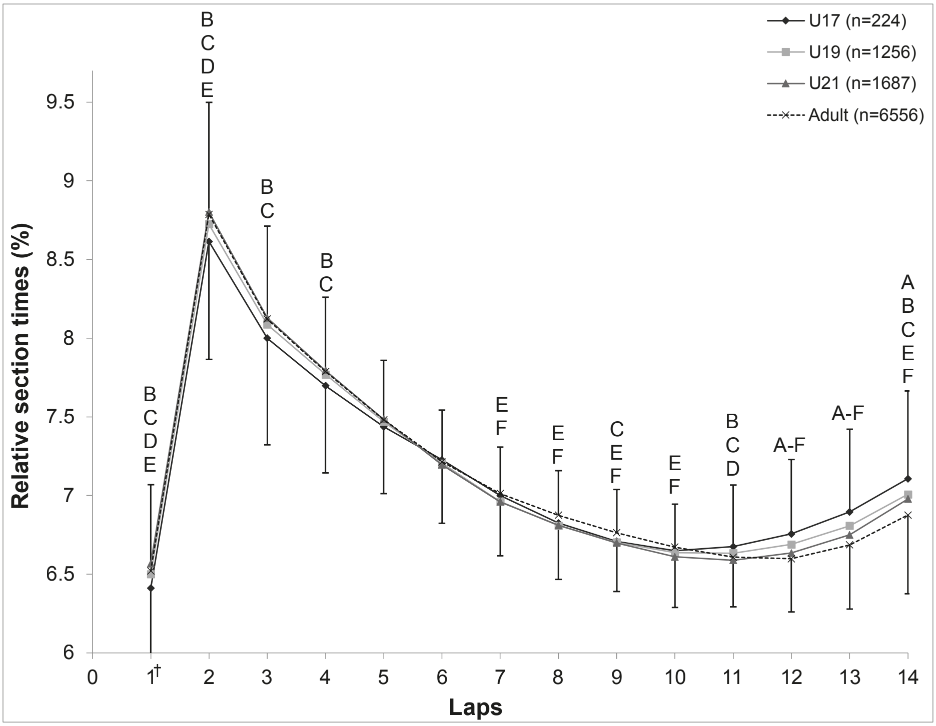

Figure 1. Relative section times of individual laps for each age group. A significant difference ($p<0.05$) in RST between: ^{A}U17 and U19, ^{B}U17 and U21, ^{C}U17 and Adult, ^{D}U19 and U21, ^{E}U19 and Adult, ^{F}U21 and Adult. † = is only ½ lap.

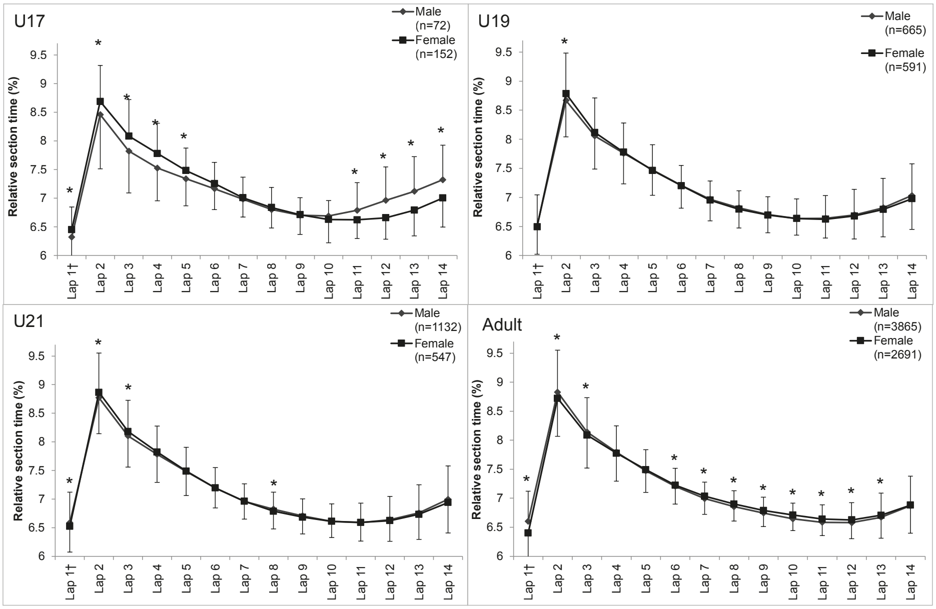

Figure 2. Relative section times (%) of individual laps for males and females in each particular age group. * = significant difference (p<0.05) † = Lap 1 accounts for only the first ½ lap.

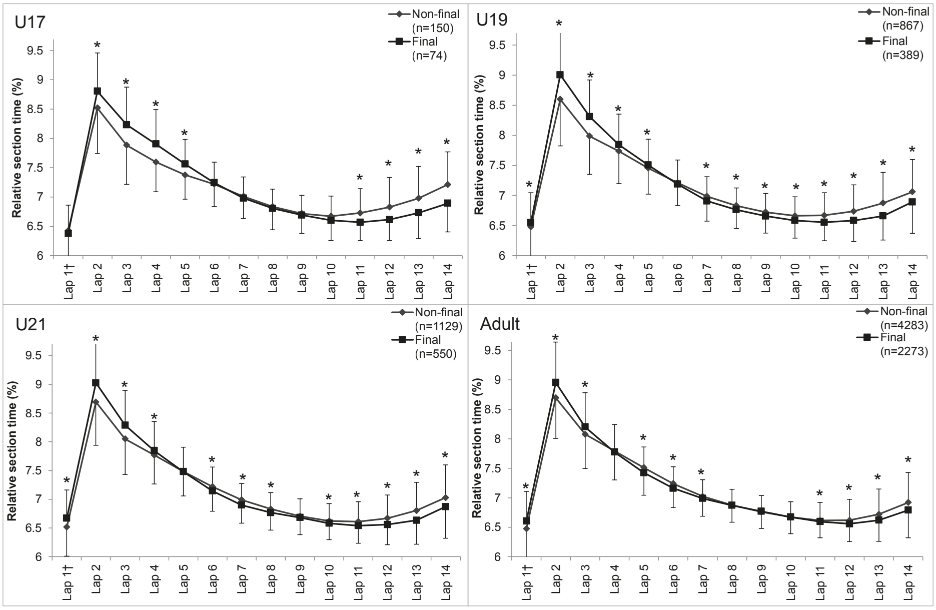

Figure 3. Relative section times (%) of individual laps for performances in finals and non-finales in each the particular age group. * = significant difference (p<0.05) † = Lap 1 accounts for only the first ½ lap.

3.2. Position analyses

The Kendall's Tau-b correlations between intermediate positioning and final ranking of the age groups are presented in Figure 4. The positional data for the individual age groups and categorized by sex, are presented in Figure 5. The positional data for the individual age groups and categorized by stage of competition, are presented in Figure 6.

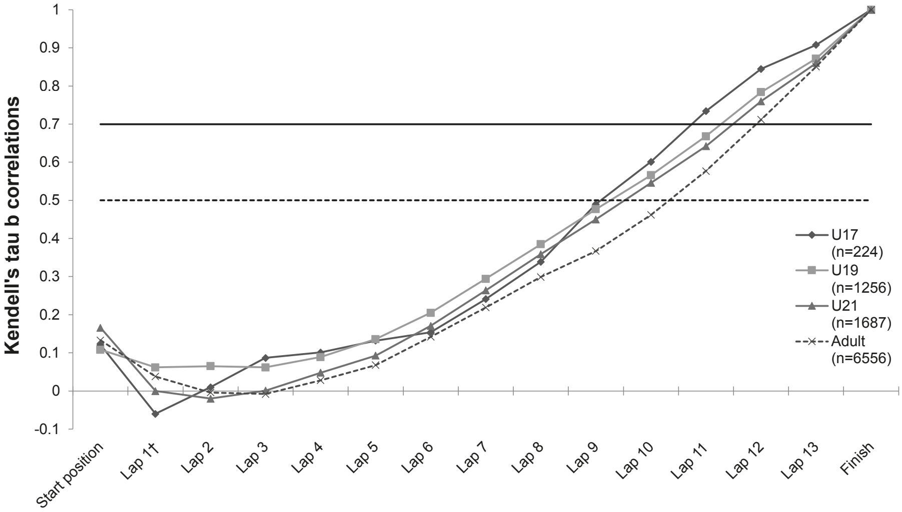

Figure 4. Kendell's tau b correlation between intermediate and final ranking during individual laps for each age group. Dotted line and solid marking a moderate and high correlation, respectively. † = Lap 1 accounts for only the first ½ lap.

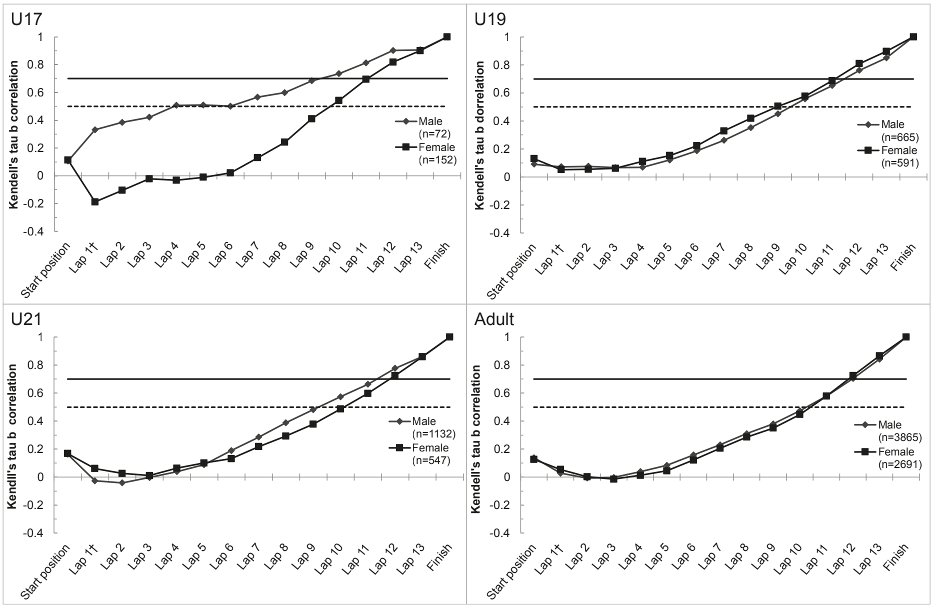

Figure 5. Kendell's tau b correlations between intermediate and final ranking during individual laps for males and females in each particular age group. Dotted and solid line marking a moderate and high correlation, respectively. † = Lap 1 accounts for only the first ½ lap.

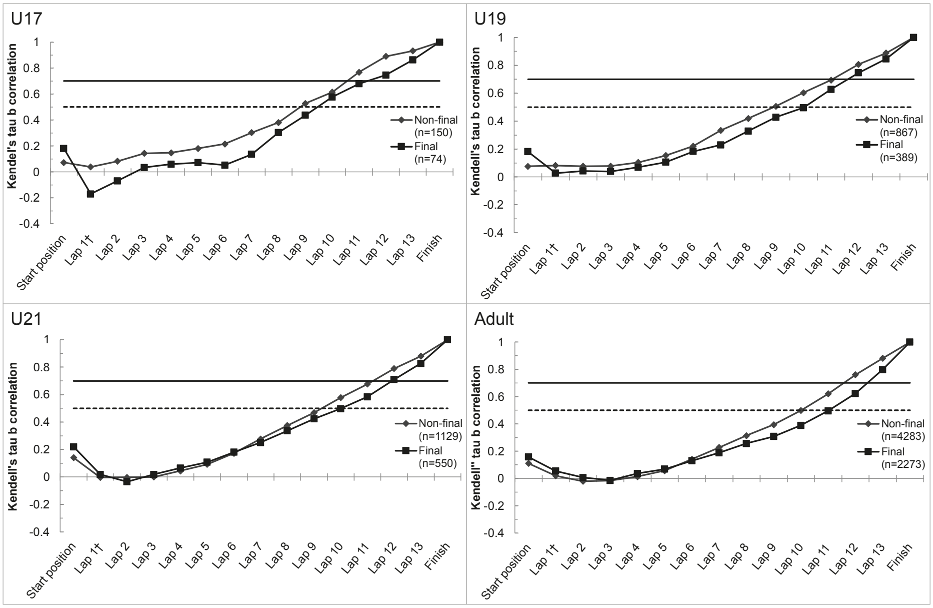

Figure 6. Kendell's tau b correlations between intermediate and final ranking during individual laps for performances in finals and non-finals in each particular age group. Dotted and solid line marking a moderate and high correlation, respectively. † = Lap 1 accounts for only the first ½ lap.

Discussion

The main aim of the current study was to provide an overview of the pacing behaviour of adolescent short-track speed skaters. It appeared that younger skaters demonstrated a relatively fast start compared to adult skaters. Vice versa, the adult skaters displayed a more conservative pacing which included a relatively slow start and fast finish, compared to younger skaters. The positioning data pointed out that younger skaters display a higher correlation between positioning in the intermediate laps and final ranking earlier on in the race, in comparison to adults. These findings support the hypothesis that the pacing behaviour of younger short-track skaters deviates from that of adult skaters in key moments of the race. The largest differences in the RST data exist between the youngest and adult age groups, and these differences seem to become smaller with age. These findings suggest that, throughout adolescence, the pacing behaviour of younger skaters changes towards that of adult skaters. Comparable to the RST data, the positional data presented a similar trend which suggests the pacing behaviour of younger skaters changes throughout adolescence to resemble that of adult skaters. These findings support the current study's hypothesis and match the outcome of previous research regarding the development of pacing behaviour in adolescent long-track skaters (21). In this respect, it seems that pacing behaviour can indeed be seen as a self-regulatory skill which is under development throughout adolescence.

A possible explanation for the difference in both the RST and positional data between younger and older skaters could be linked to experience. Previous research pointed out the importance of experience in the development of the pacing skillset (12, 14, 15, 21). As seen in previous research, the development of the skill to anticipate future physiological requirements is important in successful pacing (14, 16, 17). During the final phase of the race, lap times decrease and the level of fatigue increases (4). During the last phase of the race, skaters need to interact in a highly interactive competitive environment under fatiguing conditions. Older skaters possess more racing experience and therefore could have a more developed anticipatory skillset. This could be the reason why the pacing behaviour of adult skaters is more conservative, as they are preserving energy for the final moments of the race (4). However, an argument could be made that following the pace of an opponent can be more physiologically demanding (26). Adopting a pacing strategy aimed at completing the event as fast as possible, without adopting a similar pace as competitors, could thus potentially increase the chances of winning by lowering physiological demands. This would entail that taking leading positions early in the race could be considered more optimal. Yet, previous research on elite adult short-track skaters has shown that this strategy is not associated with better performances (25).

The results of the current study support the idea that athletes develop the underlying physical and cognitive functions needed for functioning pacing skills throughout adolescence (13, 21). It is suggested that through the gathering of experiences in training and competition, as well as evaluating previous races, athletes learn to more accurately plan their races and respond to environmental stimuli (13). Where previous research focused primarily on the planning strategy and the reaction to internal cues such as muscle fatigue (12, 16, 17, 30), the demonstrated age-related changes of pacing behaviour and positioning in a highly interactive, head-to-head sports such as short-track speed skating, make a case for an emphasis on the influence of environmental cues in addition to the internal cues, as suggested previously (5, 10, 13).

Comparing the pacing behaviour between different sexes revealed a difference in the change in pacing behaviour with age. The RST data revealed that the younger female skaters tended to demonstrate a relatively slow start to the race, compared to their male counterparts. Especially in the youngest age group, female skaters seemed to start slower and finish faster compared to male skaters. The conservative start and high-performance finish are similar to the behaviour seen in older age groups. Additionally, the positioning data revealed that the positing behaviour of female skaters in the U17 age group resembled that of older age groups far more, compared to the male skaters in the same age group. It could be stated that the pacing behaviour of younger female skaters is more similar to that of older age groups, compared to the male skaters in the same age group. A possible explanation for the difference in pacing behaviour could be the difference in the onset of puberty, and the associated changes in physical and cognitive functioning, between sexes (31, 32). As seen in previous research, pacing behaviour is dependent on several facets of cognitive functions including the anticipation of future physiological requirements, deductive reasoning, understanding of the self-physiology and deductive reasoning (14, 17, 33). As females reach puberty several years earlier compared to males, the physical and cognitive functioning which influences pacing behaviour might be further developed, resulting in a pacing behaviour which shares more resemblance with older athletes (13). Earlier research on adolescent track and field athletes seems to support this notion as it was suggested that female athletes pace their performance more conservatively in comparison to male athletes (28).

A comparison of the pacing behaviour between the different stages of competition revealed a similar pattern across all age groups. The analyses of RST data revealed that the pacing behaviour of skaters in finals included a more conservative start with a high RST percentage, and a finish with a lower RST percentage, compared to non-finals. Moreover, the positioning data indicate that the correlation between the position of a skater during an intermediate lap and the final ranking of the skater is higher in an earlier stage of the race in the non-finals. This would suggest that during finals, the final ranking is determined by actions made in the final laps. These findings conform with earlier research on elite adult athletes (4).

3.3. Practical applications

It was previously put forward that the pacing behaviour of talented adolescent long-track speed skaters seems to be an indicator of their performance at a later point of their career (21) indicating the value of pacing behaviour in talent development and selection. The current study emphasizes the importance of both age and environmental cues in pacing behaviour in short-track speed skating, extending the claim that the development and implementation of the pacing skillset are not only important in time-trial sports but also in head-to-head competition sports(5, 10, 13). It would therefore be of value to analyse and train the pacing behaviour of young athletes who are engaged in head-to-head competition, in order to guide the development of pacing behaviour in the most beneficial direction. It is suggested that the process of self-regulation could be a beneficial factor in the development of pacing behaviour (13). The employment of training sessions that sharpen self-regularity skills through reflection, planning, monitoring, adapting and evaluation could positively influence the pacing development process (13). The specific findings for age groups, sex and stage of competition in the current research could be used as a benchmark in the implementation of a self-regulatory skill-based model.

4. Conclusions

The current study is the first to analyse the pacing behaviour of adolescent athletes performing in head-to-head competition. We have taken a rigorous approach and analysed almost 10,000 races, lap times as well as positional data, of adolescent athletes and found that their pacing behaviour and positioning changes throughout adolescence towards the more conservative behaviour exhibited by adult elite athletes. These findings stress the importance of experience, physical and (meta-) cognitive development, and understanding of one's own physiology in the development of pacing behaviour, and suggest that pacing behaviour can indeed be seen as a self-regulatory skill that can be learned. Additionally, the occurrence of the development of pacing behaviour in a head-to-head type competition further emphasises the importance of environmental cues: pacing and adequately responding to environmental cues in competition is a self-regulatory skill that is under development throughout adolescence. Results are relevant in order to be able to optimally guide young athletes in terms of their pacing behaviour, and will have an impact on coaching practice. Talent development programs of head-to-head sports could benefit by increasing the focus on pacing behaviour development during adolescence.

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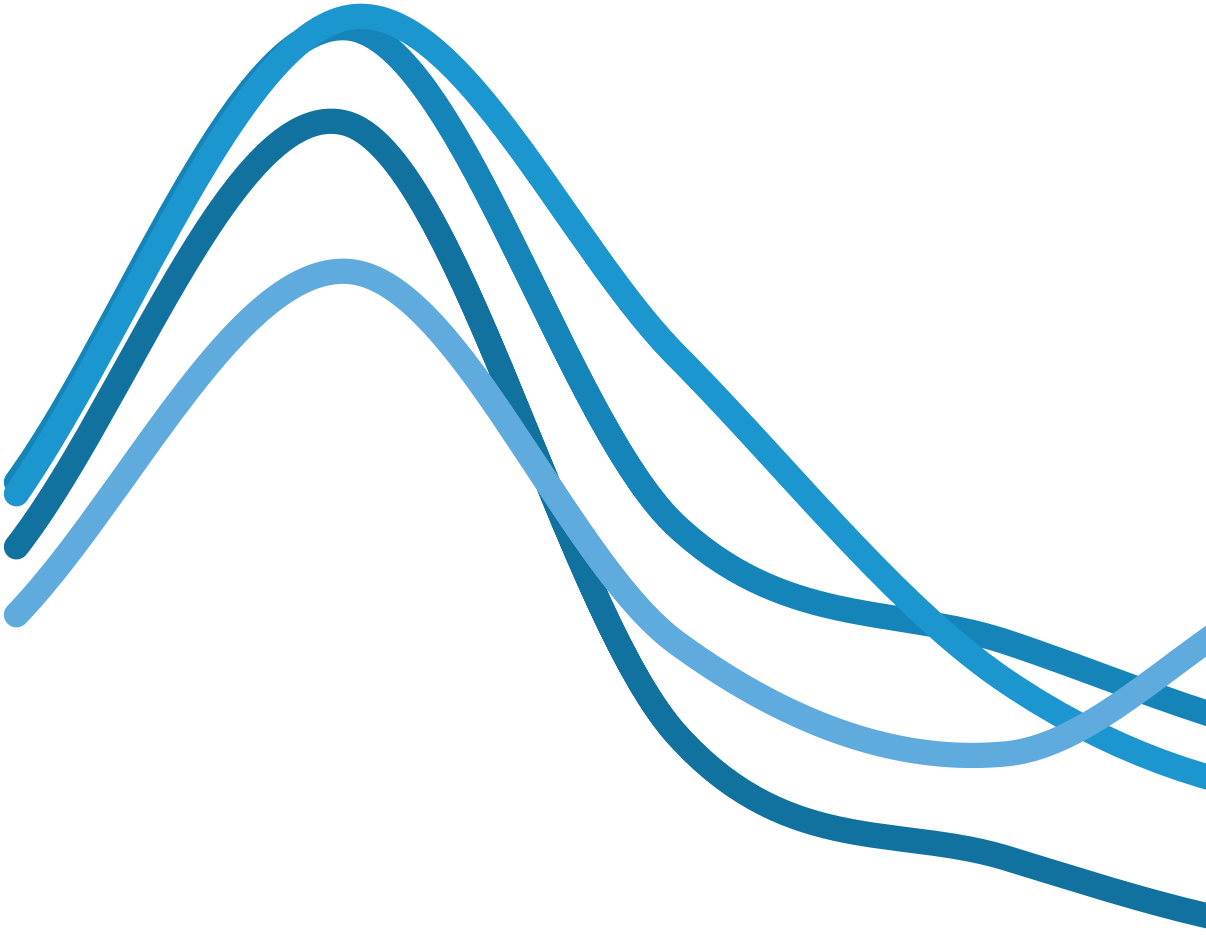
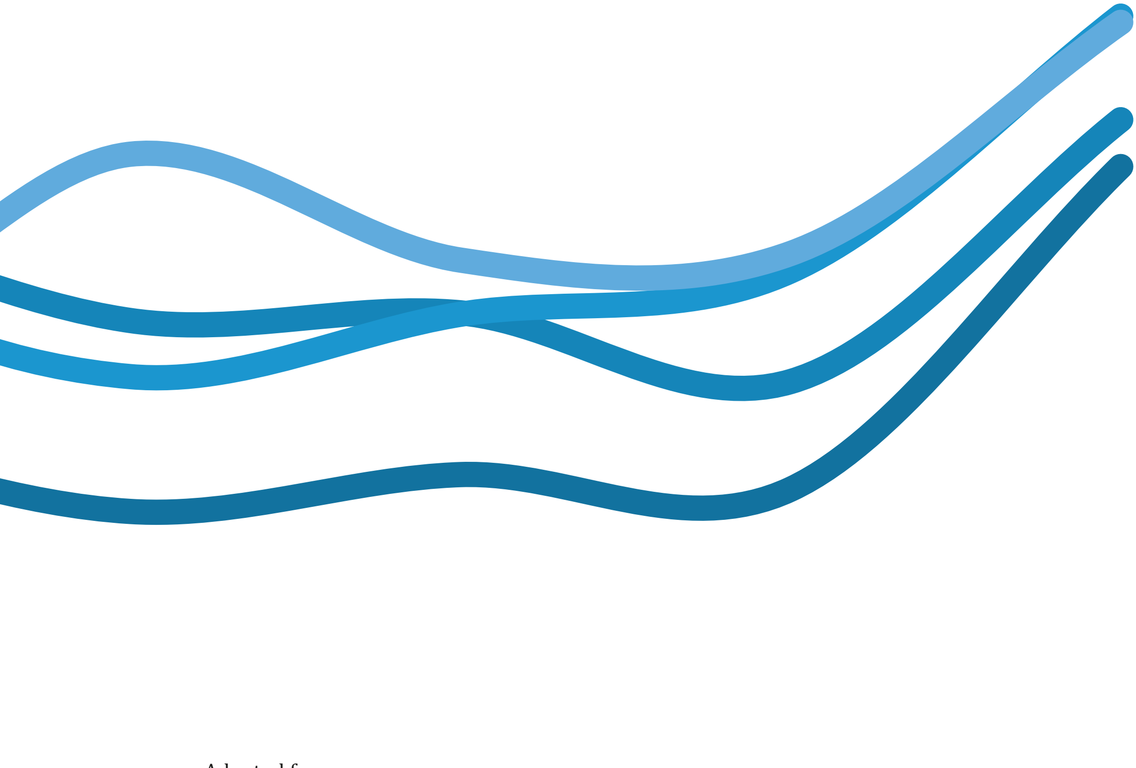


Chapter 4

Effects of experience and opponents on the pacing behaviour and 2-km cycling performance of novice adolescents



Adapted from:
Menting S.G.P., Elferink-Gemser M.T., Edwards A.M., Hettinga F.J. Effects of Experience and Opponents on Pacing Behavior and 2-km Cycling Performance of Novice Youths. *Research Quarterly for Exercise and Sport. 2019;90(4):609-618.*

Abstract

Purpose: To study the pacing behaviour and performance of novice adolescents in a well-controlled laboratory setting.

Methods: Ten healthy participants (seven male, three female, 15.8 ± 1.0 years) completed four, 2-km trials on a Velotron cycling ergometer. Visit 1 was a familiarization trial. Visits 2 to 4 involved the following conditions, in randomized order: no opponent (NO), a virtual opponent (starting slow and finishing fast) (OP-SLOWFAST), and a virtual opponent (starting fast and finishing slow) (OP-FASTSLOW). Repeated measures ANOVAs ($p<0.05$) were used to examine differences in performance (mean power output, finishing time), pacing behaviour (mean power output per 250m segment), and rate of perceived exertion (RPE) between the four successive visits and the three conditions. The expected performance outcome was measured using a questionnaire.

Results: Power output increased ($F_{3,27} = 5.65$, $p<0.01$, $\eta^2_p = 0.39$) and finishing time decreased ($F_{3,27} = 9.97$, $p<0.001$, $\eta^2_p = 0.53$) between visit 1 and visits 2, 3 and 4. In comparison to the familiarisation visit, the difference between the expected finish time and actual finishing time decreased by 66.2%, regardless of condition. The only significant difference observed in the RPE score was reported at the 500m point, where RPE was higher during visit 1 compared to visits 3 and 4, and during visit 2 compared to visit 4 ($p<0.05$). No differences in pacing behaviour, performance, or RPE were found between conditions ($p>0.05$).

Conclusion: Novice adolescents improved their cycling performance after gaining experience during the first visit, parallel with the capability to anticipate future workload, and independent of a change in pacing behaviour.

Keywords: pacing strategy, adolescence, development, competition.

1. Introduction

Pacing is widely known as the goal-directed distribution of energy over a predetermined exercise task (1, 2). This has been shown to be a decisive component of athletic performance in both time-trial (3, 4) and head-to-head events (5-7). The outcome of decision-making involved in pacing is defined as pacing behaviour (1). Pacing behaviour can be influenced by many aspects including; the perceived level of fatigue throughout the race (8), the competitive environment (9) and sport-specific demands (10). Thus far, most research on pacing behaviour has been conducted in adults, and research on the acquisition of the pacing skill and the development of pacing behaviour in adolescents is surprisingly scarce (11).

Although empirical data on the pacing behaviour of younger individuals is limited, one study of time-trial performances in young children (~5-8 year olds) has suggested it is characterised by an initial all-out use of energy, which thereafter decreases in velocity over the duration of the bout (12). Older children (~10 years old) seem to display a more U-shaped velocity distribution, suggestive of a goal-driven reservation of energy in order to execute an exercise task successfully (12, 13). Furthermore, emerging research from both time-trial and head-to-head events appears to suggest pacing behaviour of younger athletes (12-21 years old) progressively further develops in complexity towards that of adults (14, 15). The proposed theoretical basis behind this development of pacing behaviour is twofold. First, during adolescence, there are cognitive and physical changes associated with growth and maturation (16, 17). Second, the gathering of experience during exercise tasks, for example by means of training or competition, facilitates the improvement of physical and cognitive performance characteristics. Improvement of performance characteristics in turn facilitates the development of adequate pacing behaviour (11). Therefore, it is likely that the development and maturation of cognitive characteristics mediate the influence of acquired experience on pacing behaviour. As such, cognitive functions relevant to pacing include a progressively accurate self-assessment of physical capability aligned with anticipation of future physiological requirements (18, 19), meta-cognitive functions (11) and deductive reasoning (20). Underdevelopment of these functions may lead to sub-optimal pacing behaviour (12, 20).

Recent literature emphasizes the importance of environmental stimuli in the pacing process (1, 9, 21). The anticipation and response to environmental stimuli (e.g. opponents) has been suggested to be important both in competition and in the development of pacing behaviour (14). The study of Lambrick *et al.* showed that when inexperienced children (~10 years old) who were performing an 800m running task were introduced to opponents, their performance decreased with no change in pacing behaviour (13). The given explanation for this outcome was the relative inexperience of the children in a competitive environment which increases with exposure to a variety of competitive situations over the life span. Interestingly, when adult athletes were presented with a performance-matched opponent, an improvement in performance was demonstrated, which may be due to the greater familiarity of adults with competitive environments (21-23). Furthermore, it was found that the pacing behaviour of the opponent influenced that of the participant, as a faster-starting opponent evoked a faster (matched) start in the participants (6). Therefore it would seem the skills that allow an athlete to anticipate, interpret and implement pacing in the presence of an opponent are developed during adolescence (14). However, in adolescents, who have not yet fully developed the pacing behaviour of adults, it is questionable whether performance would be significantly influenced by the presence of an opponent and if so, if this influence would be to the same extent to what has been reported in adults. It is plausible that the primary driver of inexperienced young athletes, is to learn how to distribute their efforts over an exercise bout via an intrinsic improvement of their self-regulated behaviour. In contrast, adults who have already developed this pacing skill, might be more influenced by the presence of those around them.

Adolescence seems to be a crucial period in the development of pacing behaviour. Nonetheless, most research into pacing has been carried out in adults. The scarce research that has investigated the subject of pacing behaviour in youth athletes thus far consists mainly of the analysis of split times during competition (14, 15, 24). Therefore, an empirical, well-controlled laboratory study would offer the opportunity to investigate several factors that shape pacing behaviour in adolescents, without the large variation in environmental circumstances that accompanies measuring athletes in competition. The aims of the current study were to investigate what characterises the pacing behaviour of novice adolescents, whether or not their performance and pacing behaviour is influenced by experience gained over successive trials, and if the presence of an opponent influences their pacing behaviour and performance.

2. Methods

2.1. Participants

Ten participants (seven males, three females) completed the study (age: 15.8 ± 1.0 years, height: 1.79 ± 0.06 m, body mass: 62.0 ± 7.5 kg). All participants were healthy and moderately to highly active, as assessed, respectively, by the PAR-Q (25) and the short version of the IPAQ (26). All participants were active partakers in a variety of sports (dance, gym, soccer). None of the participants had any previous experience in performing a (cycling) time trial. Written informed consent was obtained from the participants and their parents or legal guardians at the start of the first visit. The study was approved by the ethical committee of the local university in accordance to the Declaration of Helsinki.

2.2. Experimental procedures

All participants completed four 2-km cycling time trials over four visits. At the start of each visit, each participant was asked two questions about their motivation (“How motivated are you to perform well on the time trial?”) and performance (“How do you think you will perform?”) concerning the upcoming trial, which were scored on a 5-point Likert scale

(5: very motivated, 1: not motivated at all; 5: very good, 1: not good at all). Additionally, participants were asked to estimate a finishing time for the upcoming trial as an indication of their capability to anticipate the workload of the exercise ("In what time do you think you will complete the time trial of two kilometre?"). The participants were not given information on their performance on any of the trials until after the completion of all visits, as the knowledge of a previous performance could influence performance in upcoming trials. Thereafter, participants performed a five minute warm-up with the instruction to perform an average power output of 150 Watts for males and 115 Watts for females (27), followed by a five minute inactive recovery period before the start of the trial.

All time trials were performed on a cycling ergometer (Velotron Dynafit, Racermate, Seattle, USA), which has been shown to be a reliable and valid tool for testing performance and pacing behaviour (28, 29). Using the Velotron 3D software, a 2-km track was created, which was straight, flat and featured no wind. During trials, the track was projected on a screen. Participants were portrayed by an on-screen avatar. During visit 1, a familiarization trial (FAM) was performed. In this trial, participants performed without the presence of an opponent. During two of the remaining three visits, the participants performed a time trial with an opponent operating different race pacing strategies, and one without an opponent (NO), all in a randomized order. The two styles of opponents were created individually for each participant on the basis of the performance during the familiarization trial (22). One opponent (OP-SLOWFAST) used a slow pace (100% of FAM) between 150-1000m and a fast pace (104% of FAM) between 1000m-2000m. The other opponent (OP-FASTSLOW) adopted a fast pace (104% of FAM) between 150-1000m and a slow pace (100% of FAM) between 1000-2000m. The initial 150m of the race was used to give the virtual opponents a start that was comparable to that of human performers. Both opponents had a total race performance which was two percent faster compared to the FAM to correct for the expected improvement of the participants after the FAM, based on the increase in performances of inexperienced children and adult cyclists (13, 22). During trials with an opponent, two avatars were visible on the screen, portraying the participant and the opponent, providing the participant with the relative distance to the opponent. At the start of each trial, participants were provided with the goal to complete the trial in the fastest possible time and to give maximal effort; whether or not they beat the opponent was not important. When an opponent was present, participants were told the opponent was of a similar performance level as the participants. Participants received no numerical feedback on heart rate, power, velocity, time passed, the distance covered, distance left or relative distance to the opponent. Participants were free to change gear throughout the time trial. Power output, velocity, distance, and gearing were monitored during the trial (sample frequency = 25Hz). The rate of perceived exertion (RPE) on a Borg-scale of 6-20 was asked after warm-up, before the start of the trial and at 500m, 1000m, and 1500m, as well as directly after passing the finish line. The participants were told the RPE collection points were random throughout the trial.

All time trials were performed on the same day of the week, with a maximum of six weeks for all the visits. Participants were asked to keep changes in activity and sleep patterns to a minimum during the testing period. Furthermore, participants were asked to abstain from intense physical exercise for 24 hours as well as the consumption of solid food for two hours and caffeine for four hours, before visits. All trials were conducted in ambient temperatures between 18-21°C.

2.3. Data analyses

To investigate the effect of the experience gained over successive trials, the outcome variables of the four consecutive visits (visit 1, visit 2, visit 3 and visit 4) were compared. In order to analyse the influence of the two different opponents, the three different conditions (NO, OP-SLOWFAST and OP-FASTSLOW) were compared.

Performance was analysed through two outcome variables: finish time and mean power output of the trial. Assumption of normality of the continuous outcome variables were checked per visit and condition using Shapiro-Wilk test. The performance variables and the answers to the questionnaire on motivation, expected performance and expected finishing time were analysed by a one-way repeated measures ANOVA to reveal a difference between the visits or conditions ($p<0.05$). A post hoc analysis in the form of paired t-test, including Bonferroni correction, was performed if a significant effect ($p<0.05$) was found. In order to study the capability to anticipate the future workload before exercise, a paired t-test was used to analyse the difference between the expected and actual finishing time for each visit.

The pacing behaviour of the participants was investigated by analysing the mean power output of each 250m segment of the 2-km trial. Assessing pacing behaviour through analyses of power output during the course of a trial is a commonly used method in literature (22). The assumption of normality was checked per visit and condition using the Shapiro-Wilk test. A two-way repeated measures analysis ($p<0.05$) was used to investigate a difference in pacing behaviour between the different visits (segments * visits) and between the different conditions (segments * conditions). If a significant interaction effect ($p<0.05$) was found, indicating a difference in pacing behaviour, a post hoc analysis in the form of paired t-test, including Bonferroni correction, would be performed.

The RPE throughout the trial was analysed using a two-way repeated measures analysis ($p<0.05$) to study the difference in RPE during the different visits (segments * visits) and the difference in RPE between conditions (segments * conditions). A significant interaction effect would indicate a difference in the RPE score over the segments for either the visits or the conditions and would instigate a paired t-test post hoc analyses, including Bonferroni correction.

In anticipation of all previously mentioned repeated measures ANOVA analyses the sphericity was tested using Mauchly's test. If sphericity could not be assumed a Greenhouse-Geisser correction was used. Cohen's d and partial eta squared (η2p) were used to report effect size (small: d = 0.2, η2p = 0.01; medium: d = 0.5, η2p = 0.06; large: d < 0.8, η2p < 0.14).

3. Results

3.1. Repeated trials

The mean (SD) of the questionnaires on motivation, expected performance and expected finishing time, as well as the actual finish time and mean power output of each visit, can be found in Table 1. During the course of the visits, there was no significant difference in the answers to the questions concerning motivation ($F_{3,27} = 1.09$, $p = 0.37$, $\eta^2_p = 0.11$), expected performance ($F_{3,27} = 0.56$, $p = 0.63$, $\eta^2_p = 0.06$) or expected finish time ($F_{1.07,\,9.61} = 2.81$, $p = 0.13$, $\eta^2_p = 0.24$). However, a significant difference between expected and actual finishing time was found during visit 1 ($t = 2.81$, $p < 0.05$, $d = 0.89$), but not during visits 2, 3 and 4 ($t = 1.69$, $p = 0.13$, $d = 0.53$; $t = 1.99$, $p = 0.08$, $d = 0.63$; $t = 1.89$, $p = 0.09$, $d = 0.60$; respectively). A significant difference in both performance variables, finish time and mean power output, was found ($F_{3,27} = 9.97$, $p < 0.001$, $\eta^2_p = 0.53$ and $F_{3,27} = 5.65$, $p < 0.01$, $\eta^2_p = 0.39$, respectively). The post hoc analyses revealed the finishing times of visits 2, 3 and 4 were significantly lower compared to visit 1 ($t = 21.35$, $p < 0.01$, $d = 1.46$; $t = 14.06$, $p < 0.01$, $d = 1.19$; $t = 13.03$, $p < 0.01$, $d = 1.14$; respectively). Additionally, the mean power output was significantly higher in visits 2, 3 and 4 compared to visit 1 ($t = 11.85$, $p < 0.01$, $d = 1.09$; $t = 9.78$, $p < 0.05$, $d = 0.99$; $t = 7.30$, $p < 0.05$, $d = 0.86$; respectively).

The mean (±SD) power output within the 250m segments of the trial for each visit are shown in Figure 1. There was a significant difference between the individual 250m segments ($F_{1.33,\,11.95} = 8.28$, $p < 0.01$, $\eta^2_p = 0.48$) and between the mean values of the different visits ($F_{3,\,27} = 5.65$, $p < 0.01$, $\eta^2_p = 0.39$). No significant interaction effect, indicating a difference in pacing behaviour between the different visits, was found ($F_{4.56,\,40.10} = 2.17$, $p = 0.08$, $\eta^2_p = 0.19$).

The mean (±SD) RPE scores are shown in Figure 2. The RPE score was significantly different between the different segments ($F_{1.66,\,14.94} = 159.03$, $p < 0.001$, $\eta^2_p = 0.95$). The average RPE score was not significantly different between different visits ($F_{3,\,27} = 0.85$, $p = 0.48$, $\eta^2_p = 0.09$). A significant interaction effect was found, indicating a difference in RPE score over the segments between the visits ($F_{3.30,\,29.74} = 3.25$, $p < 0.05$, $\eta^2_p = 0.27$). The post hoc analysis revealed that the RPE score at the 500m mark was significantly higher during visit 1 compared to visit 3 ($t = 7.57$, $p < 0.05$, $d = 0.87$) and visit 4 ($t = 18.69$, $p < 0.05$, $d = 1.37$). Moreover, the RPE score at 500m was higher during visit 2 compared to visit 4 ($t = 17.05$, $p < 0.01$, $d = 1.30$). No significant differences in RPE between the visits were found at the start, 1000m, 1500m and finish.

Table 1. Means (±SD) of the indicators of motivation, expected performance and performance outcome variables for each visit and the different conditions.

	Questioning on motivation (1-5)	Questioning on expected performance (1-5)	Expected finish time (s)	Finish time* (s)	Δ Expected and actual finishing time (s)	Mean power output* (W)
Visit 1	4 ± 1	3 ± 1	453.00±249.18	240.50±27.37	212.50±239.33†	181.03±46.36
Visit 2	4 ± 1	3 ± 1	300.00±141.42	228.33±21.12^{A}	71.67±134.40	195.70±41.08^{A}
Visit 3	4 ± 1	4 ± 1	312.00±142.97	227.69±20.97^{A}	84.31±134.21	199.54±43.87^{A}
Visit 4	4 ± 1	3 ± 1	297.00±120.37	228.97±18.40^{A}	68.03±113.61	193.50±39.84^{A}
No Opponent	4 ± 1	4 ± 1	303.00±135.98	227.16±17.17	75.85±129.00	196.73±39.15
OP-SLOWFAST	4 ± 1	3 ± 1	294.00±121.49	228.19±20.39	65.81±114.49	197.33±42.35
OP-FASTSLOW	4 ± 1	4 ± 1	312.00±147.11	229.64±22.61	82.36±138.72	194.68±43.48

Note. * = significant difference between visits, ^{A} = significantly different from visit 1, † = significant difference between expected and actual finishing time within a visit or within a condition.

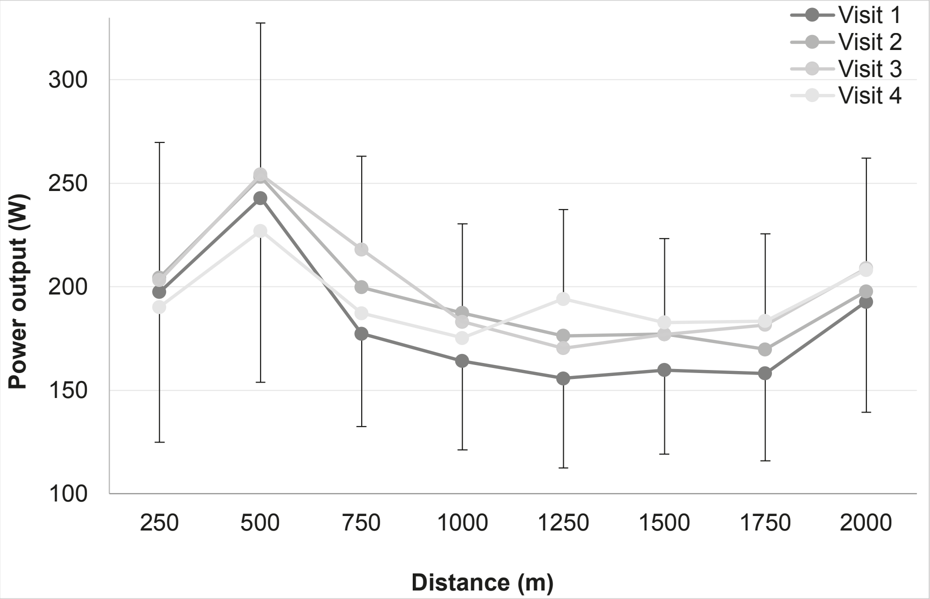


Figure 1. Mean (±SD) power output in each 250m segments for each visit.

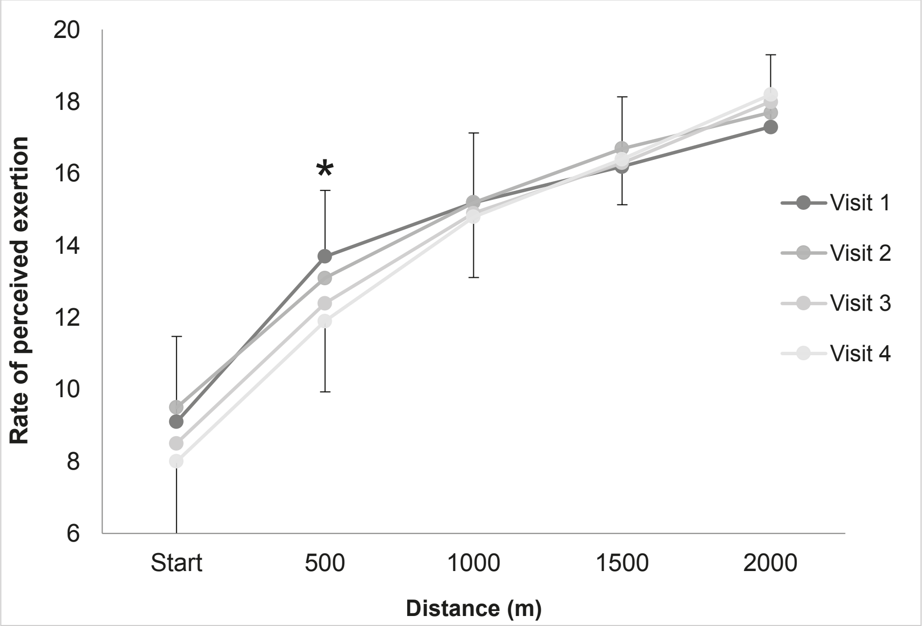


Figure 2. RPE score at the start, 500m, 1000m, 1500m and finish, for each visit. * a significant difference in RPE ($p < 0.05$) between: visit 1 and visit 3 & 4, visit 2 and visit 4.

3.2. Influence of opponents

The difference in finishing time between the opponents calculated from the FAM and the constructed opponents which participants faced was: 0.33±0.07s. The mean (±SD) finishing times of the constructed opponents were OP-SLOWFAST: 235.39±25.44s and OP-FAST-SLOW: 235.35±25.58s.

Between the conditions, there was no significant difference in the scores on motivation ($F_{1.78,16.06} = 0.78$, $p = 0.46$, $\eta^2_p = 0.08$), expected performance ($F_{1.86,16.71} = 0.55$, $p = 0.58$, $\eta^2_p = 0.06$) or expected finish time ($F_{1.57,14.10} = 0.81$, $p = 0.44$, $\eta^2_p = 0.08$) (Table 1). Additionally, no significant difference in finish time or mean power output was found between the trials with different conditions ($F_{1.88,16.48} = 0.61$, $p = 0.54$, $\eta^2_p = 0.06$ and $F_{1.720,15.484} = 0.17$, $p = 0.81$, $\eta^2_p = 0.02$, respectively) (Table 1).

The mean (±SD) power output within each 250m segment of the trial under different conditions are shown in Figure 3. A significant difference in power output over the different segments was found ($F_{1.47, 13.23} = 6.87$, $p < 0.05$, $\eta^2_p = 0.43$). No significant difference between the mean values between conditions ($F_{2, 18} = 0.17$, $p = 0.81$, $\eta^2_p = 0.02$) or interaction effect, indicating a difference in pacing behaviour ($F_{2.90,26.08} = 1.32$, $p = 0.29$, $\eta^2_p = 0.13$), were found.

Mean (±SD) scores for RPE can be found in Figure 4. The RPE score of the individual segments was significantly different ($F_{4, 36} = 144.76$, $p < 0.001$, $\eta^2_p = 0.94$). Additionally, the average RPE score of the distinct conditions was significantly different ($F_{1.63, 14.64} = 4.92$, $p < 0.05$, $\eta^2_p = 0.03$). No significant difference in RPE score over the segments between the different conditions was found ($F_{2.13, 19.18} = 0.29$, $p = 0.77$, $\eta^2_p = 0.03$).

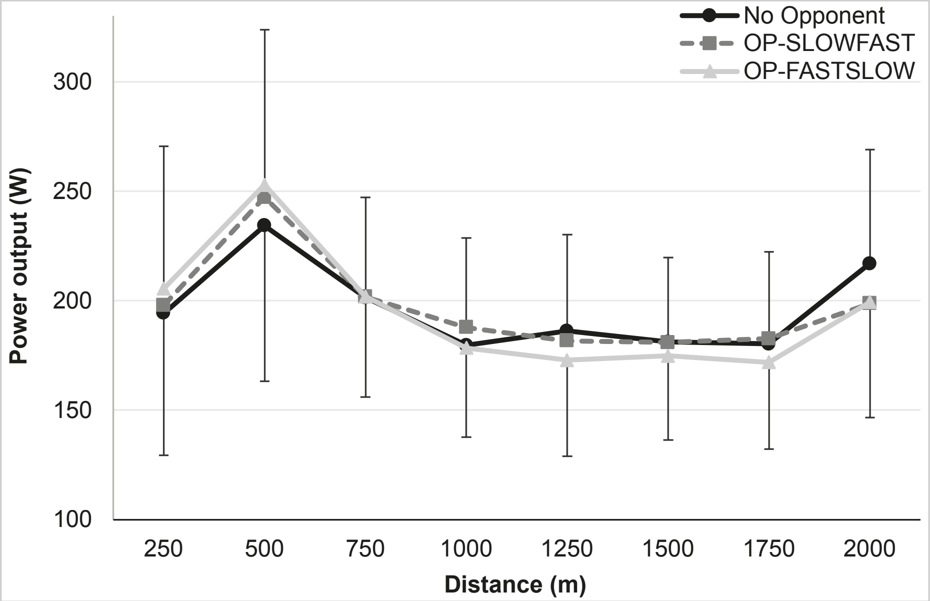


Figure 3. Mean (±SD) power output in each 250m segments for each condition.

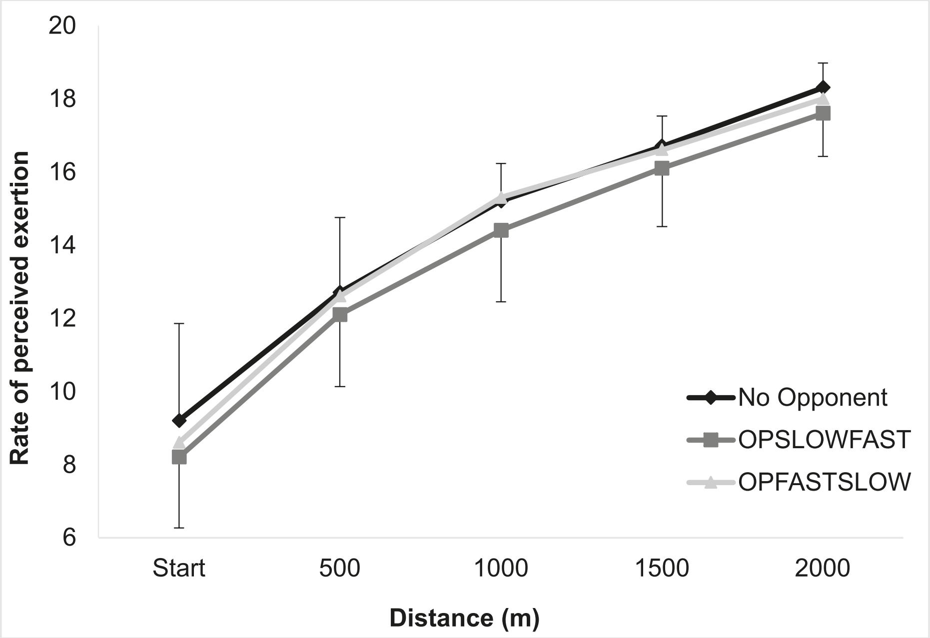


Figure 4. Mean (±SD) RPE score at the start, 500m, 1000m, 1500m and at the finish, for each condition.

4. Discussion

This study is the first to examine characteristics of the pacing behaviour of novice adolescents in a controlled laboratory setting. The findings identify that the power output of the novice adolescents decreases between the 500m and 1000m mark, and increases at the 1750m to 2000m segment. This is a more complex pacing behaviour than seen previously in young children (~5-8 years) (12), and the observed overall U-shaped effort distribution is generally associated with the goal-directed preservation of energy to execute an exercise task successfully. This suggests that increased sophistication of pacing behaviour is evident in adolescents compared to young children. It is also interesting that during the first visit, a significant difference was found between the amount of time participants thought was needed to finish the trial and the actual completion time of the trial. The variety in expected finishing time among the cohort during the first visit was also substantially larger (SD of visit 1: 249.18s) compared to other visits (average SD visits 2-4: 134.74s). Both findings attest to the novelty of the activity for the participants before the first visit and the potential impact of the acquired experience. The finding that the pacing behaviour of adolescents exhibits characteristics associated with the goal-directed reservation of energy during the execution of a novel exercise task supports the notion of an inherit pacing template already being present from a young age (13, 30).

The secondary aim of this research was to investigate the influence of the experience gained over successive trials on pacing behaviour and performance. However, no change in pacing behaviour was found throughout the visits. Nevertheless, the 8.1% increase in power output and 5.1% decrease in finishing time during the second visit indicate an improvement in performance after gaining experience during the first visit. The observation that there was no significant increase in performance during visits two, three and four suggests that a single familiarization trial was sufficient to heighten the performance in novice adolescents. A similar conclusion was reached in research on children (aged 9-11 years) performing a running task with a similar duration to the task in the current study (13). This study found a 2.6-3.1% decrease in finishing time during the second visit and no significant further decrease during the third visit. Moreover, the study did not find a significant difference in pacing behaviour between the three visits. These results strengthen the notion that novices can increase performance after gaining experience in only a single trial.

It has previously been proposed that the anticipation of workload, and the adjustment of workload anticipation during exercise form part of the underlying mechanism of the regulation of energy (18, 19, 31). In the current study, the capability to anticipate the workload of the exercise was measured by analysing the difference between the expected finish time and the actual finishing time of each visit. By comparing the first and second visits, the gap between the expected finish time and the actual finishing time decreased by 66.2%, suggesting greater awareness of task demands as experience grew. It should be noted that the condition of visit two differed between participants, as a result of the randomisation of conditions between visits two, three and four. However, there was no significant difference in expected or actual finishing time between the conditions, indicating that the increase in awareness of performance capabilities was not influenced by the condition of the second visit. Moreover, on the first visit, the expected and actual finishing times were significantly different. Contrary to this, there was no significant difference between the expected and actual finishing times during the other visits. These findings point to an improved capability to anticipate the workload of the exercise as a whole, in addition to greater confidence in the performance capability. The increase in the capability to anticipate the total workload might be the underlying mechanism of the increase in performance after the first visit.

In literature, RPE has been proposed as a mediating factor in the regulation of energy distribution by the cognitive anticipatory skill (32). The results of the current study present a decrease in RPE score at the 500m mark between visits one and visit three and four, as well as between visits two and four. A lower RPE score during the initial phase of the race may well indicate that the participants were actively changing their anticipation of the future workload during the exercise (33). Therefore, it could be suggested that the capability to anticipate the future workload during exercise takes more than one visit worth of experience to be adapted. This slower change in anticipatory capability could be the underlying mechanism which enabled a change in pacing behaviour over a longer period of time, as seen in previous studies (14, 15). Future research, preferably longitudinal, should be performed to gain more insight into the development of pacing behaviour in relation to anticipatory capability.

4.1. Influence of opponents

No difference in performance or pacing behaviour of novice adolescents was found between the different conditions in the current study. In contrast, previous studies found a decreased performance in novice children (9-11 years old) facing opponents (13) and an increase in performance in novice 19-year-olds facing opponents (34). Previous literature states the adaptation of the skill to pace in the presence of opponents is not yet fully developed in young athletes (14), and therefore novice adolescents might not yet be able to use the presence of opponents to increase their performance, as seen in adults who have been found to perform better when opponents are present (21-23). It could be that the attentional needs of young exercisers in the adolescence development phase are more aimed at properly pacing an exercise bout and internally developing their self-paced behaviour and that they, therefore, consider opponents to a lesser extent, and for the very young, it might therefore be detrimental to performance. The current group of novice adolescents (15.8±1.0 years old) were in an age range in between the two previous studies in 9-11 year-olds (13) and 19-year-olds (34). It is, therefore, possible that for young exercisers in this specific age range, an increase in performance through the gathering of experience, as discussed previously, seems more important for performance improvements, while the presence of opponents seems of lesser importance.

Furthermore, previous research pointed to the notion that the instructions regarding the presented opponents as well as the behaviour of the opponents, could determine the impact on participant performance (21, 23). In the current study, the participants had the goal of finishing the 2-km trial as fast as possible, regardless of beating the opponent. It seems plausible that the lack of influence of the opponent could be caused by a lack of engagement with the opponent. It should also be acknowledged that the participants in the current study were active in a variety of both individual and team sports. Previous research has pointed out that sports background influences the goal orientation of an athlete, and therefore, impacts the behaviour of athletes to the presence of opponents during exercise performance (35). It would therefore be interesting for future studies to investigate the effect of different exercise backgrounds, goal orientations and instruction regarding opponents, on performance and pacing behaviour in adolescents.

5. Conclusion

The pacing behaviour of novice adolescents exhibits characterisations which are associated with goal-directed reservation of energy during exercise, attesting to the existence of a pacing template in this population. The experience gained during a single trial seems sufficient to cause an improvement in performance, but not a change in underlying pacing behaviour. The large increase in performance after only one visit is theorized to be caused by an improved capability to accurately anticipate the workload of the exercise as a whole. The capability to anticipate future workload during exercise, and regulate the energy distribution accordingly, might be among the underlying mechanisms of the long-term changes in pacing behaviour that occur throughout adolescence. The lack of influence from the presence of opponents could be appointed to the development phase of the adolescents, in which they are more focused on developing the self-regulated pacing of a bout of exercise and to a lesser extent, on the presence of opponents. As the current study is the first to analyse the performance and pacing behaviour of novice adolescents in a controlled environment, future research should be conducted to further investigate the factors underlying the development of pacing behaviour and performance in this age group. A suggested starting point for this research is to further explore the influence of self-regulatory skills and anticipation of workload on the development of pacing behaviour and performance.

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Chapter 5

Pacing behaviour development and acquisition: a systematic review

Adapted from:
Menting S.G.P., Edwards A.M., Hettinga F.J., Elferink-Gemser M.T. Pacing Behaviour Development and Acquisition: A Systematic Review. *Sports Medicine – Open. 2022;8(1):143*

Abstract

Background: The goal-directed decision-making process of effort distribution (i.e. pacing) allows individuals to efficiently use energy resources as well as to manage the impact of fatigue on performance during exercise. Given the shared characteristics between pacing behaviour and other skilled behaviour, it was hypothesized that pacing behaviour would adhere to the same processes associated with skill acquisition and development.

Methods: The Pubmed, Web of Science and PsychINFO databases between January 1995 and 2022 were searched for articles relating to the pacing behaviour of individuals 1) younger than 18 years of age, or 2) repeatedly performing the same exercise task, or 3) with different levels of experience.

Results: The search resulted in 64 articles reporting on the effect of age (n=33), repeated task exposure (n=29) or differing levels of experience (n=13) on pacing behaviour. Empirical evidence identifies the development of pacing behaviour starts during childhood (~10 years old) and continues throughout adolescence. This development is characterized by an increasingly better fit to the task demands, encompassing the task characteristics (e.g. duration) and environmental factors (e.g. opponents). Gaining task experience leads to an increased capability to attain a predetermined pace and results in pacing behaviour that better fits task demands.

Conclusions: Similar to skilled behaviour, physical maturation and cognitive development likely drive the development of pacing behaviour. Pacing behaviour follows established processes of skill acquisition, as repeated task execution improves the match between stimuli (e.g. task demands and afferent signals) and actions (i.e. continuing, increasing or decreasing the exerted effort) with the resulting exercise task performance. Furthermore, with increased task experience attentional capacity is freed for secondary tasks (e.g. incorporating opponents), and the goal selection is changed from achieving task completion to optimizing task performance. As the development and acquisition of pacing resemble that of other skills, established concepts in the literature (e.g. intervention-induced variability and augmented feedback) could enrich pacing research and be the basis for practical applications in physical education, healthcare, and sports.

Keywords: pacing, skill, development, junior, acquisition, experience, sports, exercise.

1. Background

Humans are unable to sustain high-intensity physical work indefinitely, and thus exercise performance has limitations, of which the causes are diverse depending on the specific activity (1). Sustained physical work over a defined performance duration has been shown to result in either an involuntary decline in motor skill execution or requires an increasing effort to maintain performance level (2). These phenomena are interlinked with changes in sensations that regulate the physiological integrity of the exerciser, such as localised pain, nausea and heat stress, which collectively represent the concept of fatigue (2). To deal with these phenomena in a sports setting, the exerciser needs to manage the balance of exertion required to successfully complete the task's goal, with an optimal distribution of energy resources adapted to the duration of the event (1, 3). This balances the power losses needed to overcome velocity-related frictional forces and power production (4), while avoiding premature deterioration of motor skill performance due to overwhelming or catastrophic fatigue (5). Achieving this balance is of particular relevance in technical sports such as speed skating (6). In order to perform this feat, exercisers engage in the process of decision-making regarding how and when to exert effort to successfully complete physical tasks (7, 8). At a fundamental level, the continuous decision to be made by the exerciser is whether to increase, decrease or continue exerting the same level the effort (9). This decision is influenced by factors such as the exercise task characteristics (e.g. exercise duration (10) and biomechanical traits (6)) and the environment (e.g. presence of opponents (11) or temperature (12)), in combination with afferent signals from the skeletomuscular system (1). This goal-directed decision-making process regulating the distribution of effort over a predetermined exercise task has been defined as pacing (7, 13). Given that humans are not entirely rational decision-makers (14), factors like motivation (15), mood (16), and self-efficacy (17) impact decision-making and subsequent task performance. It is important to state that the self-regulatory elements of the pacing process are thought to be cyclical; the experience that is gained with each iteration of the task is used to recalibrate the informed decision-making for the next task execution (18).

Pacing fits the description of a skill, as it is task-specific, goal-directed behaviour that is improved with increased training and experience (19, 20). Skills are often investigated at a behavioural level; the study of skilled behaviour is concerned with the quantification of the extent to which a given behaviour achieved the goal that was intended or instructed (19). When considering pacing in this context, the outcome of the goal-directed decision-making process regarding the distribution of effort could therefore be defined as 'pacing behaviour'. Quantifying pacing behaviour has generally been achieved by plotting an outcome measure for effort (e.g. power output) over time (21, 22). The view of pacing as a skill reflects that it goes through development and has to be acquired (23, 24). Skill development encompasses the effect of age, specifically in maturing children and adolescents, on skilled behaviour (19). Any real-world exercise task necessarily entails both cognitive and motor components, which undergo drastic development during childhood and adolescence (25).

To illustrate: on average, the adolescent growth spurt starts at approximately 9 years of age in girls and about 11 years of age in boys, with a peak height velocity at an average age of 12 and 14 years old, for girls and boys respectively (26, 27). Physical attributes which play a key role during exercise, such as total lung capacity, alveolar surface, stroke volume and cardiac output of the heart, and muscle mass, develop accordingly (28, 29). Additionally, the period between 10 and 24 years old is distinguished by a reorganisation of the neural circuitry of the higher brain centres (30, 31). The higher brain centre to develop most during this period is the prefrontal cortex, the area of the brain associated with abstract thinking, planning and decision-making (31, 32). Neurological evidence suggests that the prefrontal cortex is essential to pacing as it is said to facilitate the integration of afferent feedback into top-down control of motor unit recruitment [55]. As pacing encompasses a complex psychophysiological process (1, 33), it seems more than likely that it develops throughout childhood and adolescence (1, 18, 34). Developing the skill to adequately pace an exercise task is crucial in a individuals' development as it provides a feeling of competence, motivating children and adolescents to engage more in exercise, with all the associated health benefits in later life (1). Vice versa, inadequate development of pacing behaviour could negatively impact exercise performance while also affecting individuals' long term exercise practices, health and well-being (34, 35). A repeated inaccuracy in the distribution of effort during repeated exercise tasks over a longer period of time could lead to task overexertion, which could result in overtraining, injuries, burn-out and disincentivisation to exercise, eventually causing drop-out of exercise and physical activity (1, 35). At an acute level, a sub-optimal development of pacing behaviour could also yield problems for populations who experience difficulty self-regulating effort (36), such as people with an intellectual impairment (37). A better understanding of the pathway and underpinning mechanisms of pacing behaviour development would therefore be a valuable tool to aid children's development (18, 34).

Skill acquisition is defined as the relatively permanent change in behaviour resulting from prior experience (19, 38). It is thought that skill acquisition goes through phases (19, 25, 39). Initially, learners focus mainly on associating stimuli and actions in order to achieve the task goal. As acquisition continues, the relationship between variations in behaviour and task performance is used as a recalibration of the skill: good strategies are maintained, and inappropriate ones are discarded. The late stage of skill acquisition is often evidenced by the level of automatization; the learner performs the task using less of their conscious attention, leaving cognitive capacity for the execution of secondary tasks. When categorizing pacing as a skill, it is logical to assume that similar processes underlie the process of learning how to pace an exercise task. This allows for the application of lessons from skill acquisition literature in the field of pacing. Studying pacing in a skill acquisition framework could, therefore, not only provide valuable information to the ongoing discussion regarding the debated workings of the pacing process (15, 40) but also provide practical information to coaches and healthcare professionals who aim to correct or fine-tune an individual's distribution of effort by means of practice, to improve physical activity performance in both sports or healthcare settings (21, 41).

The relation between pacing behaviour and various physiological (1, 13), biomechanical (42), psychological (43) and, more recently neurological (44) variables have been extensively studied to gain a deeper understanding of the symbiotic relation between pacing behaviour and exercise task performance. However, the development of pacing behaviour during childhood and adolescence and the acquisition of the skill through experience have received limited attention, despite holding the promise of a wealth of theoretical knowledge and practical applications. This review, therefore, aims to investigate the development of pacing behaviour during childhood and adolescence as well as the acquisition of the skill through experience. To achieve this aim, the existing literature will be systematically analysed for the effect of age (up until 18 years old) and gathering experience on pacing behaviour. Recognizing the similarities between pacing behaviour and skilled behaviour, it is hypothesized that pacing behaviour would adhere to the same characteristics associated with skill acquisition and development. If this is indeed the case, lessons learned for skill acquisition and development could be used to enrich the field of pacing research with future research goals and form practical guidelines to improve exercise performance.

2. Methods

The current systematic review will be restricted to pacing behaviour in a sports and exercise setting, including only articles investigating a healthy population (for more information on pacing behaviour in a healthcare setting we recommend the review of Abonie *et al.* (41)). The study of pacing behaviour has a valuable role in healthcare and rehabilitation settings, such as when reacquiring skills after neurological injury (36, 41). However, the majority of literature investigating pacing behaviour is set in a sports science setting where competition and maximal effort trials are common. The sports laboratory environment is well suited as a basis for experimental research, as it facilitates a standardized approach to a physical performance task in a controlled setting, measured by validated and accurate equipment (45). The PubMed, Web of Science and PsychINFO databases were searched for literature pertaining to the development and acquisition of pacing behaviour. The following search strategy was used:

1) Sport [Mesh]

AND

2) Pacing OR Pacing behaviour OR Pacing strategy OR Race analysis

AND

3) Develop OR Learn OR Experience OR Novice OR Age OR Children OR Adolescence OR Junior OR Youth OR Boy OR Girl.

Included articles had to be written in English, published between January 1995 and January 2022 and peer-reviewed. The option for human participants was selected for PubMed and PsychINFO, in Web of Science (AND Human*) was added to line 1 of the search strategy. Following the literature on skill learning and development (19, 20), the included articles had to report on one or a combination of the following topics: the pacing behaviour of individuals younger than 18 years of age or the pacing behaviour of individuals repeatedly performing the same (or a very similar) exercise task or the effect of a period of practice on pacing behaviour (e.g. through a training program) or the comparison of pacing behaviour between groups with different levels of experience (i.e. novices vs. experts). To provide an extensive overview of the available literature, no selection was made regarding the type of exercise task (e.g. endurance, team-sport, resistance).

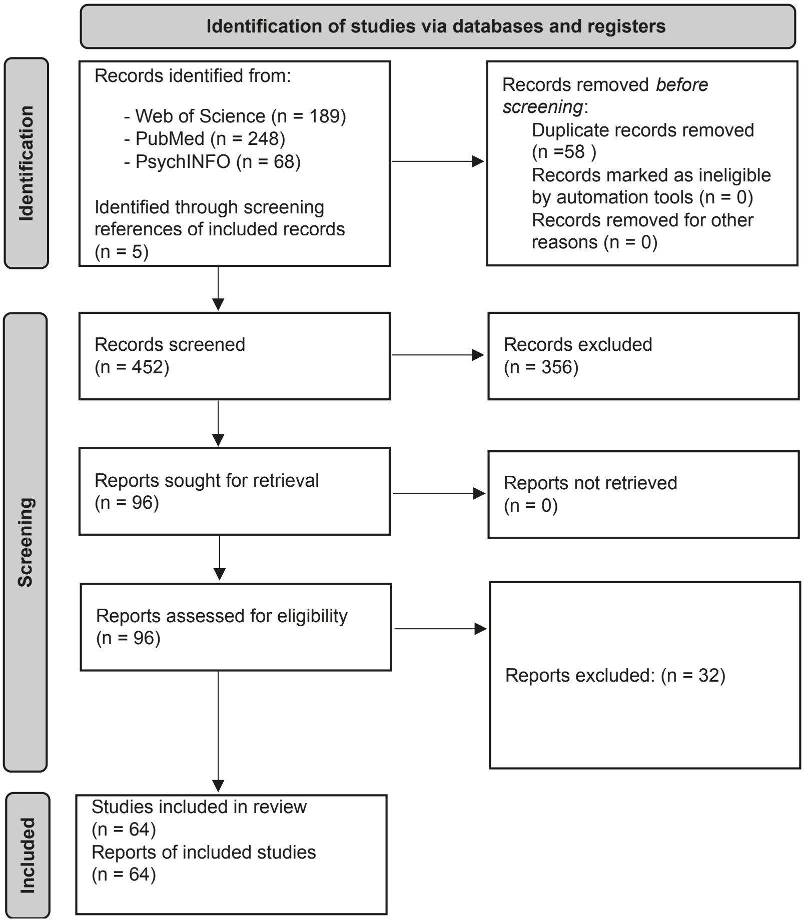

Figure 1. Flow diagram of the literature selection process with included articles (n) after each stage.

Included articles had to quantify pacing behaviour by expressing a measure of effort (e.g. energy store depletion, power output, velocity) over a subset of the full exercise task (e.g. percentage of task completed). The initial search resulted in 505 articles (248 PubMed, 189 Web of Science, 68 PsychINFO). After eliminating duplicates, 447 articles remained. Screening the titles and abstracts, followed by screening the full text, lead to an exclusion of 388 articles, leaving 59 included articles (Figure 1). To these included articles, the authors added five articles, which did not occur in the literature search, but instead were found through the reading of the introduction and discussion sections of included articles (specifically marked in Table 1). These five articles met the inclusion criteria and were deemed to yield valuable information regarding the aim of the current study.

3. Results

3.1 The development of pacing behaviour in individuals under 18 years of age.

The articles included in this evaluation comprise a broad selection of exercise tasks and research designs (Table 1). The majority of the articles investigated tasks related to endurance sports, encompassing cycling (n = 19, distance: 1500m-20 km), running (n = 16, distance: 400m - 42.2 km), rowing (n = 6, distance: 1-2 km), swimming (n = 7, distance: 50-1500 m), speed skating (n = 4, distance: 1500-m) cross-country skiing (n = 3, distance: 4.3 – 90 km) or another endurance sport (n = 4). Team sports were investigated in two articles. The other studies investigated individuals performing an exercise circuit (n = 2), a repeated jumping (n = 1), sprinting (n = 1) or resistance (n = 1) task. In total, 41 studies investigated pacing behaviour in a controlled laboratory or field setting, whereas 21 articles investigated the pacing behaviour of athletes during competition. Two studies combined both study designs.

3.2 The development of pacing behaviour in individuals under 18 years of age.

A total of 33 included articles reported on the pacing behaviour of individuals under the age of 18 years, distributed between the age ranges of 5-10 (n=1), 10-14 (n=4) and 14-18 (n=28) years old (Table 1). Six studies compared the pacing behaviour of children and adolescents of differing ages, four of which used a cross-sectional design (46-49) and two using a longitudinal design (50, 51).

When cross-sectionally comparing the pacing behaviour of schoolchildren performing a 3-4 minute running task, the groups with an age averaging 5.6 and 8.7 years old exhibited an all-out pacing behaviour, characterized by a fast start and a gradual decline in speed until the end of the task (47). Conversely, groups of older children (averaging 11.8 and 14.0 years old) exhibited a parabolic distribution of effort, with a fast start and an end-spurt finish but a relatively slower middle section. This parabolic distribution has also been reported by two other articles studying the pacing behaviour of children between 10 and 13 years old, performing similar exercise tasks (52, 53). Four included studies compared the pacing behaviour of adolescents and adults, performing middle-distance tasks of running (54, 55), swimming (48), and cross-country skiing (56), reporting that adolescents exhibited a parabolic distribution of effort, whereas adults exhibited a more even pace. Indeed, when long-track speed skaters competing in a 1500-m race were longitudinally measured at 15, 17 and 19 years of age, the skaters exhibited a development of pacing behaviour towards that of adult skaters, characterized by a relative slower start and faster middle section (51).

Parallel to development in the distribution of effort itself, the influence of environmental factors on pacing behaviour seems to develop with age. The presence of other exercisers was reported to have a detrimental effect on exercise performance in younger children (10.3±0.7 years old) (53), no effect in adolescents (15.8±1.0 years old) (57) and resulted in an improvement in performance in adults (58). An alteration of pacing behaviour was reported to be the cause of the change in exercise performance (53, 58). Further corroboration was provided by two studies investigating short-track speed skating, a head-to-head type of competition featuring a highly interactive environment (46, 50). Throughout adolescence, short-track speed skaters seemed to develop both their positioning during the race as well as their capability to preserve energy during the initial phase of the race (46, 50). These adaptations indicate an improved integration of environmental factors in the athletes' pacing behaviour and are linked to a higher velocity during the critical final laps resulting in improved race performance (59).

3.3 The effect of experience on pacing behaviour.

The effect of prior experience on pacing behaviour has been investigated in thirteen included articles (Table 1) by means of comparing the pacing behaviour of adult exercises of differing levels of experience performing a predetermined exercise task. More experienced exercisers are not only better able to exercise at a prescribed pace (60), but also exhibit a pacing behaviour more suited to the needs of the specific exercise task. Generally, this is expressed as an all-out behaviour during short tasks (61) (<120 seconds), or a more even pacing behaviour during longer exercise tasks (62-64) (>120 seconds). Experienced individuals are also able to successfully incorporate environmental factors (e.g. terrain) into their pacing behaviour, aiding their performance (65, 66). Novice exercisers seem to prefer information regarding task completion (distance) and mainly report dissociative, outward monitoring thoughts (67, 68). Experienced exercisers, on the other hand, prefer information concerning task performance (speed) and primary report associative, task-focused thoughts (concerning power and cadence) (67, 68).

A total of seven articles reported on the acquisition of pacing behaviour through repeatedly exposing adult novices to the same exercise task. Two of these studies incorporated a training program between repeated bouts of exercise (69, 70). All seven studies involved exercise tasks with a duration longer than 120 seconds (minimum: 189.4 seconds (71), maximum: 2708.35 seconds (72)), and all reported a change in pacing behaviour with repeated task exposure. Within three studies, this was expressed by a decrease in effort during the first section of the task and an increase in the final section (71-73). Four studies reported an increase in effort during the initial and middle sections and a decrease during the final section (67, 69, 70, 74). Two studies reported that the adaptation of power output distribution during consecutive tasks was paralleled by the anaerobic energy expenditure and blood lactate levels, indicating a change in the management of energy reserves over the bout duration (70, 71). Lastly, the manipulation of the effect of gaining experience on pacing behaviour by interventions such as withholding information on task duration (75), providing only a half familiarisation (72), or withholding duration feedback or providing false feedback during the trial (5% improvement compared to actual performance) (76), lead to a maladaptation of pacing behaviour and a decrease in exercise performance.

4. Discussion

This review provides the first consolidated evidence that pacing behaviour in exercisers up to 18 years old develops with age. This demonstrates that pacing behaviour development starts in childhood and continues through adolescence. All included studies examining the effect of repeated task exposure on pacing behaviour in adults (n = 7) support the hypothesis that pacing behaviour is acquired through the gathering of exercise task experience, similar to other skilled behaviour. Manipulation of the skill acquisition process by interfering with the gathering of task experience results in a maladaptation of pacing behaviour (n = 3). It is, therefore, apparent that pacing is similar to other skills, in so far that it has a developmental pathway and appears not to reach maturity until adulthood, by which time there is still capacity to further improve through task experience.

4.1 Pacing behaviour development

The characteristics of pacing behaviour among young children (<9 years old) tend to manifest in inconsistent approaches to the task demands, encompassing both the task characteristics (e.g. workload) and the environment (e.g. other competitors). An example is the adoption of an all-out approach of maximal effort until fatigue in an exercise task lasting over 120 seconds, in which an even distribution is known to lead to better performance (77, 78). However, with age, a development towards a parabolic distribution of effort is evident in tasks with similar demands. This parabolic pacing behaviour includes a conservation of effort at the start of the exercise, reflecting an increased involvement of goal-directed decision-making regarding effort distribution. The development of pacing behaviour continues during adolescence, with the manifestation of pacing behaviour which increasingly fits the task demands. As part of this development, exercisers are not only able to pace their efforts during an isolated time trial event, but also in complex situations in which environmental factors (e.g. opponents) need to be taken into consideration (79, 80).

Given that pacing behaviour is similar to other skilled behaviour, it is likely that the origin of the development of pacing behaviour can be traced to primary features of childhood and adolescence: physical maturation and cognitive development. Indeed, various physical maturity milestones, such as the growth spurt and the trajectory of muscle mass development (26-29), seem to match the roadmap of pacing behaviour development, as described above. Unfortunately, only four included studies reported on the pacing behaviour of children within the age-range of the growth spurt (10-14 years old) and none of these articles reported on the relationship between a measure for physical maturation and pacing behaviour (47, 49, 52, 53). With regard to cognitive development, Micklewright *et al.* (47) reported the same development of pacing behaviour could be found based on children's ages as based on children's scores for cognition, as measured by Piaget's stages of intellectual development. It could therefore be proposed that pacing behaviour development is linked not specifically to age, but rather to the rate of cognitive development. Comparing the stages of cognitive development proposed by Piaget to the roadmap of pacing behaviour development during childhood and adolescence strengthens this hypothesis. Piaget's third stage (i.e. concrete operational stage) spans the ages 7 to 11. During this stage, children gradually gain the capability to concentrate on more than one aspect of a problem simultaneously and mentally represent actions or events based on previous experience (24). These mental capabilities could provide children with the aptitude to recall and appreciate that making decisions regarding effort distribution before and during exercise (i.e. a conservation of effort during the opening phase of the exercise), could improve their overall task performance. However, children at this stage are limited to pondering situations that are real or based on their own experiences (24). This could explain why the presence of opponents has a detrimental effect on the pacing behaviour of children (53), as the presence of opponents likely provides a stronger stimulant than the abstract notions of hypothetical future performance improvement, afforded by adopting a slower pace. Piaget's fourth stage of cognitive development (i.e. formal operational stage) ranges from 11 to 20 years old (24). During this stage, individuals gain the capability of considering ideas that are not based on reality, observable objects or experience-based thoughts (24). Additionally, individuals acquire the aptitude to systematically generate and consider multiple possible solutions to a problem (24). These mental capabilities provide a better grasp on the hypothetical future rewards from pacing one's efforts and likely underpin the continuation of the development of pacing behaviour throughout adolescence. Furthermore, these cognitive capabilities facilitate the adaptable pacing behaviour needed in complex competitive environments and therefore enable the integration of environmental factors (e.g. opponents) into the development of pacing behaviour, which occurs during adolescence.

4.2 The acquisition of the skill pacing

The current study is the first to investigate the available literature for the effect of experience on pacing behaviour. From the consolidated literature, it can be concluded that there is an evident effect of gathering experience on pacing behaviour across exercise types and durations. More experienced exercisers are not only better at adopting a prescribed pace but also exhibit a pacing behaviour that better suits the task demands and competitive environment. All included studies featuring repeated tasks revealed that with experience, novice exercisers adapt their pacing behaviour. Although the direction of change seemed to ostensibly differ between studies, collectively, all studies reported a change towards a more even distribution of effort as experience increased (Figure 2). Within skill learning literature, the behaviour of novices is characterized by large errors and relatively large corrections for these errors (25). As the learning process proceeds, individuals learn to associate between the task stimuli, their elected actions and the resulting task performance (19, 25). Similarly, the proposed explanation for the effect of experience on pacing behaviour is a reduction of the mismatch between the exerciser's individualized performance capabilities and the task demands, encompassing both the task characteristics (e.g. workload) and the environment (e.g. terrain) (70-72, 74-76, 81). This mismatch results in the exerciser exerting too much effort (i.e. overestimation of the exerciser's performance capabilities or underestimation of the task demands) or not enough (i.e. underestimation of the exerciser's performance capabilities or overestimation of the task demands). As the pacing process is continuous, repeating mismatches between stimuli and actions can result in an undulating pace over the course of a task. Unnecessary accelerations and decelerations are detrimental to performance, as even minor fluctuations in velocity result in a greater overall energy cost (77). However, as the task is repeated, exercisers learn to associate the stimuli (e.g. task demands and afferent signals) and actions (i.e. continuing, increasing or decreasing the exerted effort) with the resulting task performance. This knowledge results in more informed decision-making, reducing the occurrence of inefficient adoptions of overly aggressive or conservative pace. Within tasks longer than 120 seconds, this results in a more even distribution of effort, which is linked to increased task performance (77, 78).

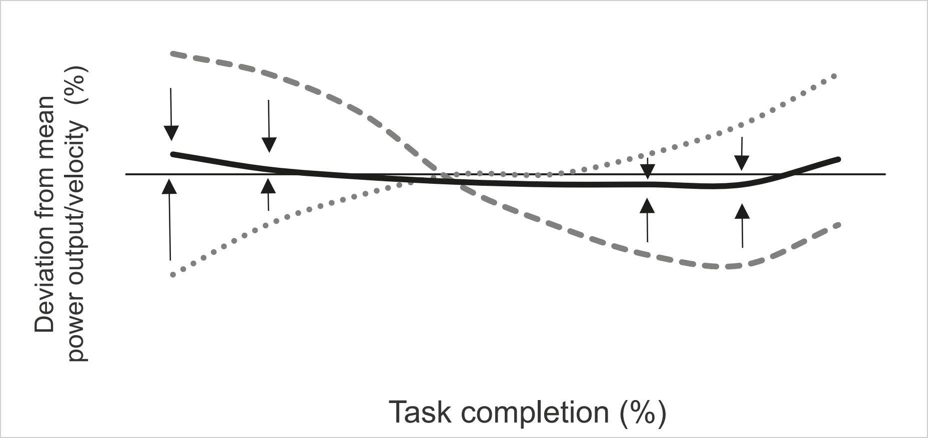

Figure 2. Example of repeated exercise task exposure affecting the pacing behaviour of novice adult exercisers. Grey dotted: exercisers initially exerting not enough effort, grey striped: exercisers initially exerting to much effort, black bold solid: more even pacing behaviour. Arrows: change with increased exercise task experience. The horizontal solid line represents the mean power output/velocity. This example is based on the collective results of included studies that reported on the change in pacing behaviour resulting from repeatedly exposing adult novices to the same exercise task (>120 seconds).

Furthermore, within skill acquisition literature, it is stated that as individuals gain more experience with a task, less attention is needed for the same level of task performance, allowing for secondary tasks to be performed simultaneously (19, 82). The possession of residual attention capacity could explain why more experienced exercisers are able to process and integrate environmental factors, such as the terrain and the behaviour of opponents. Additionally, skill acquisition literature states that the main goal for novices is to achieve a crude level of success in a task (19, 39). Indeed, as novices lack a reference point for the workload required for a specific exercise task, novice exercisers are thought to have the primary goal of finishing the exercise without lasting negative consequences (67, 70). To reach this goal, novice exercisers mainly acquire information regarding task completion (e.g. elapsed distance or time) (67) and concentrate on dissociating themselves from the afferent signals of fatigue (e.g. pain and discomfort) by means of outward thought (68). Although this might help novice exercisers complete the exercise task, it also hinders their capability to match their afferent signals to the task demands (83). Alternatively, experienced exercises have the knowledge that they are able to finish the task (without lasting negative consequences), which allows them to set the goal of realising the best possible task performance. Experienced exercisers therefore direct their thoughts towards and gather information about factors relating to their task performance (e.g. power, cadence and speed) (67, 68).

A point should be made, that as each individual's performance capabilities differ and the task demands remain constant, optimal pacing behaviour will slightly differ between individuals (84). This variation between individuals is likely the cause of the variation of pacing behaviour between athletes at the elite level (85, 86). The acquisition process, as described above, results in a better match of an individuals' performance capabilities to the task demands, facilitating a more appropriate pacing behaviour and improving task performance. It is through repeating and optimizing these acquisition processes that the match between individual performance capacities and task demand is perfected, and an individual's pacing behaviour is optimized.

4.3 Practical applications

It is assumed that pacing is evident in almost all non-reflex physical activity and that it is fundamental to the successful completion of physical tasks (1). Given this, adequate pacing behaviour development could provide a feeling of competency, allowing for more task enjoyment and inhibition of drop-out from physical activity, with all the associated health benefits (1, 87). Although in the current study, skill development and acquisition have been treated as separate processes, it is evident that gathering experience is a key factor in skill development (24). From this stems the notion that children and adolescents should be provided with the opportunity to practice exercise tasks to optimally facilitate skill development (24). Four out of five studies included in this review that investigated children and adolescents during repeated tasks reported a change in pacing behaviour and/or an improvement of exercise task performance (53, 88-90). When asked to estimate the completion time of a 2-km cycling time trial before starting the trial, novice adolescent exercisers reported a significant ($p<0.05$) difference between the expected (453.00 ± 249.18 seconds) and actual (240.50 ± 27.37 seconds) finish time during the first trial (57). However, the gap between the expected finish time and the actual finishing time decreased by 66.2% after the first trial, indicating a better matching of performance capabilities and task demands as task experience increased. These findings emphasize the importance of providing children and adolescents with the opportunity to gather exercise experience in order to develop their pacing behaviour over time. However, it is important to acknowledge that even with ample practice, variation in physical maturity and cognitive development will constitute some children to be able to adequately distribute their efforts at a relatively young age, whereas others might not exhibit this behaviour until they are much older. Coaches and parents are therefore advised to monitor the level of pacing behaviour development and gradually incorporate increasingly challenging pacing exercises during the course of childhood and adolescence in order to support the development of pacing behaviour.

To facilitate and optimize the pacing skill acquisition, lessons from skill acquisition literature suggest that exercisers should start with establishing a stable pacing behaviour (91, 92). It is suggested that in novice adults a relatively stable pacing behaviour occurs after three or four sessions of repeated task exposure (70, 72, 93). However, this number could increase as variation in task demands increases (e.g. a highly interactive competition environment). After establishing a stable pacing behaviour, intervention-induced variability could provide exercisers with opportunities to test variants of their established pacing behaviour, enlarging their familiarity with the association between incoming stimulants, decisions made and the resulting task performance (25, 94). This could lead to the discovery of a more fitting pacing behaviour for the specific exercise task. In addition, variable practice could lead to a greater generalisation and flexibility of the exercisers' pacing behaviour, allowing them to respond better to novel situations (e.g. the behaviour of competitors) (91). Lastly, the provision of augmented feedback could also be used to adapt the difficulty of the task in order to provide an adequate challenge and optimize learning (92). When practising the same task, novice exercisers might be helped by providing frequent and immediate feedback, whereas experienced exercisers might be challenged by the decrease, delay, or removal of feedback.

4.4 Future directions

Although the match between milestones in pacing behaviour development and the changes in physical maturation and cognitive development form a logical framework, more (longitudinal) studies are needed to deepen the knowledge of the link between age, physical maturation, cognitive development and pacing behaviour development. Considering the relevant links between cognitive development and pacing behaviour development, the next step in research could be to dive deeper into which specific sections of cognitive functioning would underlie the development of pacing behaviour. Elferink-Gemser and Hettinga (18) previously proposed a model in which the pacing process mirrors the self-regulatory process and suggested that improvement in meta-cognitive functions could be underpinning the development of pacing behaviour within childhood and adolescence (18). Indeed, meta-cognition has been shown to be under development during childhood and adolescence (95, 96), positively related to exercise performance (97, 98) and can be measured by validated instruments (96, 99). Future experimental research could therefore be done to find whether the development of meta-cognitive functioning is indeed part of the underlying mechanism of pacing behaviour development. It is evident that experience plays a key part in pacing behaviour development. Unfortunately, this relationship is often oversimplified in literature, as researchers assume a strictly causal relationship between age and experience. By uncoupling experience and age, future research could further unravel the intricate role of experience within pacing behaviour development. Furthermore, it has been proposed that acquiring the skill to pace an exercise task is facilitated by the acquisition of other skills, including accurately perceiving time (100), inhibiting distracting stimuli (101), as well as planning and evaluating (18, 102). Investigating the relationship between these other skills and pacing could provide a better understanding of what it takes to acquire this complex psychophysiological skill. Lastly, in the current review, the acquisition of pacing is most notably analysed by observing the effect of providing or manipulating experience on pacing behaviour. However, within the literature, definitions of skill acquisition commonly include the notion that learning has a relatively permanent effect on behaviour (19, 25). To test this, experimental designs to test learning include retention tests. Within the current review, no studies were found that measured the retention of the skill after a period without practice. To further explore the effect of experience on pacing behaviour, future research designs should consider including retention tests.

5. Conclusion

The current review aimed to investigate the development of pacing behaviour during childhood and adolescence as well as the acquisition of the skill through experience. This was achieved by assembling and analysing the (sport) scientific literature discussing the effect of age (up to 18 years old) and gathered experience on pacing behaviour. The findings of this study demonstrated the first consolidated evidence that children display an initial development of decision-making regarding effort distribution from around 10 years old, a development that continues in adolescence. Based on shared milestones, a case can be made that pacing behaviour development is underpinned by an interconnected relation of physical maturation, cognitive development and gathered experience. The skill to adequately pace exercise tasks could provide children with an increased sense of competence and enjoyment in physical activity and exercise, emphasising the importance of monitoring and practising pacing exercise tasks during childhood and adolescence. Task repetition results in an adaptation of pacing behaviour towards the task demands, including task characteristics (e.g. workload) and the environment (e.g. terrain). These changes can be explained by knowledge from skill acquisition literature: pacing behaviour is acquired because with experience i) the match between stimuli, actions and task results improves, ii) attentional capacity is freed for secondary tasks, iii) the task goal switches from task completion to improved task performance. The resemblance between the development and acquisition of pacing to the same processes in other skills invites the practical application of established concepts in skill acquisition and development literature (e.g. intervention-induced variability and augmented feedback) to the field of pacing research. This integration provides the field with exciting future research questions as well as practical applications in physical education, healthcare, and sports.

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Table 1. Overview of the included articles (n = 64), categorized by sport and distance.

Study	Sport	Distance	No. of subjects (sex)	Age* (mean ± SD)
Foster et al (103)	Cycling	1500-m	9 (7 male)	
Corbett et al (71)	Cycling	2-km	9 (9 male)	
Menting et al (57)	Cycling	2-km	10 (7 male)	15.8 ± 1.0
Konings et al (58)	Cycling	4-km	12 (?)	
Ansley et al (104)[a]	Cycling	4-km	7 (7 male)	
Williams et al (73)	Cycling	4-km	22 (22 male)	
Mauger et al (75)	Cycling	4-km	18 (18 male)	
Mauger et al (105)	Cycling	4-km & 6-km	16 (16 male)	
Jones et al (106)	Cycling	16.1-km	20 (20 male)	
Jeukendrup et al (107)	Cycling	16-km	12 (12 male)	
Boya et al (67)	Cycling	16.1-km	20 (20 male)	
Whitehead et al (68)	Cycling	16.1-km	20 (20 male)	
Martin et al (101)[a]	Cycling	20-min (14.8 ± 0.6 km) (11.8 ± 0.6 km)	11 (11 male) 9 (9 male)	
Marquet et al (108)	Cycling	20-km	21 (21 male)	
Micklewright et al (76)	Cycling	20-km	29 (29 male)	
Hibbert et al (72)	Cycling	20-km	30 (12 male)	
Schmit et al (109)	Cycling	20-km	22 (22 male)	
Micklewright et al (110)	Cycling Running	5-km 100-km	20 (15 male) 34 (32 male)	

Repeated task exposure.	Level of experience.
Three trials, a minimum of 48 hours apart	Experienced cyclists & speed-skaters (training 10 hours/week)
Three trials within two week period.	Novices
Four trials, within six weeks.	Novices
Four trials, 7 days apart.	Experienced cyclists (≥2 years)
Three consecutive trials, 17 minutes apart.	Experienced cyclists (training 400-800 km/week)
Two consecutive trials, 17 minutes apart.	Novices
Four consecutive trials, 17 minutes apart.	Experienced cyclists (training 11.5 ± 3.5 hours/week, 1 competition per week)
Four consecutive trials, 17 minutes apart.	Experienced cyclists (training 12 ± 3 hours/week, 1 competition per week)
Three trials within three weeks (two-seven days apart)	Experienced cyclists (>1 year)
Two trials, 7-14 days apart.	Experienced cyclists (training 3x/week, >1 competition per year)
Two trials within a six to eleven-day period.	● Experienced cyclists (14.1±13 years, training 8.5±2.1 hour/week) ● Novices.
	● Experienced cyclists (>2 years) ● Novices.
	● More experienced cyclists (>5 years) ● Less experienced cyclists (~2 years).
Two trials separated by a 1-week training program.	Experienced cyclists (≥3 years, training ≥ 12 hours/week)
Three trials, three-seven days apart.	Experienced cyclists (>2 years, 6.1 ± 5.2 years)
Seven trials, minimum of 48 hours apart.	Novices
Two trials, 11 ± 4 days apart.	Experienced triathletes (≥ 3 years, training 7 sessions/week)
	● Novice ● Experienced runners (5.6 ± 8.9 ultramarathons in past 2 years, training 61.4 ± 23.0 km/week)

Table 1. (Continued)

Study	Sport	Distance	No. of subjects (sex)	Age* (mean ± SD)
Foster et al (70)	A: Cycling B: Rowing C: Rowing D: Cycling	A: 3-km B: 2-km C: 2-km D: 10-km	?	
Cerasola et al (111)	Rowing	1000-m	96 (48 male)	17-18
Filipas et al (112)	Rowing	1500-m	18 (11 male)	11 ± 1.06
Kennedy & Bell (69)	Rowing	2-km	38 (19 male)	
Dimakopoulou et al (113)	Rowing	2-km	15 (15 male)	15.37 ± 1.34
Schabort et al (89)[a]	Rowing	2-km	8 (8 male)	16.0 ± 0.7
Hanon & Gajer (61)	Running	400m	30 (15 female	
Blasco-Lafarga et al (55)	Running	600-m & 2x4x200-m	9 (9 male) 10 (10 male)	17.00 ± 0.66 25.29 ± 4.32
Micklewright et al (47)	Running	450-m 600-m 750-m 900-m	26 (15 male) 29 (15 male) 27 (14 male) 24 (16 male)	5.6 ± 0.5 8.7 ± 0.5 11.8 ± 0.4 14.0 ± 0.0
Chinnasamy et al (52)	Running	750-m	36 (19 male)	12.6 ± 0.5
Lambrick et al (53)	Running	800-m	13 (8 male)	10.3 ± 0.7 (male) 10.6 ± 0.5 (female)
Green et al (60)	Running	3x 800-m	12 (?) 16 (?)	
Watkins et al (114)	Running	4-min (~1100m)	10 (5 male)	
Diaz et al (54)	Running	3-km	9 (9 male) 6 (6 male)	15.2 ± 0.7 24 ± 5.6
Deaner & Lowen (115)	Cross-country running	5-km	3948 (2032 male)	14-19
Stevens et al (116)	Running	5-km	17 (17 male)	

Repeated task exposure.	Level of experience.
A: six trials, two-three days apart. B: three trials, two-three days apart. C: Two sets of two trials, one month of training program apart. D: three trials.	Novices
	Experienced rowers (competing in Youth Olympic Games)
	Experienced rowers (1.5 ± 0.85 years of rowing experience)
Two trials, a 10-week training program (4 rowing, 2 strength sessions per week) apart.	A mixed group of experienced (> 1 year) and novice (< 1 year) rowers.
	Experienced rowers (training seven sessions per week)
Three trials, three days apart.	Novices
	● World-class ● National ● Regional
	● More experienced ● Less experienced
	Novice schoolchildren
Two trials	Novice schoolchildren
Four trials, on four separate days.	Novice schoolchildren
	● Collegiate ● Recreational
Five trials, at least 3 days apart.	Experienced (recreational level, training 4 ± 1 run sessions/week)
Two trials, one competitive season apart.	● More experienced (8.1 ± 2 years) ● Less experienced (18 ± 8 months).
	Experienced (competing in Virginia State Championships 5 km meet)
Two trials, 5-10 days apart.	Experienced

Table 1. (Continued)

Study	Sport	Distance	No. of subjects (sex)	Age* (mean ± SD)
Couto et al (117)	Running	10-km	19 (19 male)	15 ± 2
Knechtle et al (118)	Running	42.2-km	1 (1 male)	15.3
Santos-Lozano et al (63)	Running	42.2-km	190228 (129912 male)	
Trubee et al (64)	Running	42.2-km	32121 (20053 male)	
Deaner et al (62)	Running	42.2-km	2929 (1676 male)	
Morais et al (119)	Swimming	50-m	86 (86 male)	15-18
Dormehl & Osborough (49)	Swimming	100-m & 200-m	112 (56 male)	14.44 ± 0.69 16.98 ± 0.84
Skorski et al (90)	Swimming	200-m & 400-m & 800-m	16 (9 male)	16.9 ± 2.1
Skorski et al (120)	Swimming	400-m	15 (10 male)	18 ± 2 (14–23)
Turner et al (121)	Swimming	7 x 200-m incremental test	8 (8 male)	15 ± 1
Scruton et al (122)[a]	Swimming	7 x 200-m incremental test	15 (?)	15 ± 1.5
McGibbon et al (48)	Swimming	1500m	89 (89 male) 102 (102 male) 70 (70 male) 67 (67 male)	< 17 18-19 20-21 22 <
Barbosa et al (123)	Triathlon	Sprint Olympic	5902 (3196 male) 3314 (2225 male)	17 ± 2 21 ± 2
Wiersma et al (51)	Long-track speed skating	1500-m	104 (104 male)	15.25 ± 0.55 17.25 ± 0.55 19.25 ± 0.55

Repeated task exposure.	Level of experience.
	Experienced (36 months (12–48 months))
	Experienced
	● More experienced (professionals) ● Less experienced (amateurs)
	● Experienced (elite) ● Less experienced (non-elite)
	● More experienced runners ● Less experienced runners (total number of races, total number of marathons, personal bests for the 5K and marathon, and earliest year with a recorded race).
	Experienced (European Junior Championships)
	Experienced (competing at international schools swimming championships, 49.6- 96.8% of the junior world record).
Two trials, 7 days apart.	Regional to national level (training 34.7 ± 5.6 km/week)
	Competing at national level or higher (≥4 years of training)
Four trials, one week, nine weeks and 20 weeks apart.	Competing at national level (> 6 years of training)
Two trials, within three-four days.	Regional level (26-33 km/week)
	Experienced (top 100 of FINA world rankings)
	Experienced (World Triathlon Series)
Five competitive seasons. (three measurement points)	Experienced (8-20 races at the start of the study)
	● More experienced ● Less experienced (1500-m races completed).

Table 1. (Continued)

Study	Sport	Distance	No. of subjects (sex)	Age* (mean ± SD)
Stoter et al (124)	Long-track speed skating	1500-m	120 (56 male)	17.6 ± 1.1
Menting et al (46)	Short-track speed skating	1500-m	224 (72 male) 1256 (665 male) 1687 (1132 male) 6556 (2691 male)	< 17 < 19 < 21 senior (> 21)
Menting et al (50)	Short-track speed skating	1500-m	140 (140 male)	15.19 ± 0.26 16.11 ± 0.29 17.05 ± 0.29 18.03 ± 0.31 18.97 ± 0.31 19.56 ± 0.03
Sollie et al (56)	Cross-country skiing	4.3-km 13.1-km	11 (11 male) 8 (8 male)	14.4 ± 0.5 22.6 ± 4.3
Formenti et al (125)	Cross-country skiing	10-km	11 (11 male)	16.45 ± 1.67
Carlsson et al (66)	Cross-country skiing	90-km	9691 (8788 male)	
Alves et al (126)	Race walking	10-km & 20-km	29 (14 males)	
Sealey et al (127)	Outrigger canoeing	1-km	11 (0 male)	
Moss et al (65)	Cross-country Mountain biking	86-km	8182 (7178 male)	16.5-65+
Sampson et al (128)	Rugby league	24-min small sided games	16 (16 male)	14.9 ± 0.5
Johnston et al (129)	Rugby league	Tournament	28 (28 male)	16.6 ± 0.5
Christi et al (81)	Cricket	14 shuttle sprints	24 (24 male)	
Moss & Twist (130)	Handball	Repeated Shuttle-Sprint and Jump Ability test	8 (8 male)	16.1 ± 1.0

Repeated task exposure.	Level of experience.
To trials, at least one year apart (subgroup of 12 [7 male] skaters were included in longitudinal analyses)	Experienced (national and international level)
	Experienced (competing in junior and senior international competitions)
Six competitive seasons. (six measurement points)	Experienced (competing in the Junior World Championships)
	Experienced (national level)
	Regional and national (training 12-15 hours/week)
	● More experienced (>3 years) ● Less experienced (< 4 years).
	● More experienced (49-240 months) ● Less experienced (5-48 months).
Four trials within two weeks.	Experienced rowers (>2 years) (training 4-11 sessions/week)
	● More experienced ● Less experienced cyclists (previous races completed).
	Amateur level
	Amateur level
	● More experienced (early in batting line-up) ● Less experienced (late in batting line-up)
	National level

Table 1. (Continued)

Study	Sport	Distance	No. of subjects (sex)	Age* (mean ± SD)
Burdon et al (74)	Exercise circuit	Tasks 1-4: <15-min Tasks 5-6: < 2min	35 (17 male)	
Gross et al (131)	Alpine skiing	90-second box jump test	9 (9 male)	16.8 ± 1.3 (range 16–18)
Reid et al (132)[a]	Elbow flexion maximal voluntary contractions	12x 5 seconds	14 (0 male)	15.2 ± 2.1

a = included additional to the literature search. ● = comparison between groups of a different experience levels. * = Age only reported for studies investigating individuals younger than 18 years of age.

Repeated task exposure.	Level of experience.
Three trials, within 10 days with 24 hours separating each trial.	Novice
Two trials, a 8-day HIT block comprising of 10 sessions, apart.	Experienced (for an elite sports school)
	Novice

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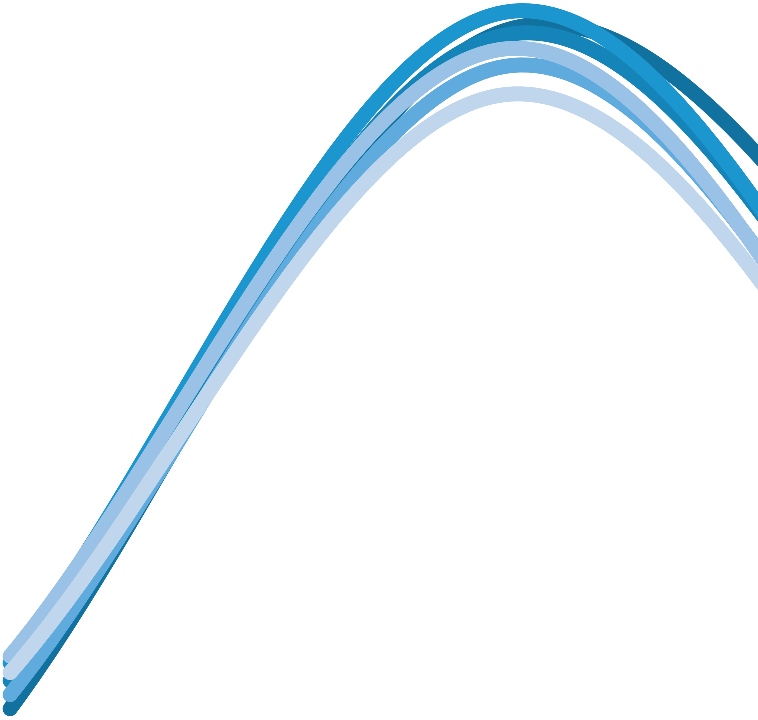

Chapter 6

Pacing behaviour development of short-track speed skaters: a longitudinal study

Adapted from:

Menting S.G.P., Huijgen, B. C., Konings, M. J., Hettinga, F., & Elferink-Gemser, M. T. Pacing Behavior Development of Youth Short-Track Speed Skaters: A Longitudinal Study. *Medicine & Science in Sports & Exercise. 2020;52(5):1099-1108.*

Abstract

Purpose: To analyse the development of pacing behaviour of athletes during adolescence, using a longitudinal design.

Methods: Lap times of male short-track speed skaters (140 skaters, 573 race performances) over two or more 1500-m races during Junior World Championships between 2010 and 2018, were analysed. Races were divided into four sections (laps 1-3, 4-7, 8-11 and 12-14). Using MLwiN ($p<0.05$), multilevel prediction models in which repeated measures (level-1) were nested within individual athletes (level-2), were used to analyse the effect of age (15-20), race type (fast, slow) and stage of competition (final, non-final) on absolute section times (AST) and relative section times (RST; percentage of total time spent in a section).

Results: Between the ages of 15 and 20, total race time decreased (-6.99s) and skaters reached lower AST in laps 8-11 (-2.33s) and 12-14 (-3.28s). The RST's of laps 1-3 (1.42%) and 4-7 (0.66%) increased and laps 8-11 (-0.53%) and 12-14 (-1.54%) decreased with age. Fast races were more evenly paced compared to slow races, with slow races having a predominantly slow first half and fast finish. Athletes in finals were faster (2.29s), specifically in laps 4-7 (0.85s) and laps 8-11 (0.84s).

Conclusion: Throughout adolescence, short-track speed skaters develop a more conservative pacing behaviour, reserving energy during the start of the race in order to achieve a higher velocity in the final section of the race and a decrease in total race time. Coaches should take into consideration that the pacing behaviour of young athletes develops during adolescence, prepare athletes for the differences in velocity distribution between race types and inform them on how to best distribute their efforts over the different stages of competition.

Keywords: pacing, development, head-to-head competition, performance analysis, adolescence, multilevel modelling

1. Introduction

The goal-directed distribution of energy over a predetermined exercise task (1), a process of decision-making regarding how and when to spend energy (2), has been defined as pacing. Pacing has proven to be an essential aspect of athletic performance, both in time-trial (3, 4) and head-to-head competition (5-7). The final outcome of an individuals' goal-directed distribution of energy over the race is termed pacing behaviour (2). A range of factors which influence pacing during an exercise task have been identified, including, amongst others: the duration of the event (8), the perceived level of exertion (9), and sport-specific demands (10). In addition, recent literature emphasizes the importance of the competitive environment in regard to pacing behaviour (2). Yet, little is known about how athletes acquire the skills to successfully pace in races, and there is little information on the development of pacing behaviour in young athletes (11).

Although the first signs of the formation of a pacing template appear during late childhood (~10-11 years old) (12, 13), recent research in both time-trial and head-to-head events established that throughout adolescence, the pacing behaviour of younger athletes further develops to ultimately resemble that of adults (14, 15). Menting *et al.* provided a theoretical basis behind this development (11). First, adolescence is characterised by both cognitive and physical changes associated with growth and maturation (16, 17). One key development is that of the pre-frontal cortex (18), which has been associated with self-regulatory learning and executive functioning (19), both of which are imperative for adequate pacing (20). Second, in most athlete development programs the amount and quality of training and competition increases profoundly during adolescence, providing young athletes with an increase in the quantity and quality of opportunities to gather exercise experience. Lastly, coaches could influence the pacing behaviour development by influencing the athlete's motivation, providing advice in goal setting, and providing high-quality learning environments in which the pacing behaviour can be optimally developed (11). Emphasising the importance of pacing development during adolescence, a longitudinal study in long-track speed skaters suggests that the development of pacing behaviour in developing athletes has a decisive influence on the performance level at the adult level (14). In addition, the capability to appropriately distribute energy in the long term also seems vital in safeguarding athlete well-being. If an athlete's capability to adequately distribute their energy is hampered, it could lead to them investing too much energy during an exercise task (for example during training and competition) (21, 22). If this happens repeatedly, it could lead to overtraining, burn-out and drop-out (23). This is especially true for developing athletes who, during adolescence, often endure high training loads for a long period of time in order to reach the elite level (24). In order to optimally guide developing athletes it seems to be essential to have a good understanding of both the general and sport-specific development of pacing behaviour during adolescence (11).

Much of the previous literature studying the effect of age and experience on pacing behaviour has been cross-sectional in design, comparing athletes from different age groups, experience or performance levels (13, 15, 25). A cross-sectional design can provide a good general image of skill development, given that the sample size is large enough. However, in order to properly study the development of a particular skill over a period of time, a longitudinal design is desirable. In longitudinal studies, the same variable(s) are observed repeatedly over a period of time, therefore allowing for exclusion of time-invariant unobserved individual differences (26). The only study to longitudinally analyse the development of pacing behaviour throughout adolescence was a study on long-track speed skaters performing 1500-m races (14). That study concluded that the absolute velocity of junior skaters increased in all sections of the race. However, when normalising the velocity distribution, it became apparent that with age, skaters developed a more conservative velocity profile. Accompanying the results in long-track speed skaters, a cross-sectional study analysing short-track speed skaters concluded that the pacing behaviour and positioning behaviour of skaters changes throughout different stages of adolescence (15). With each older age group (under 17, under 19 and under 21), the normalised velocity distribution and the positioning resembled that of adult skaters to a greater extent, with skaters adopting a more conservative pacing behaviour. Although there are small physiological differences between long- and short-track speed skating, there seems to be a consensus that the sport disciplines are rather comparable from a physiological perspective (27). However, where long-track speed skating is a classic time trial sport, short-track speed skating features head-to-head competition, involving highly interactive races with up to nine skaters (6). Therefore, athletes incorporate factors such as drafting and avoiding collisions in their pacing behaviour (6). Previous research showed that the importance of the competition, the number of competitors and the stage of the competition, all influence the performance and pacing behaviour of short-track speed skaters (28). Furthermore, due to the head-to-head nature of short-track speed skating, the winner is the athlete who crosses the finish line first, regardless of the time it takes the skater to complete the race. Consequently, there is a large variation in total race time compared to long-track speed skating, as short-track speed skaters are not concerned with setting a fast finishing time, but with crossing the finish line first. To account for this phenomenon, previous literature categorised races as either ‘slow’ or ‘fast’ (e.g. race type) and found a significant difference in pacing behaviour in adult athletes between the race types (6). Following the notion that the competitive environment has a critical role in pacing behaviour (29), a longitudinal study involving a highly interactive head-to-head sport, such as short-track speed skating, would enrich the current literature.

In order to gain a thorough understanding of the development of pacing behaviour in athletes during adolescence, an increase in longitudinal studies seems indispensable. Therefore, the current study investigated the development of pacing behaviour of short-track speed skaters, on a year by year basis, applying a longitudinal study design. It was hypothesised that the pacing behaviour of these athletes would develop throughout adolescence to show a more conservative profile, characterised by a relatively slower start and a faster finish. Additionally, the current study investigated the influence of the competitive environment (race type and stage of competition) on the pacing behaviour of younger athletes. Following the findings in adults (30), it is hypothesized that the pacing behaviour of younger skaters will be impacted by the behaviour of other competitors, facilitating either a slow or fast race. Additionally, based on findings in adults (6, 28), it is hypothesized that young skaters will exhibit a more conservative pacing behaviour as athletes progress through the stages of competition.

2. Methods

2.1. Participants and events

The finishing times, lap times and date of birth of all male competitors competing in the 1500-m (13.5 laps) at the yearly Junior World Championships between 2010 and 2018 were gathered. The lap times were recorded electronically with an accuracy of at least one-hundredths of a second, as is demanded by the International Skating Union. All competitive events followed a qualification structure in which skaters qualify directly for the next round by finishing first or second. Additionally, participants could qualify indirectly by setting the fastest finishing time of a specific qualification round or through advance by jury decision. All data were publicly available through the International Skating Union website (http://www.sportresult.com/federations/ISU/ShortTrack/) therefore, no written consent was asked from the participants. The study was approved by the local ethical committee and is in accordance with the Declaration of Helsinki.

A total of 1487 race performances were collected. The occurrence of a fall or disqualification could affect pacing behaviour. For this reason, races including disqualified skaters were excluded, as were race data of skaters who had fallen or had missing data (43.5% of total race performances collected). These exclusion criteria are in line with previous literature (6). The age of a skater was calculated by taking the date of the competition and subtracting the date of birth. The variable of age was converted to a categorical variable in order to show differences between skaters of specific ages. For example: a 16-year old skater was defined as a skater within the age range 15.50 – 16.49 years. To correct for outliers in age, the decision was made to exclude race performances of skaters who were not between 14.5 and 20.5 years old (0.6% of total race performances collected). Previous studies established that the number of competitors and the stage of the competition significantly influenced the pacing behaviour and performance of elite short-track speed skaters (28). Hence, data from races with more than seven or less than five skaters were excluded (1.3% of total race performances collected) and data was split in finals (quarter-finals, semi-finals and finals) and non-finals (heats and preliminaries). To account for race type, a race was classified as ‘fast’ or ‘slow’ when the winner of a particular race was faster or slower than the average completion time of all race winners. In order to properly study longitudinal development, only data from skaters who performed in at least two different age groups, during Junior World Championships, in various seasons was included. Therefore, all data from skaters who performed in just one age group (i.e., during one Junior World

Championship) was excluded (16.1%). It should be noted that due to the qualifying nature of the Junior World Championships, included skaters can have multiple race performances in one age category. After exclusions, 573 race performances (38.6%) from 140 different skaters were included for analysis. Of the included skaters, 53.6% had data within two, 30.7% in three, 13.6% in four and 2.1% in five different age groups. Table 1 shows the mean age of included skaters and the number of included race performances, per age category.

Table 1. Number of included performances per age category.

		Number of race performances				
Age category	**Age (mean ± SD)**	**2**	**3**	**4**	**5**	**Total**
15	15.19 ± 0.26	11	9	9	3	32
16	16.11 ± 0.29	24	29	16	3	72
17	17.05 ± 0.29	35	48	28	5	116
18	18.03 ± 0.31	77	48	26	3	154
19	18.97 ± 0.31	69	58	23	4	154
20	19.56 ± 0.03	20	14	11	0	45
Total included race performances		236	206	113	18	573

2.2. Study design

The 1500-m race was split into four sections: laps one to three, four to seven, eight to eleven and laps twelve to fourteen. With lap one effectively being a half lap, this adds up to a total of 13.5 laps. In order to analyse how skaters distribute their velocity over a race, total race time and absolute section time (AST) (i.e. time to complete a section) over the four sections of the race were taken as outcome measures. Furthermore, in order to analyse pacing behaviour independent of possible differences in total race time between skaters, each AST was converted into relative section time (RST), which presents the percentage of total race time spent in one section. A comparative approach has been taken in other longitudinal and cross-sectional studies investigating pacing behaviour throughout adolescence (14, 15).

2.3. Data analyses

Due to the qualifying nature of the short-track speed skating competition, there is considerable variability in the number of measurements among skaters. Hence, traditional repeated measurement analyses of variance was not possible. Longitudinal changes in pacing behaviour were investigated using multilevel modelling program MlwiN (31). Multilevel modelling was developed to analyse nested data, allowing for longitudinal analyses of datasets which include a varying number of measurements between participants as well as a variety in temporal spacing between the different measurements. In the current study, hierarchy was defined as repeated measures (level 1) nested within the individual skaters (level 2). Dependent variables in these models were total race time, absolute section times

(AST1-3, AST4-7, AST8-11, and AST12-14) and relative section times (RST1-3, RST4-7, RST8-11, and RST12-14) for the four race sections. The predictive variables included were: age category (15, 16, 17, 18, 19 and 20), race type (fast, slow) and stage of competition (final, non-final). The goodness of fit for each model was evaluated using the − 2*Log Likelihood. Differences in outcome measures between age categories were assessed by comparing the mean of the coefficient and its standard error (SE) (coefficient/SE >1.96 = significant).

3. Results

The models created for the outcome measures can be found in Table 2 (AST and total race time) and Table 3 (RST). Each model consists of a constant value and a coefficient for the appropriate predictive variable. As all predictive variables (e.g. age, race type and stage of competition) in the model are categorical of nature, the coefficient will represent the difference between one chosen sample category and the other possible categories. The age category 15 was used as a sample category for age. In the case of race type, races categorised as 'slow' are the sample category. For stage of competition, 'finals' are the sample category. This effectively means that if a race is categorised as 'slow', 'final' or '15', the coefficient for race type, stage of competition and age, will be multiplied by 0. Conversely, if a race is categorised as 'fast', 'non-final' and age category 16 through 20, the various coefficients will be included in the models' prediction. This way, the models are used to make predictions for outcome measures for the different combinations of predictive variables: age, race type and stage of competition. For example:

The AST1-3 for a 17 year old, in a fast non-finale was predicted as:
AST1-3 = (constant) + (17) + (fast) + (non-final)
AST1-3 = 38.47 + 0.59 -5.98 + 0.25
AST1-3 = 33.35

The RST12-14 for a 15 year old, in a slow non-final was predicted as:
RST12-14 = (constant) + (15) + (slow) + (non-final)
RST12-14 = 20.49 + 0 + 0 + -0.16
RST12-14 = 20.33

Following the principles of the models, the coefficients also indicated the effect that a variable (age, race type, stage of competition) has on the outcome measure (AST, RST and total race time). For example, in the model for total race time, the coefficient for race type is -10.44. This means that the model predicts that fast races have a total race time which is 10.44s less compared to slow races.

As AST and total race time are indicated in seconds, a lower outcome of these variables represents a higher velocity. The models created for AST's and total race time can be found in Table 2. Visual representations of the predictions of these models can be found in Figure

1. The RST is reported in percentages of the total race spent in a specific section. Therefore, a lower RST indicates that a skater was relatively faster and therefore distributed more effort in that section of the race. The predictions made by the models for the RST's can be found in Table 3, as well as visually presented in Figure 2. In order to visualize the pacing behaviour of skaters over a full race, the predictions of the four models for the AST's, and the four models for the RST's, are presented alongside each other in Figure 3.

Table 2. Multi-level model for the absolute section times (AST) presented for each race section and total race time. * = significant difference from sample category (p <0.05).

Race phase				Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
Laps 1-3	Fixed effects	Constant		38.49	0.66	<0.001	37.16	39.81
		Fast*		-5.98	0.29	<0.001	-6.56	-5.39
		Non-final		0.25	0.29	0.39	-0.34	0.84
			16	0.36	0.740	0.63	-1.12	1.84
			17	0.59	0.70	0.40	-0.80	1.98
			18	0.18	0.68	0.79	-1.17	1.54
			19	0.68	0.68	0.32	-0.68	2.04
			20	0.47	0.81	0.56	-1.16	2.10
	Random effects	level 1: season		11.80	0.79			
		level 2: individual		0.26	0.40			
		Deviance		3052.50				
		Deviance empty model		3397.16				
Laps 4-7	Fixed effects	Constant		47.30	0.52	<0.001	46.26	48.34
		Fast*		-5.01	0.23	<0.001	-5.47	-4.55
		Non-final*		0.85	0.23	<0.001	0.39	1.32
			16	-0.08	0.58	0.885	-1.25	1.08
			17	0.21	0.55	0.71	-0.89	1.30
			18	-0.49	0.53	0.35	-1.56	0.57
			19	-0.27	0.53	0.61	-1.34	0.79
			20	-0.86	0.64	0.18	-2.14	0.41
	Random effects	level 1: season		7.29	0.49			
		level 2: individual		0.15	0.24			
		Deviance		2775.80				
		Deviance empty model		3134.14				
Laps 8-11	Fixed effects	Constant		41.37	0.34	<0.001	40.69	42.05
		Fast		0.06	0.13	0.67	-0.21	0.33

Table 2. (Continued)

Race phase				Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
		Non-final*		0.84	0.13	<0.001	0.58	1.10
			16*	-1.37	0.34	<0.001	-2.06	-0.69
			17*	-1.61	0.33	<0.001	-2.26	-0.96
			18*	-2.05	0.33	<0.001	-2.71	-1.39
			19*	-2.32	0.33	<0.001	-2.98	-1.65
			20*	-2.33	0.41	<0.001	-3.16	-1.50
	Random effects	level 1: season		2.03	0.12			
		level 2: individual		2.43	0.36			
		Deviance		2272.71				
		Deviance empty model		2366.55				
Laps 12-14	Fixed effects	Constant		32.10	0.37	<0.001	31.37	32.84
		Fast*		0.84	0.14	<0.001	0.57	1.12
		Non-final		0.21	0.13	0.12	-0.06	0.47
			16*	-1.62	0.35	<0.001	-2.32	-0.93
			17*	-2.09	0.33	<0.001	-2.76	-1.43
			18*	-2.60	0.34	<0.001	-3.28	-1.92
			19*	-3.08	0.34	<0.001	-3.76	-2.40
			20*	-3.28	0.43	<0.001	-4.14	-2.43
	Random effects	level 1: season		2.07	0.14			
		level 2: individual		4.40	0.60			
		Deviance		2352.87				
		Deviance empty model		2470.69				
Total race time	Fixed effects	Constant		160.33	1.20	<0.001	157.92	162.74
		Fast*		-10.44	0.51	<0.001	-11.46	-9.42
		Non-final*		2.29	0.50	<0.001	1.29	3.29
			16*	-3.70	1.30	<0.01	-6.29	-1.11
			17*	-3.62	1.22	<0.01	-6.07	-1.18
			18*	-5.54	1.22	<0.001	-7.98	-3.11
			19*	-5.76	1.22	<0.001	-8.20	-3.32
			20*	-6.99	1.51	<0.001	-10.00	-3.98
	Random effects	level 1: season		31.49	2.13			
		level 2: individual		10.86	2.32			
		Deviance		3722.28				
		Deviance empty model		4072.14				

Table 3. Multi-level model for the relative section times (RST) presented for each race section. * = significant difference from sample category ($p < 0.05$).

Race segment			Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
Laps 1-3	Fixed effects	Constant	24.07	0.34	<0.001	23.39	24.75
		Fast*	-2.29	0.15	<0.001	-2.59	-2.00
		Non-final	-0.26	0.14	0.07	-0.55	0.03
		16*	0.62	0.37	<0.01	-0.13	1.36
		17*	0.89	0.35	<0.05	0.19	1.59
		18*	0.96	0.35	<0.01	0.27	1.65
		19*	1.25	0.35	<0.001	0.56	1.94
		20*	1.42	0.42	<0.01	0.57	2.27
	Random effects	level 1: season	2.67	0.18			
		level 2: individual	0.54	0.15			
		Deviance	2271.99				
		Deviance empty model	2485.77				
Laps 4-7	Fixed effects	Constant	29.48	0.24	<0.001	29.01	29.96
		Fast*	-1.20	0.10	<0.001	-1.40	-1.00
		Non-final	0.11	0.10	0.28	-0.09	0.31
		16*	0.73	0.26	<0.01	0.22	1.25
		17*	0.82	0.25	<0.01	0.33	1.31
		18*	0.74	0.25	<0.01	0.26	1.22
		19*	0.87	0.25	<0.001	0.38	1.35
		20*	0.66	0.30	<0.05	0.07	1.26
	Random effects	level 1: season	1.36	0.09			
		level 2: individual	0.28	0.08			
		Deviance	1885.94				
		Deviance empty model	2014.31				
Laps 8-11	Fixed effects	Constant	25.95	0.22	<0.001	25.51	26.39
		Fast*	1.69	0.10	<0.001	1.49	1.88
		Non-final*	0.22	0.10	<0.01	0.03	0.41
		16*	-0.51	0.24	<0.05	-1.00	-0.03
		17*	-0.63	0.23	<0.01	-1.09	-0.17
		18*	-0.58	0.23	<0.01	-1.03	-0.13
		19*	-0.70	0.23	<0.01	-1.15	-0.25
		20*	-0.53	0.28	0.05	-1.07	0.02

Table 3. (Continued)

Race segment			Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
	Random effects	level 1: season	1.23	0.08			
		level 2: individual	0.10	0.05			
		Deviance	1784.0				
		Deviance empty model	2039.67				
Laps 12-14	Fixed effects	Constant	20.49	0.24	<0.001	20.00	20.97
		Fast*	1.89	0.10	<0.001	1.69	2.09
		Non-final	-0.16	0.10	0.10	-0.35	0.04
		16*	-0.71	0.25	<0.01	-1.21	-0.20
		17*	-0.99	0.24	<0.001	-1.47	-0.51
		18*	-1.09	0.24	<0.001	-1.57	-0.60
		19*	-1.37	0.24	<0.001	-1.86	-0.89
		20*	-1.540	0.30	<0.001	-2.14	-0.94
	Random effects	level 1: season	1.15	0.08			
		level 2: individual	0.82	0.14			
		Deviance	1889.77				
		Deviance empty model	2170.00				

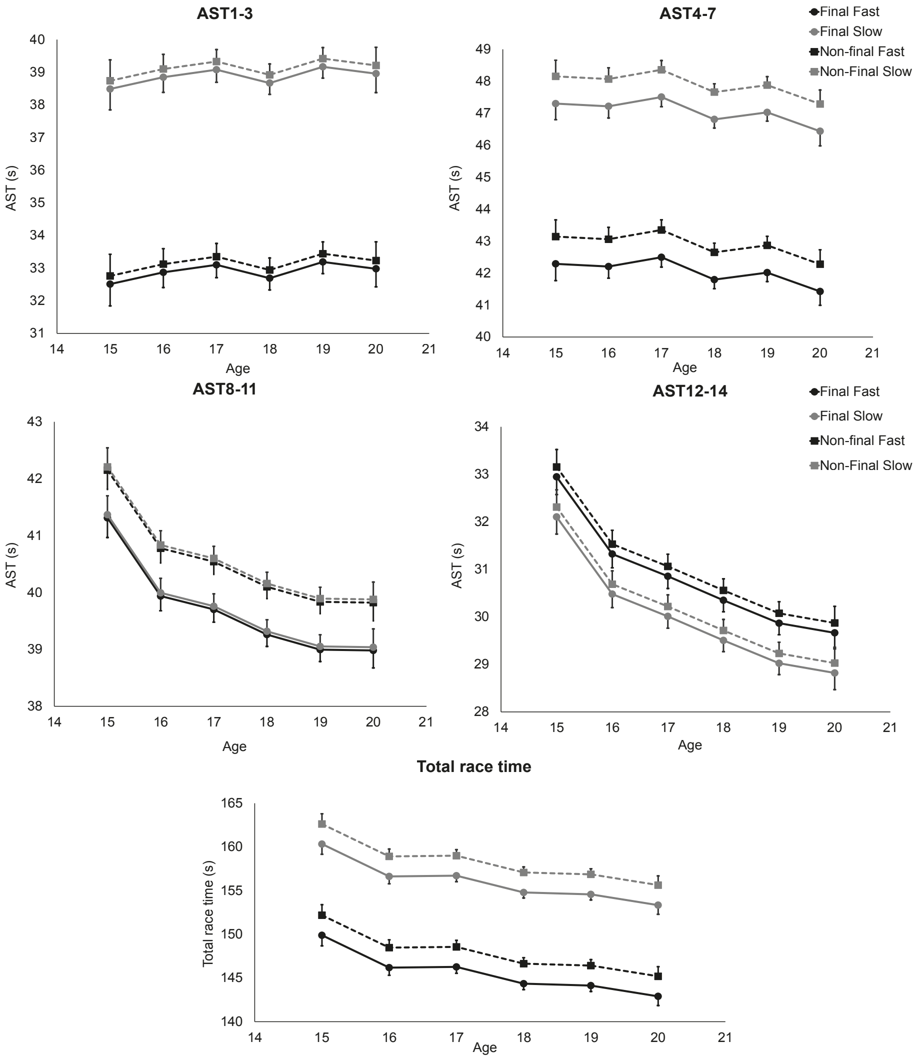

Figure 1. Predicted absolute section times (± 1 SE) per race section and total race time, presented for each age category. Symbols indicate; grey = slow races, black = fast races, circles = finals, and squares = non-finals.

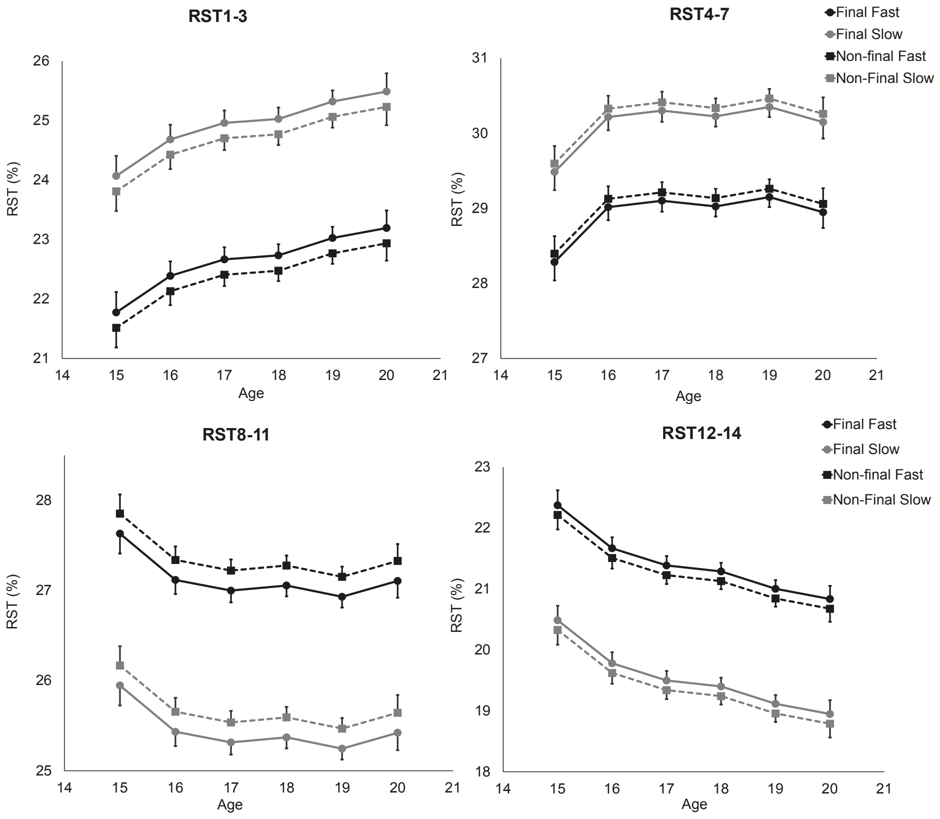

Figure 2. Predicted relative section times (± 1 SE) per race section, presented for each age category. Symbols indicate; grey = slow races, black = fast races, circles = finals, and squares = non-finals.

3.1. Age categories

Comparing total race time between the age categories, the following age categories reported a higher total race time: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20, 18 vs 20. No difference between age categories was found for AST1-3 and AST4-7. AST8-11 was higher in the following age categories: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20. Subsequently, AST12-14 was higher in age categories: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20 and 18 vs 19-20. There was a difference in RST between the age categories throughout the race. The RST1-3 was lower in the following age categories: 15 vs 17-20 and 16 vs 19-20. The RST4-7 was reported to only be significantly lower in age category 15 compared to all other age categories. Conversely, the RST8-11 was modelled to only be higher in age category 15 compared to all other age categories. The RST12-14 was higher in age categories: 15 vs 16-20, 16 vs 18-20, 17 vs 19-20 and 18 vs 19-20. Summarized, skaters in an older age group set a faster total race time by reaching a higher velocity in the second part of the race. Furthermore, older skaters were relatively slower during the first half of the race and relatively faster during the second half of the race. The differences in normalized velocity in the first three sections of the races significantly contrasted the 15 and 16 year old skaters against the skaters in the older age categories. In the last section, with every step to an older age category, skaters were relatively faster compared to all younger skaters.

3.2. Race type

The total race time, AST1-3 and AST4-7 were higher in races classified as slow compared to those classified as fast. AST12-14 was lower in fast races compared to slow races. There was no effect for race type on AST8-11. These findings point out that skaters in slow races had a lower velocity during the first half of the race, but were faster during the final three laps of the race, compared to skaters in races classified as fast. The RST1-3 and RST4-7 were lower in races classified as fast, compared those classified as slow. Vice versa, the RST8-11 and RST12-14 were higher in fast races, compared to slow. Therefore, skaters in fast races are relatively faster in the first half of the race and slower in the second half of the race. Contrariwise, skaters in a slow race are relatively slow in the first half of the race and have a high relative velocity in the second part of the race.

3.3. Stage of competition

The total race time, AST4-7 and AST8-11 were higher in non-finals compared to finals. There was no difference between the stages of competition for AST1-3 and AST12-14. Altogether, the finals were in total faster compared to the non-finals, with the skaters in the finals reaching a higher velocity in the middle part of the race. There was only significant difference in RST8-11 between the stages of competition. Skaters in finals were found to have a lower RST8-11. It should, however, be acknowledged that there is a trend suggesting RST1-3 is higher in finals compared to non-finals ($p = 0.07$). Therefore it can be suggested that skaters in the finals are relatively slower in the first section and faster during the third section of the race compared to the non-finals.

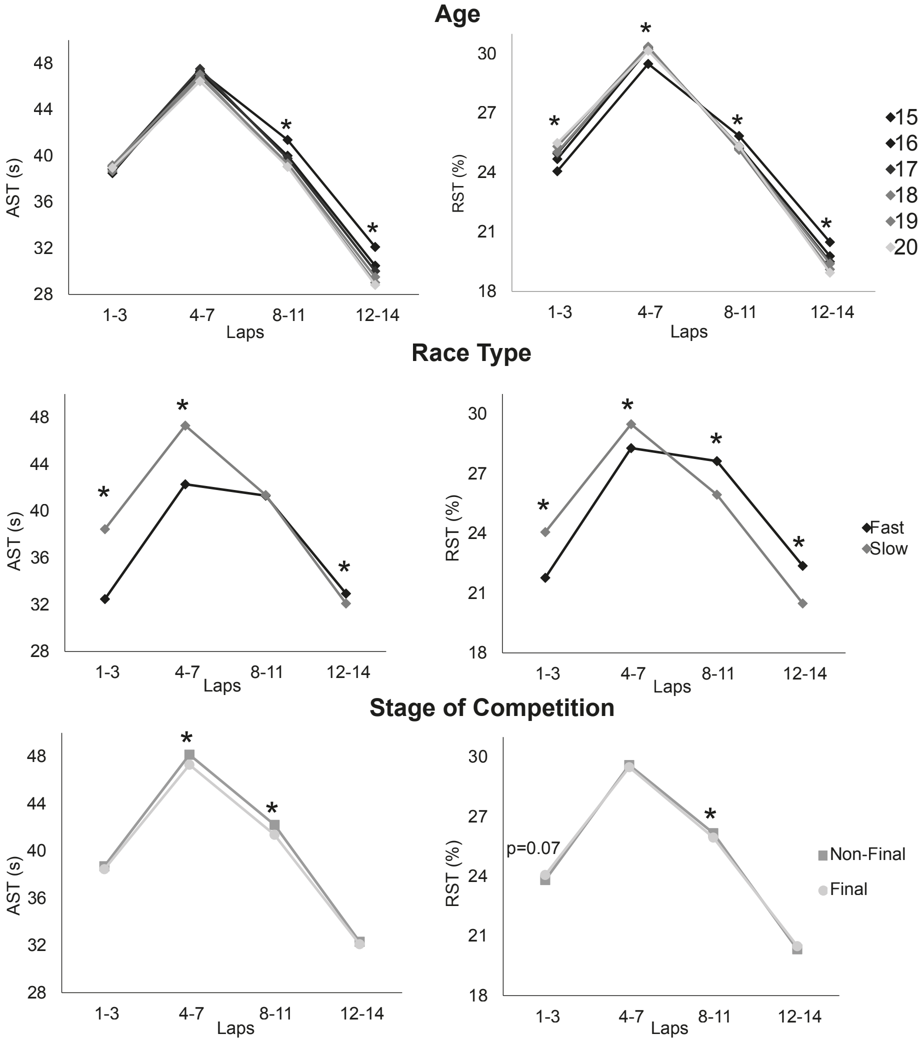

Figure 3. Absolute and normalized velocity distribution of skaters: the predicted values for the absolute and relative section times per race section for each age category, race type and stage of competition. *p<0.05

4. Discussion

The current study was the first to use a longitudinal design to investigate the development of pacing behaviour of young short-track speed skaters on a yearly basis, as well as investigate the influence of race type and stage of competition on their pacing behaviour. As hypothesised, the pacing behaviour of short-track speed skaters developed throughout adolescence. With age, the pacing behaviour became more conservative, characterized by a relatively slower start and faster finish. Furthermore, the total race time decreased with age, parallel with an increase in velocity during the last half of the race. Lastly, both the race type and stage of competition influenced the pacing behaviour of the short-track speed skaters, indicating that the competitive environment is an aspect of athletic performance to account for already at a young age.

The model for total race time predicted the largest development between the 15 and 16 years old: a drop of -3.70s, equal to a 2.31% decrease in total race time. Between the ages of 16 and 20, there was a -3.29s (2.14%) decrease in total race time, averaging 0.82s (0.52%) a year. In addition, there was a notable difference in the distribution of velocity between the age categories. In the first half of the race, there was no predicted difference in velocity between age categories. In the final two sections of the race, however, the predicted absolute velocity was higher with each age category. These findings indicate that older skaters can set a better finish time because they are able to reach a higher velocity in laps 8-11 and laps 12-14. Notable here are the large differences between age categories 15 and 16 (1.37s for laps 8-11 and 1.62s for laps 12-14, respectively), compared to the difference between age categories 16 and 20 (0.96s for laps 8-11 and 1.66s for laps 12-14, respectively). Previous research showed that the final phase of the race is most crucial to winning the race (6). The current findings suggest that older adolescent skaters also achieve a higher velocity in this critical final part of the race. One explanation for this could be that older skaters possess more developed physical attributes and a better skating technique, therefore being able to achieve a higher velocity in general. However, the models for relative section times reveal an additional explanation.

The use of relative section times allows for a comparison of pacing behaviour controlled for differences in total race time. In general, the models in the current study predicted that with age, the skaters develop a more conservative pacing behaviour, characterized by a relatively slower start and faster finish. Remarkably, the development of normalized velocity distribution was most evident when comparing 15 and 16 year old skaters to the other age categories. These findings are conform with a previous study which compared cross-sectional data from short-track speed skaters, grouped by age: younger than 17, younger than 19, younger than 21 and adults (older than 21) (15). The group with skaters younger than 17 presented the largest difference in normalized lap times compared to the other groups, specifically in four initial and four final laps of the race. Combining the development in normalized velocity distribution with the finding that with age, skaters reach a higher velocity in the final half of the race, points to the following idea: short-track speed skaters develop their pacing behaviour throughout adolescence, increasing the preservation of energy during the starting section of the race, in order to achieve a higher velocity in the critical final laps of the race, resulting in a decrease in total race time. This development is most evident around the 15-16 year span, becoming more gradual towards adulthood. Interestingly, Wiersma *et al.* reported that in the time-trial based sport of long-track speed skating, elite skaters distinguished themselves from sub-elite and non-elite by a distinct development of pacing behaviour in the period from 15 to 18 years old (14). The development in long- and short-track speed skating seems similar: in both disciplines, skaters develop a more conservative behaviour in which the conservation of energy during the start of the race results in a higher velocity in another section of the race and an overall decrease in total race time. Furthermore, the 15-16 year old mark constitutes a relatively large shift in behaviour in both disciplines. It could be speculated that this resemblance could entail that, like in long-track speed skating, the development of pacing behaviour of young short-track speed skaters could prove to be a marker for future performance level. However, future research should be done to further explore this hypothesis.

A possible underlying mechanism for the rapid development at the 15-16 year old mark could be found in the occurrence of a multitude of physical and cognitive changes in athletes of this age (11). Studies have shown that males on average attain their peak height velocity at 14 years old. Muscle mass (32), aerobic capacity (33) and morphological characteristics of the heart (34), all develop during this age period. These physiological changes have a direct impact on the physical capacities of young athletes, and consequently impact their pacing behaviour. Another likely underlying mechanism is the development of the self-regulatory skillset and core executive functions (11). The self-regulatory skillset comprises aspects of motivation, self-efficacy as well as (meta-) cognitive functions such as the capability to reflect, plan, monitor and evaluate a goal-directed process such as pacing (35). Complementary literature generally includes under the core executive functions; the ability to maintain information within the working memory for quick retrieval, the ability to deliberately inhibit or override dominant, automatic, or pre-potent responses and the ability to shift between multiple tasks, operations, or mental sets (20). Both skill-sets are suggested to be vital for adequate pacing behaviour and performance (20, 35). A variety of self-regulatory skills and core executive functions are shown to develop between 12 to 21 years old (35, 36). However, there is evidence to suggest that the pre-frontal cortex related (meta-) cognitive skills develop at different rates (36). It could be hypothesised that the cognitive functions that play an important role in the development of pacing behaviour in short-track speed skating, develop specifically during the 15-16 year period. To confirm this hypothesis, further exploration of the relation between pre-frontal cortical related (meta-) cognitive skills, pacing behaviour and athletic performance development is needed.

Considering the difference in pacing behaviour between race types, it is evident that the pacing behaviour in short-track speed skating is influenced by the velocity in the first section of the race. A fast start of the race will lead to a rather evenly paced race, whereas in a race with a slow start, the velocity increases considerably in the second half of the race. These findings are not fully unexpected. Previous research in adult elite short-track speed skaters found that skaters adjust their pacing behaviour in response to the behaviour of other competitors in the early stages of 1500-m competitions (30). A possible reason for the variability in behaviour could be tactical. It has previously been brought forward that following the pace of an opponent can be more physiologically demanding compared to self-pacing a race (37). Consequently, some skaters will opt to take the lead in the race in order to control the pace. On the other hand, positioning oneself closely behind an opponent could reduce air frictional losses by 23% due to drafting (38). Additionally, positioning in another position than the leading position allows the athlete to directly observe their opponents (30). The planning of race tactics and anticipating the behaviour of opponents seems to have substantial impact on the course and outcome of a short-track speed skating race. This further emphasizes the importance of developing the self-regulatory skillset and core executive functions in short-track speed skating.

Compared to the age of the skaters and the type of race, the stage of competition had a less pronounced influence on the skaters' pacing behaviour. The finals were predicted to be faster compared to the non-finals (2.29s). The difference in performance was most notable in the middle section. Interestingly, previous research in elite adult short-track speed skaters pointed to a pronounced change in pacing behaviour throughout a tournament (6, 28). The pacing behaviour of adult skaters was observed to become more conservative, featuring a slower start and fast finish, towards the finals. It would seem, therefore, that adult skaters adapt their pacing behaviour throughout the stages of competition, and adopt the most conservative pacing behaviour in the finals (28). It has previously been put forward that athletes not only pace individual races, but also regulate their effort over longer periods of time (e.g. stages of competition, seasons, Olympic cycles) (39). There is some evidence to suggest that young athletes have difficulties with planning an effective regulation of effort (40). It could therefore be suggested that the planning of energy distribution over a longer period than a single race is a skill which is still being developed in young athletes. If this is the case, it should be recognized as a potential concern, as it has previously put forwards that inadequate regulation of effort over long-term could lead to overtraining, burn-out and drop-out among young athletes (23).

The current study is the first to use multilevel modelling to longitudinally analyse pacing behaviour development. Using a repeated measurement of variance approach (as done in the majority of the literature on pacing), the analyses would have only included data of three skaters (in comparison to the 140 included skaters in the current study), as only three skaters performed in all five different age groups. It has been put forward that more (longitudinal) research on pacing behaviour development in young athletes is needed (11). Following the example set in the current study, multilevel modelling could be used in future studies to provide the much needed longitudinal analysis of pacing behaviour development in other sports in which there are varying number of measurements between participants, as well as a variety in temporal spacing between measurements.

5. Conclusion

The current study is the first to study the development of pacing behaviour in a head-to-head sport throughout adolescence, using a rigorous longitudinal approach. Between 15 and 20 years of age, short-track speed skaters become faster by developing the capability to reserve energy in the starting section of the race in order to reach a higher absolute velocity in the second half of the race. The most notable shift in this development seems to occur when skaters are 15-16 years of age. In young, as in adult skaters, the pace set in the initial laps dictates the velocity changes in the rest of the race. This phenomenon is suggested to stem from the various tactical choices made by athletes, balancing between the advantages afforded by either drafting or pace control. Lastly, the impact of the competitive environment (e.g. the stage of competition) on the pacing behaviour of young short-track speed skaters is less pronounced compared to adult skaters. Coaches are advised to monitor the pacing behaviour development of athletes, make athletes aware of the tactical advantages of setting a slow or fast initial pace and instruct them on how to pace themselves throughout the different stages of competition, in order to optimise their pacing behaviour and in turn their athletic performance.

6. Acknowledgements

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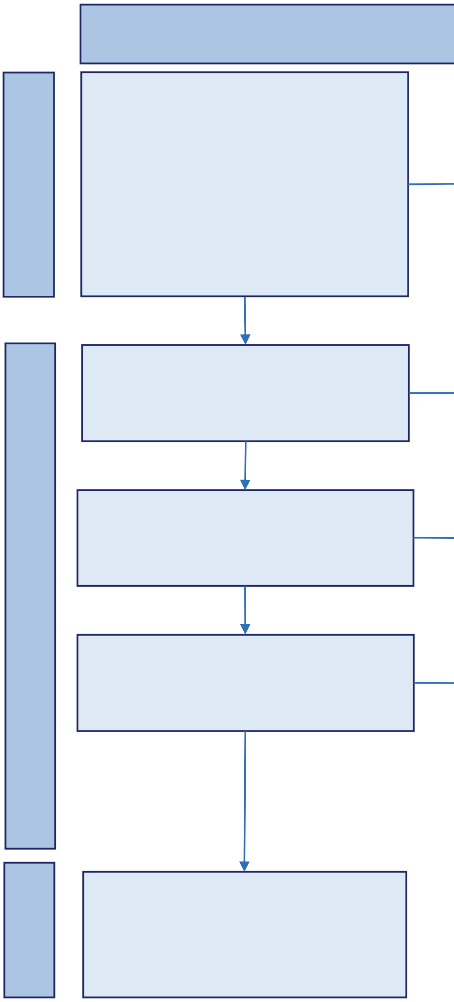
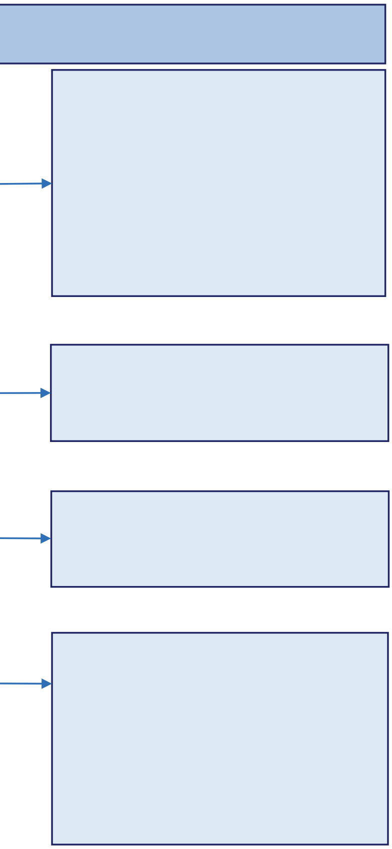


Chapter 7

Pacing in lane-based head-to-head competitions: a systematic review on swimming



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Abstract

Athletes' energy distribution over a race (e.g. pacing behaviour) varies across different sports. Swimming is a head-to-head sport with unique characteristics, such as propulsion through water, a multitude of swimming stroke types and lane-based racing. The aim of this paper was to review the existing literature on pacing behaviour in swimming. According to PRISMA guidelines, 279 articles were extracted using the PubMed and Web of Science databases. After the exclusion process was conducted, 16 studies remained. The findings of these studies indicate that pacing behaviour is influenced by race distance and stroke type. Pacing behaviour in swimming and time-trial sports share numerous common characteristics. This commonality can most likely be attributed to the lane-based racing set-up. The low efficiency of swimming, resulting from propulsion through the water, induces a rapid accumulation of blood lactate, prompting a change in swimmers' biomechanical characteristics, with the goal of minimising changes in velocity throughout the race. Although the literature on adolescent swimmers is scarce, young swimmers demonstrate a more variable pacing behaviour and have more difficulty in selecting the most beneficial energy distribution.

Keywords: pacing behaviour, swimming, athletic performance, psychology, adolescent, talent development.

1. Introduction

Pacing behaviour can be defined as the outcome of an individual's continuous, goal-directed, decision-making process regarding the distribution of energy resources over time (1, 2). In head-to-head and time-trial sports environments, the goal of the pacing process is to achieve optimal performance, which requires that athletes deplete all possible energy stores prior to finishing the race, but not so fast that a meaningful slowdown occurs before the end of the race (3, 4). The application of a broad range of theoretical models and the findings of experimental studies have shown that pacing behaviour is primarily influenced by the duration of the competitive event (3-5). In addition, recent studies have shown that different competitive environments influence pacing behaviour (6, 7). Lastly, in the finals of elite competitions in multiple sports, the pacing behaviour of more successful performers seems to differ from that of less successful performers (8, 9). The representation of an athlete's pacing behaviour can be termed the 'pacing profile'. Although general pacing profiles have been distinguished (10), it is assumed that pacing behaviour is associated with the different biomechanical and physiological limitations of the athlete (11) as well as with the different competitive environments (7, 12) the athlete competes in. Although the pacing process is already present in some form in young children (13), the brain areas associated with pacing behaviour continue to develop throughout adolescence (1, 14-16). Studies have shown that pacing behaviour develops during adolescence in elite athletes (17, 18). Moreover, adolescent athletes whose pacing profiles resemble profiles of adult elite performers earlier on in their development seem to achieve a higher performance level in their later careers compared to their peers (18). Therefore, an exploration of how adolescent athletes pace their races and develop their pacing behaviour throughout adolescence is particularly salient.

Swimming is a head-to-head sport entailing a unique combination of characteristics. Firstly, swimmers propel themselves through water, which requires more energy than overcoming air resistance during running or cycling races (19, 20). Because of the extensive energy loss to the environment, it is essential for swimmers to reduce drag and optimise propulsion (21, 22). Increased propulsion can be achieved by increasing the number of strokes for a given distance, defined as the stroke rate (SR), or by increasing the distance covered per stroke, namely the stroke length (SL). Due to the propulsion through water, an increase in SR will induce an increase in drag and, therefore, an increase in the amount of energy lost to the environment (22). Hence, elite swimmers mostly increase SL and reduce drag compared with non-elite swimmers (22). It has been posited that to ensure an optimally paced race, a swimmer should minimise fluctuations in velocity throughout the race, thereby minimising energy loss to the environment in the form of drag (12, 22). Moreover, a key phase of the race is the underwater phase that follows the start and turns. During this phase, the highest race velocity is achieved due to the increased impulse following the dive or push-off from the wall and the decrease in drag as a result of the adoption of a streamlined body position (23, 24). Competitive swimming entails several different stroke types and various race lengths, each associated with a specific technical skill set and energetic demand (25-27). The race distance in a pool ranges from 50 m to 200 m for the breaststroke, backstroke and butterfly events and up to 1,500 m for freestyle races (28). In open water, races can range from 5 to 25 km (29). Moreover, pool swimming competitions are generally organised as a qualifying structure comprising heats, semi-finals and finals. A final characteristic is that during pool swimming events, the competitors are separated by lanes. Consequently, competitors do not have to compete to be positioned in the ideal line, as is common in other head-to-head competitions such as (track-) cycling, running, short-track speed skating or Boat Race rowing.

Because of the unique combination of characteristics in the sport of swimming, the pacing behaviour in swimming could deviate from those observed in other sports. The present review is aimed at offering insights into sport-specific pacing behaviour in swimming. The primary aim is to provide an overview of studies on this subject. As there is a wide range of distances covered in swimming events, each of which entails particular energetics and techniques, it was decided to focus on 100–800 m pool races. The duration of these events (the world records for the 100 m and 800 m freestyle races are 46.91 s and 452.12 s, respectively (28)) best match those of other sports, such as track cycling as well as short- and long-track speed skating, as described in the literature (8, 9, 11, 30, 31). In addition to providing an overview of the literature, potential factors that influence the pacing behaviour of swimmers were identified and discussed. As adolescence is a crucial phase of pacing behaviour development, a particular focus of the review is on studies that explore the pacing strategies of adolescent swimmers (aged 12–21 years).

2. Methods

Following PRISMA guidelines, the PubMed and Web of Science databases were searched for studies about pacing behaviour in swimming up to until April 2017 using the following combination of terms:

(1) Pacing (OR performance strategy* OR energy distribution* OR pacing behaviour* OR velocity profile)
AND
(2) Swim*
NOT
(3) Triathlon* OR Animal* OR Fish* OR Pacemaker* OR Bacter*

The inclusion terms focused on articles written in English and published in peer-reviewed journals, covering pacing behaviour in swimming in relation to performance. Therefore, all included articles described pacing profiles with outcome variables such as lap times or (normalised) velocity distribution over the race. Additionally, the variability of pacing profiles over multiple races, expressed as the coefficient of variation (CV), was analysed in several studies. To provide an extensive overview of the literature, included articles featured participants of all age groups and performance levels. The initial search yielded 279 articles. After duplicate studies had been discarded, a total of 244 articles remained. The titles and abstracts of the remaining articles were read and papers lacking relevant links to pacing behaviour in swimming were excluded, resulting in 22 potential articles. After reading the bodies of these remaining articles, six were excluded because the articles did not meet the inclusion criteria. Therefore, a total of 16 studies were reviewed (Figure 1). Quality assessment of the articles was performed following guidelines provided by Letts *et al.* (32). Articles with a score above seven were considered of good methodological quality. Pacing profiles have been described in previous studies using velocity expressed as a percentage of the mean velocity in the race (e.g., 'normalised velocity'). This method provides a way of comparing the profiles of participants whose performance levels, sex and age differ. To avoid any misinterpretation in the description of pacing profiles, the definitions of general pacing profiles provided by Abbiss and Laursen (2008) and adapted for swimming by Mauger, Neuloh, & Castle (2012) were used in the current review (10, 33). In a negative pacing profile, the velocity increases throughout the race. By contrast, velocity decreases in a positive pacing profile. In an even pacing profile, the velocity remains constant throughout the race. In a parabolic-shaped pacing profile, the velocity decreases after the initial phase of the race and subsequently increases in the final phase. Finally, the fast-start-even pacing profile is characterised by a high velocity in the initial phase, followed by a lower, constant velocity during the remainder of the race. To the authors' knowledge, there are no specific percentages determined in the literature whereby these pacing profiles can be quantified.

As the qualification of participant performance level varied throughout the different included articles, there was a need for a standard qualification system to compare the outcomes reported in the included articles properly. Therefore, performance levels were categorised based on the world record in the year of publication of the article. Participants were divided into three groups: elite, sub-elite and competitive. Elite swimmers were defined as those with performances within 110% of the world record (24). Sub-elite swimmers were defined as those whose total race time was 110–120% of the world record. Finally, competitive swimmers were defined as swimmers who performed in a competitive environment but whose total race time exceeded 120% of the world record.

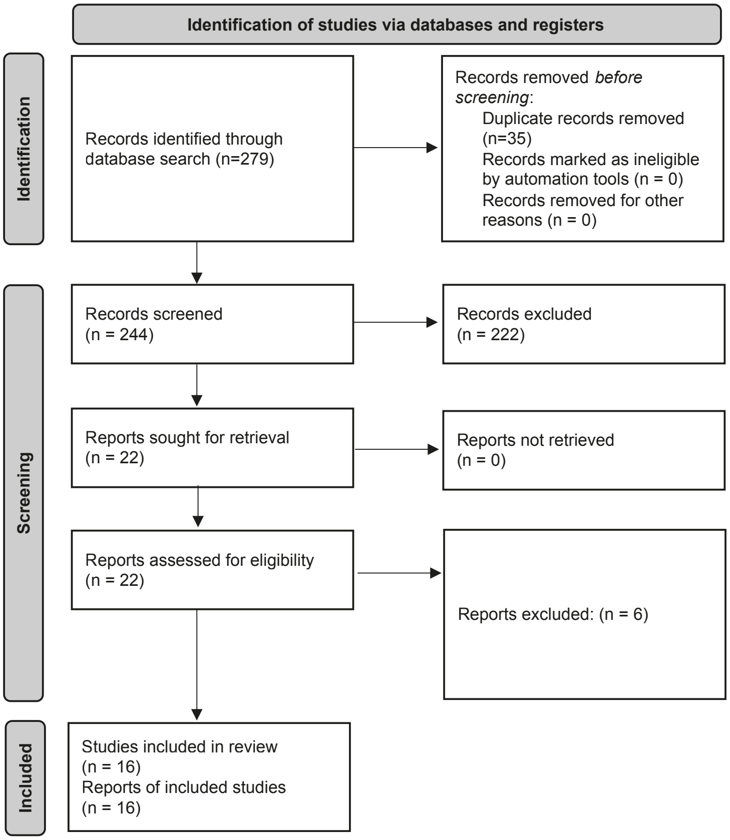

Figure 1. Flow diagram of the literature selection process, including the number of articles excluded at each stage.

3. Results

3.1. General pacing profiles

All of the reviewed articles (n = 16) were of good methodological quality (with total scores ≥ 7; Table 1). Therefore, studies were not distinguished based on qualitative weight. Table 2 presents a summary of the characteristics and outcomes reported in the reviewed articles. In the majority of studies, the participants were elite (n = 9), followed by sub-elite (n = 4) and competitive swimmers (n = 3). Most of the studies analysed freestyle swimming (n = 13), followed by breaststroke (n = 5), backstroke (n = 3) and butterfly (n = 3). The pool lengths were 25 m (n = 3), 50 m (n = 11), and not specified in two studies. The pacing profiles identified in the studies were positive (n = 11), negative (n = 2), even (n = 3), parabolic (n = 8) and fast-start-even (n = 8). In a majority of the articles (n = 11), pacing profiles were analysed using data collected during actual swimming competitions (e.g. ‘real competition’). The articles which collected data in real competition analysed races from either a combination of the heats, semi-finals and finals (n = 6), only the semi-finals and finals (n = 3) or exclusively the finals (n = 2). Additionally, several studies were conducted in more controlled settings (e.g., ‘simulated competition’) in which participants were tasked with swimming a time trial without an opponent (n = 6). One article explored data collected during real and simulated competition scenarios entailing one or two opponents. No significant difference was found between pacing profiles in simulated competitions (with an opponent) and in real competitions ($p>0.22$). However, in real competitions, absolute velocity was higher during all sections of the race ($p<0.001$) (34). Three of the studies conducted in a simulated competition examined the effect of an imposed manipulation of swimmers’ pacing behaviours on their performance outcomes. Only one study of swimmers in real competition related observed pacing profiles to total race time.

A total of 12 of the 16 reviewed studies showed a higher velocity in the starting phase of the race. This phenomenon was observed for all four distances (100 m: n = 3, 200 m: n = 7, 400 m: n = 8, 800 m: n = 3) and all stroke types. Pacing profiles for 100 m and 200 m races showed a high velocity during the first 50 m (35-39). For the 400 m profile, a high velocity either occurred during the first 50 m (40, 41) or 100 m (37). In the 800 m freestyle races, a high velocity was reported for the initial 100 m freestyle (34, 36). The high velocity during the starting phase was reported in several studies that excluded the first 15 m of the race in the velocity measurements (33, 35). Correspondingly, it was reported in studies in which swimmers were instructed to start from the water (42, 43). Thus, it can be stated that the high velocity during the starting phase occurs independently of the dive start.

Table 1. A quality assessment of the included articles in alphabetical order applying the guidelines developed by Letts et al.

Assessment questions →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
1. Dormehl and Osborough (2015)	1	1	1	0	0	1	0	0	1	1	1	1	0	0	8
2. Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes (2011)	1	1	1	0	0	1	0	0	1	1	1	1	0	0	8
3. Lipinska, Allen, and Hopkins (2016)	1	1	1	0	0	1[a]	0	0	1	1	0	1	1	0	8
4. Mauger, Neuloh, & Castle (2012)	1	1	1	0	0	1[b]	0	0	1	1	1	1	1	1	10
5. Mytton *et al.* (2015)	1	1	1	0	1	1[a]	0	0	1	1	1	1	0	1	10
6. Nikolaidis and Knechtle (2017)	1	1	1	0	0	1[a]	0	0	1	1	1	1	1	1	10
7. Robertson, Pyne, Hopkins, & Anson (2009)	1	1	1	0	0	1[a]	0	0	0	1	1	1	1	1	9
8. Saavedra, Escalante, Garcia-Hermoso, Arellano, & Navarro (2012)	1	1	1	0	0	1[a]	1	1	1	1	1	1	0	0	10

Table 1. A(Continued)

Assessment questions →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total
9. Schnitzler, Seifert, & Chollet (2009)	1	1	1	0	0	1	0	0	1	1	1	1	1	0	9
10. Skorski, Faude, Abbiss, *et al.* (2014)	1	1	1	0	0	1	1	1	1	1	1	1	1	1	12
11. Skorski, Faude, Caviezel, & Meyer (2014)	1	1	1	0	0	1[a]	1	1	1	1	1	1	1	1	12
12. Skorski, Faude, Rausch, & Meyer *et al.* (2013)	1	1	1	0	0	1	0	0	1	1	1	1	1	1	10
13. Taylor, Santi, & Mellalieu (2016)	1	1	1	0	0	1[b]	0	0	1	1	1	1	0	1	9
14. Thompson, MacLaren, Lees, &Atkinson (2003)	1	1	1	0	0	1	0	0	1	1	1	1	0	0	8
15. Thompson, MacLaren, Lees, & Atkinson (2004)	1	1	1	0	0	1	0	0	1	1	1	1	0	0	8
16. Veiga and Roig (2016)	1	1	1	0	0	1[b]	0	0	1	1	1	1	0	1	9

a = records were in the public domain. b = no informed consent but there was ethical approval. Included questions (scored either 0 or 1): 1.Was the aim of the study and purpose stated clearly? 2.Was relevant background literature reviewed? 3.Was the study design appropriate for the research question? 4.Were the participants relevant to the research question and was their selection well-reasoned? 5.Was the sample size justified? 6.Was informed consent obtained? 7.Were the outcome measures reliable? 8.Were the outcome measures valid? 9.Were results reported in terms of statistical significance? 10.Were the data collection methods appropriate for the research design? 11.Did a meaningful picture of the phenomenon under study emerge? 12.Were conclusions appropriate given the study findings? 13.Are there any implications for future research given the results of the study? 14.Were limitations of the study acknowledged and described by the authors?

3.2. Race distance

Different features in the pacing profile were observed depending on the race distance. In all three studies of 100 m races, it was observed that the pacing profiles of swimmers, both elite and competitive, were positive (35-37). The pacing profiles of swimmers in races over 200 m were analysed in 10 studies. In studies that focused on 200 m competitions, both real and simulated, in 25 m and 50 m pools, elite swimmers showed a high-velocity start followed by a large decrease in velocity during the second lap, a small decrease in velocity during the third lap and a constant velocity up to the end of the race (38, 39, 42). In one study that investigated competitive swimmers performing 200 m freestyle, the velocity increased in the final lap (2.1%) (36). The pacing profiles of swimmers in 400 m races were examined in a total of 10 studies. Elite swimmers performing freestyle and medley in real competitions displayed parabolic pacing profiles, with significantly higher velocities during the first and last sections than in other sections of the race ($p<0.001$) (37, 38, 40, 44). Swimmers with parabolic pacing profiles performed significantly better than the swimmers who displayed one of the other pacing profiles. This finding applied to both males ($p<0.001$) and females ($p<0.001$) (45). Two studies found that during 400 m races in real competitions, the most common pacing profiles among elite swimmers performing freestyle were the fast-start-even and parabolic profiles (33, 45). Three studies examined the pacing profiles of swimmers performing in 800 m races. A first section at a fast pace, followed by a gradual decrease in the normalised velocity during the 200–700 m and increased normalised velocity during the final 100 m was observed among adolescent sub-elite swimmers (34). A study of in elite female swimmers performing freestyle during real competition confirmed these characteristics, reporting a gradual decrease in velocity throughout the race, with the slowest lap time in the eleventh lap (500–550 m) (46). Among competitive freestyle swimmers, split times increased during the 100–200 m (8.8%) and 200–600m sections (0.2% – 1.0%) and decreased during the 600–700m (0.3%) and 700–800m sections (3.4%) ($p<0.001$) (36).

3.3. Stroke types

In addition to the duration of the race, certain deviations in pacing behaviour were caused by the different stroke types. Elite swimmers in 200 m freestyle, butterfly and backstroke races tended to display a fast-even profile, with a fast first 50 m section for all three stroke types ($p<0.001$ for all other sections). Additionally, in the freestyle and backstroke events, the second 50 m lap was also faster than the third and fourth laps ($p<0.001$) (38). The pacing profile of swimmers performing breaststroke was characterised by a high velocity during the first 50 m lap and a gradual decrease in normalised velocity with every 50 m lap ($p<0.001$) (38, 47, 48). Furthermore, more variability was observed in the pacing profiles of swimmers performing breaststroke during the entire race (38). Individual medley events were examined in two studies. Elite swimmers participating in 200 m and 400 m individual medley real competitions demonstrated a parabolic pacing profile in which they performed butterfly strokes for the smallest percentage of the total race time, followed by freestyle, backstroke and breaststroke (37, 44).

3.4. Biomechanics and metabolic systems

The metabolic systems used in swimming competitions were described in three studies (42, 47, 48). One study that investigated a 200 m freestyle race reported that the percentage of the total metabolic power output covered by the aerobic energy system increased over the duration of the race, from 45% during the first lap to 83% in the third lap, with a drop to 66% during the final lap. Conversely, the coverage of the anaerobic system decreased over the duration of the race, from 55% during the first lap to 17% during the third lap, with a small increase to 24% during the final lap (42). It was reported that as the race time increased, the blood lactate peak value correspondingly increased, which was linked to increased fatigue throughout the race (42, 47, 48). In all four studies that measured biomechanical characteristics in adult swimmers, the SL decreased throughout the race. One study on sub-elite swimmers performing freestyle in a 400 m race showed a drop in SL after the first 50 m and during the last 100 m, whereas the SR remained unchanged during the race (43). However, the other three studies reported a decrease in SL accompanied by an increase in SR (42, 47, 48). Additionally, swimming performance was subdivided into surface and underwater swimming within one study, who reported that although the velocity in surface swimming decreased by 6–8% over a 200 m freestyle race, the underwater velocity remained constant (39).

3.5. Medallists vs non-medallists

The pacing behaviour of swimmers in the finals of elite competitions was compared in three studies. Two studies found that the pacing behaviour expressed in lap times, and therefore representing absolute velocity, was similar for swimmers ranked in first to sixteenth (37) or first to eighth (40) place. However, a comparison of the normalised velocity showed that medallists had a relatively lower normalised velocity in both the first 100 m (102.2 ± 1.2% vs 103.1 ± 1.1%, $p<0.05$) and the second 100 m (97.7 ± 0.8% vs 98.2 ± 0.6%, $p<0.001$) compared to swimmers ranked fourth to eighth place. In the third 100 m, there was no difference between medallists and non-medallists (98.5 ± 1.0% vs 98.4 ± 0.6%, $p=0.63$). In the final 100 m, medallists had a higher normalised velocity compared to non-medallists (101.8 ± 1.7% vs 100.5 ± 1.2%, $p<0.05$) (40). Among elite swimmers performing a 200 m medley, it was observed that medallists had a higher absolute velocity than non-medallists (fourth to sixteenth place) throughout the race. However, medallists invested more time in butterfly and freestyle strokes ($p<0.001$) and less in backstroke ($p<0.001$) and breaststroke ($p<0.05$) than swimmers ranked in ninth to sixteenth place (44). In the 400 m medley, medallists invested more time in butterfly strokes ($p<0.001$) and less in backstroke ($p<0.05$) and breaststroke ($p<0.05$) compared with swimmers ranked in ninth to sixteenth place (44).

3.6. Pacing in adolescent swimmers

Three studies focused on the pacing behaviours of adolescent swimmers. One study found no difference in the pacing profiles of younger and older adolescent swimmers (group 1: aged 14.4 ± 0.7 years; group 2: aged 17.0 ± .8 years) performing in 200 m freestyle real competitions (35). The pacing profile observed in this study corresponds to the profile displayed by elite swimmers competing in the same event (38, 39). A comparison of adolescent sub-elite swimmers (aged 16.9 ± 2.1 years) with elite adult swimmers (aged 22.8 ± 2.9 years) participating in 200 m and 400 m freestyle races revealed that the variability of the pacing profiles of both adult and adolescent swimmers was low throughout the race. However, in the last quarter of the race, the variability was higher among adolescent swimmers than among adult swimmers (34, 38). Furthermore, the findings of a study of sub-elite adolescent swimmers (males: 19.2 ± 2.0 years, females: 16.2 ± 1.8 years) participating in a 400 m freestyle race revealed better performances of seven out of 15 swimmers in a trial with an imposed manipulated pacing profile compared with performances in trials entailing a self-regulated pace (41).

4. Discussion

Pacing behaviour in swimming is characterised by a high-velocity start and is influenced by racing distance. The study findings indicate that when the racing distance increases, the swimmers' pacing profiles change from being positive (100 m races) to being more parabolic (400 m and 800 m races). In elite finals, the best-performing swimmers demonstrated a higher absolute velocity throughout the race (37, 40, 44). However, the pacing profiles of the top three performers differed from those of the other finalists (40, 44). Namely, medallists showed a lower normalised velocity during the first half of the race and a higher normalised velocity during the last portion of the race (40). Notably, all of these characteristics are similar to those reported in studies of time-trial competitions (3, 4, 9, 11, 18, 30, 49). Swimming is a head-to-head competition in which the winner is the athlete who covers the given race distance first, regardless of the time taken. Nevertheless, distinct differences between athletes' pacing behaviours were observed in 400 m swimming and 1,500 m running competitions, although both sports entail head-to-head competitions of similar duration (40). Additionally, the characteristics of the pacing profile in swimming are similar to those of athletes in time-trial sports. This similarity is most likely caused by the separation of competitors through the use of lanes, thereby preventing tactical behaviour as seen in classic head-to-head sports (e.g., drafting behind an opponent), which enables a swimmer to be more independent of other competitors. This explanation is supported by the fact that studies on rowing, another head-to-head sport in which competitors are separated by lanes, have reported pacing behaviour which resembles pacing profiles of time-trial sports (50, 51).

The different stroke types are a distinctive feature of pool swimming. There appear to be marked differences in swimmers' pacing profiles associated with different stroke types (38, 39), indicating that stroke type affects pacing behaviour. Most notably, the pacing profiles of swimmers performing breaststroke, in contrast to other strokes, were characteristically positive (38, 47, 48). In addition, in races, the variability of pacing profiles was higher for swimmers performing the breaststroke than that for swimmers performing other strokes (38). A possible explanation could be found in the finding that the breaststroke technique features a large intra-cyclic variation of swimming velocity (25). Higher intra-cyclic variations in velocity prompt more mechanical work by swimmers and consequently induce greater energy expenditure (25). This increased energy expenditure could be the reason for the decrease in swimming velocity in the last lap as well as the increased variation throughout the race.

A comparison of the contribution of energy systems in the course of a swimming race to a track cycling task of similar duration (141.3 ± 4.5 s for swimming vs 133.8 ± 6.6 s for cycling) reveals a clear difference between the two sports (42, 49). The contribution of the anaerobic system during swimming is around 56% after the first 50 m, thereafter decreasing with a corresponding increase in the aerobic contribution during the race, which reaches a high point of 83% during the third lap (42). In track cycling, the contribution of the anaerobic energetic system is around 75% during the first 30 seconds (49), which is comparable to the first 50 m in swimming. The aerobic system only takes over as the predominant energy system at the 100 s mark (49). This difference in the contributions of the two energetic systems could be attributed to low efficiency in swimming caused by the increased energy loss to the environment. This low efficiency could place a greater demand on the anaerobic system to maintain velocity. Consequently, the accumulation of blood lactate, and associated symptoms of fatigue, occur faster during a swimming event than in a track cycling event of the same duration. This relatively fast onset of blood lactate accumulation is also reflected in biomechanical characteristics. As blood lactate level increases over the duration of the race, SL tends to decrease (42, 43, 47, 48). However, as noted in previous studies, it is essential to minimise large variations in velocity throughout the race (12, 22). Therefore, to maintain velocity, swimmers must increase SR during the race. Notably, a high SR is associated with a higher level of drag than a high SL and a low SR. Additionally, it appears that whereas elite swimmers maintain underwater velocity during the race, surface velocity decreases (39). This finding accords with the previously mentioned goals of minimising drag and maintaining velocity throughout the race. As for the underwater phase of the lap, drag is minimised through the streamlined body position. Consequently, the highest velocity is achieved during this phase of the race. A recent study that examined behavioural differences in pacing between and within the laps of elite swimmers confirmed the occurrence of changes in biomechanical characteristics resulting from increasing fatigue as well as the maintenance of constant underwater velocity throughout the race (52). This study concluded that swimmers' pacing profiles within the first lap evidenced a decreasing velocity because of the loss of velocity following the dive. The dive is the fastest part of the race because of the initial acceleration as well as the airborne locomotion, compared with the rest of the race in which locomotion occurs in water (24). Additionally, the swimmers' pacing behaviour within the second and third laps is characterised by a decrease in velocity at the end of the lap as they prepare to turn and by an increase of velocity during the underwater phase attributed to decreased drag.

Because of the scarce literature on adolescent swimmers' pacing behaviour (n = 3), it is difficult to provide a detailed description of the pacing behaviour of adolescent swimmers. No direct differences in the pacing profiles of adolescent and adult swimmers were found. However, the pacing profiles of adolescent swimmers were evidently more variable, and these swimmers demonstrated difficulty in self-selecting the most beneficial pacing profile. This could indicate that adolescent swimmers struggle to regulate their energy distribution in the most efficient manner. This inability to pace efficiently was also found in a study of adolescent swimmers (15 ± 1.5 years) performing a swimming incremental step test (53). Adolescent swimmers' incompetence in stabilising their pacing behaviour may be related to the finding that pacing skills are contingent on prior experience and the level of (meta-) cognitive functioning, requiring time to fully develop (4, 13, 14, 54). A recently proposed model for developing athletes' pacing skills emphasises the importance of both the experiential and self-regulatory aspects of skill learning (14). Self-regulation has proven essential for an efficient training regime (55). By supporting the multiple cyclical facets of self-regulation learning (reflection, planning, performance and evaluation), coaches can facilitate the development of young athletes' pacing behaviour. The importance of this development was recently highlighted in a longitudinal study of adolescent speed skaters (18). The findings indicated that adolescent athletes whose pacing profiles resemble those of elite performers in an earlier stage of their development went on to achieve higher performance levels in their later careers compared to their peers at the adolescent level (18). As swimmers' pacing behaviours resemble those of athletes in time-trial sports like speed skating, it is plausible that swimmers also demonstrate a similar relation between the development of their pacing behaviour and their performance in later stages of their careers. Further research on the development of pacing behaviour in swimming is required to address this question.

5. Conclusion

The present study is the first systematic investigation of the body of literature on pacing behaviour in pool swimming. Although swimming is a head-to-head sport, the pacing behaviour of swimmers in this type of competition is similar to that of athletes in time-trial sports. A positive profile is evident in shorter races (100 m), whereas a more parabolic profile is prevalent in the longer races (400 and 800 m). Additionally, elite medallists demonstrate more conservative pacing behaviour, characterised by a lower normalised velocity in the initial phase of the race and a higher normalised velocity in the final phase. Given the unique characteristics of the breaststroke event, the swimmers' pacing profile markedly deviates from those of other strokes, being more positive. Blood lactate accumulates throughout the race, prompting a decrease in SL and a consequent increase in SR during the course of the race to minimise variations in velocity. The pacing profiles of adolescent swimmers are more variable than those of elite swimmers, and young swimmers tend to have difficulty effectively regulating their energy distribution to achieve the highest performance outcome. The relationship between pacing behaviour and performance development in swimmers needs to be further explored in future studies.

6. Declaration of interests

The authors report no potential conflicts of interest that are related to the content of this review.

Table 2. An overview of the reviewed studies on pacing behaviour in pool swimming ordered by race distance (n =16).

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Dormehl & Osborough (2015)	100m[1], 200m[1]	Male (n=56), Female (n=56)	Group 1: 14.4±0.7 Group2: 17.0±0.9	Competitive	Freestyle	Real competition (heats, semi-finals and finals)
Robertson, Pyne, Hopkins, & Anson (2009)	100m[2], 200m[2], 400m[2]	Male (n=1530), Female (n=1527)	n/a	Elite	100m, 200m: Freestyle, breaststroke, butterfly, backstroke. medley. 400m: Freestyle, medley	Real competition (semi-finals and finals)
Nikolaidis & Knechtle (2017)	100m[2], 200m[2], 400m[2], 800m[2]	Males (n=2260), Females (n=2221)	25-94	Competitive	Freestyle	Real competition (heats, semi-finals and finals)

Methods	**Statistical analyses**	**Pacing profile**	**Main results**	**Main findings**
Races collected at international schools swimming championships[1]. Race split up in quarters. For 200m: laps 1, 3 and 5 for quarter 1, 2 and 3. Quarter 4 is combination of laps 7 and 8 Measurements: -Race time -Velocity per quarter. (Velocity of first quarter was measured between 15m and 20m to account for dive. Remainders over a 10m midsection of the pool)	-Repeated measurements ANOVA's -Post-Hoc (Bonferroni)	-Positive	-No difference in pacing profile between groups 100m: -Velocity decreased for each quarter. 200m: -Velocity decreased for each quarter except for the last quarter in which it did not differ from the third quarter.	-No difference in pacing profile between two age groups 100m: -Decrease of velocity throughout the race 200m: -The velocity decreased gradually decrease until the third quarter of the race. It remained unchanged in the final quarter.
Races collected during OG, WC, EC and CG over a 7 year period. Measurements: -Total race time -Split times (50m or 100m) -Placing for top 16 finishers	Lap times of finalists and semi-finalists, the mean lap times for all the swimmers (placed 1–16) were plotted between-athletes and within-athletes.	100m: Positive 200m: Fast-start-even. 400m: Parabolic	-Winners maintained a lead through each of the intermediate laps. -Pacing profile: faster first lap (~1-3s) , followed by evenly paced middle laps and an evenly paced or slightly faster (~1s) final lap. -The most successful(top 3 of 16) swimmers were faster in all the laps.	-Similar pacing profile for all 16 swimmers. -Pacing profile: 100m: positive. 200m and 400m: a fast first lap followed by evenly paced middle laps and an evenly of faster final lap.
Races were collected during the Masters championships 2014. Measurements -50m split times (200m, 400m) -100m split times (800m) -Total race time	-Mixed-design factorial ANOVA -Post-Hoc (Bonferroni) test. Effect size eta squared ($\eta 2$): small ($0.010 < \eta 2 \leq 0.059$), moderate ($0.059 < \eta 2 \leq 0.138$) and large ($\eta 2 > 0.138$).	-Parabolic -Positive	100m: Velocity 1st lap > 2th lap (+11.6%) 200m: Velocity: 1st lap > 2th lap (+11.6%) > 3th lap (+3.8%) < 4th lap (–2.1%) ($P < 0.001$, $\eta 2 = 0.847$), - Larger changes in older age groups than in the younger groups, both in women ($P < 0.001$, $\eta 2 = 0.195$)and men ($P < 0.001$, $\eta 2 = 0.200$). 400m: -Swimming time: 50–100 m (+11.1%), 101–150 m (+2.9%), 151–200 m (+1.2%), 201–250m (unchanged), 251–300 m (+0.5%), 301–350 m (–0.6%), 351–400 m (–4.5%) ($P < 0.001$, $\eta 2 = 0.856$). -Larger changes in older age groups than in the younger groups, both in women ($P < 0.001$, $\eta 2 = 0.176$) and men ($P < 0.001$, $\eta 2 = 0.131$). 800m: -Swimming time: 100–200 m (+8.8%), 201–300 m (+1.0%), 301–400 m (+0.5%), 401–500 m (+0.2%), 501–600 m (+0.2%), 601–700 m (–0.3%) 701–800 m (–3.4%) ($P < 0.001$, $\eta 2 = 0.842$). - Larger changes in older age groups than in the younger groups in men ($P < 0.001$, $\eta 2 = 0.105$).	-In 100m freestyle a positive pacing profile is found. -There is a general pacing profile in the 200m, 400m and 800m freestyle in master swimmers. A large increase in swimming time during the second lap, a decrease or a constant during the other laps and increase in swimming time during the last lap(s). -There are larger changes in swimming time by lap in the older age groups than in the younger groups.

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Thompson, MacLaren, Lees & Atkinson (2003)	200m. 175m	Male (n=9)	21.2±2.6	Sub-Elite	Breaststroke	Simulated competition (without opponent)
Thompson, MacLaren, Lees, & Atkinson (2004)	200m	Male (n=9)	22.5±4.5	Competitive	Breaststroke	Simulated competition (without opponent)
Figueiredo, Zamparo, Sousa, Vilas-Boas, & Fernandes (2011)	200m[1]	Male (n=10)	21.6±2.4	Elite	Freestyle	Simulated competition (without opponent)

Methods	Statistical analyses	Pacing profile	Main results	Main findings
200m test trial 3 paced 175m trials. Measurements: -50m split times -HR -RPE -La (post-trial)	-Dependent t-tests -one-way ANOVA -Factorial ANOVA -Post hoc (Tukey's HSD)	-Even -Positive -Negative	-Difference in split times (p<0.01) -No difference in finishing times (p<0.05). -The 200 test trial: positively paced (split time: 72.2±8.6s; finish time: 148.0±13.2s) -RPE: even < positive, 200m trial trial (p < 0.05). -HR: negative trial < others (p < 0.05)	-The pacing strategy of choice was positive pacing. -Even pacing shows reduced blood lactate & RPE compared to positive paced. -Performance: even = positive.
200m test trial 3 paced 200m trials: -98% of 200m time -100% of 200m time -102% of 200m time Measurements: -50m split times -HR -Respiratory exchange ratio (RER) (post-trial) -La (post-trial)	-Dependent t-tests a -One-way ANOVA -Factorial ANOVA -Post-hoc (Tukey's HSD)	-Positive	-Finishing times: different (F=28.37, p<0.01). 102% > 100% (0.8%, p<0.05). - 102% was positively paced (t=4.88, p<0.006). -RER and blood lactate 102% > 100% & 98% (p<0.05) -PRE: 102% > 98% (p<0.05) -HR: at 100m 102% > 98% (F=4.00, p<0.03). No difference at 200m.	-Positive pacing profile in 102% trial. -102% trial was completed only 0.8% faster to even-paced 100% trial (non-significant difference).
50m, 100m, 150m and 200m trial at 200m velocity. No dive, no underwater phase. Measurements: -50m split times. -Velocity during every 50m. -VO_2 -La (post-trial) -Aerobic, anaerobic (lactate and alactic) -Total energy expenditure	-One-way repeated measures ANOVA -Post-Hoc (Bonferroni -Cohen's f; small (0 ≤ f ≤ 0.10), medium (0.10 < f ≤ 0.25); and large effect size (f > 0.25).	Fast-start-even.	-Velocity: first lap > other laps ($F_{3,27}$=24.72, p<0.01, f=1.04) -Split time: first lap < other laps ($F_{3,27}$=30.753, p<0.001, f=1.23) -Aerobic contribution: stable the last 3 laps, lower in 1st lap ($F_{3,27}$=110.515, p<0.001, f=5.69). -Anaerobic anlactic contribution: 1st lap > other laps ($F_{3,27}$=925.91, <0.01, f=5.69) -Anaerobic lactate contribution: 1st lap > other laps ($F_{3,27}$=66.131, p<0.001, f=1.73) -Total energy expenditure: 1st & 4th lap > other laps ($F_{3,27}$=19.578, p<0.001, f=0.59) -Total energy expenditure: 2th lap > 3th lap ($F_{3,27}$=29.137, p<0.001, f=0.80).	-Aerobic contribution increases over the race whiles anaerobic alactric contribution decreases. -Anaerobic lactate contribution increased in the final lap

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Veiga & Roig (2016)	200m[2]	Males (n=64), Females (n=64)	n/a.	Elite	Butterfly, backstroke, breaststroke, freestyle.	Real competition (semi-finals and finals)
Saavedra, Escalante, Garcia-Hermoso, Arellano, & Navarro (2012)	200m[2], 400m[2]	Male (n=821), Female (n=822)	n/a	Elite	Medley	Real competition (semi-finals and finals)

Methods	Statistical analyses	Pacing profile	Main results	Main findings
Races collected during the FINA WC 2013. Measurements: -average underwater velocity -average free swimming velocity -average lap velocity	-Repeated-measurement ANOVA -Univariate analyses using Wilks' methods.	-Positive pacing	-Free swimming velocity: 1st lap > 2th lap (−0.08 m·s^{-1}, −0.07 to −0.09 m·s^{-1}, P =0.001) 2th lap > 3th lap > 4th lap (both −0.02 m·s^{-1}, −0.01 to −0.03 m·s^{-1}, P = 0.001). -Underwater velocity : 1st turn > 2th turn (−0.03 m·s^{-1}, −0.01 to −0. m·s^{-1}, P = 0.005), 2th = 3th turn (0.01 m·s^{-1}, −0.01 to 0.03 m·s^{-1}, P = 0.55). -Average velocity: 1st lap > 2th lap (−0.15 m·s^{-1}, −0.15 to −0.16 m·s^{-1}, P = 0.001) 2th lap >3th lap (−0.03 m·s^{-1}, −0.02 to −0.03 m·s^{-1}, P = 0.001). 3th lap = 4th lap (−0.01 m·s^{-1}, −0.02 to 0.00 m·s^{-1}, P = 0.29).	-The free swimming velocity decreases across the 200 m race laps, the velocity in the underwater swimming is not affected by the race progress and is faster than free swimming. -Average velocity decreases after first lap, and slightly after second lap, is maintained during third and fourth lap.
Races were collected during OG. WC, EC, CG, PPC, U.S. Olympic team trials, Australian Olympic team trial in 2000-2011. Measurements: -Total race time -50m split times -percentage of total time spend in a lap.	-A two-way ANOVA sex*classification -Post-Hoc (Bonferroni)	-Parabolic	200m: -The percentage of time spend per stroke: Butterfly men (22.59±0.42), women (22.65±0.42) < freestyle men (23.20±0.42), women (22.90±0.46) < backstroke men (25.62±0.53), women (25.52±0.52) < breaststroke men (28.59±0.60), women (28.93±0.65) -The best swimmers: greater percentage in butterfly and freestyle (p<0.001) and less in backstroke (p<0.001) and breaststroke (p<0.021) compared to the lowest classified swimmers. 400m: -The best swimmers: greater percentage in butterfly and backstroke (p<0.001) and less in backstroke (p<0.018) and breaststroke (p<0.024) compared to the lowest classified swimmers.	-The smallest percentage of time was spend in butterfly followed by freestyle, backstroke and breaststroke. -Best swimmers spend more time in butterfly and freestyle and less in breaststroke and (in 400m) backstroke

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Skorski, Faude, Caviezel, & Meyer (2014)	200m^2, 400m^2	Male (n=158)	22.8±2.9	Elite	200m: freestyle, butterfly, backstroke, breaststroke. 400m: freestyle	Real competition (heats, semi-finals and finals)
Skorski. Faude, Rauch, & Meyer. (2013)	200m^2, 400m^2, 800m^2	Male (n=9), Female (n=7)	16.9±2.1	Sub-Elite	Freestyle	Simulated competition (with opponents) & Real competition (heats, semi-finals and finals)

Methods	Statistical analyses	Pacing profile	Main results	Main findings
Races of top 50 swimmers collected during 22 national and international events as well as the races of the finals (1th-16th place) of the PPC and EC. Measurements: -Overall race times -50m split times -Normalized velocity	-Repeated measures ANOVA (factor 1, competition; factor 2, section of the race) -Post-Hoc (Scheffé).	-Fast-start-even -Positive -Parabolic	-Average performance improvement from heat to final was 1.2% (CL 0.6-2.2%). -Pacing pattern: Fast-start-even pattern in 200m freestyle, butterfly and backstroke. Velocity in 1th lap > others.(P<.001) and 2th lap > 3th and 4th in freestyle and backstroke (P<.001). Positive profile in breaststroke (P<.001). Parabolic profile in 400m freestyle. Velocity in 1st lap > others (P<.001). Last lap > others (P<.001). -Heat paced similar to finals (interaction: all P>.06). 50m split times were faster finals (P<.02). -Normalized pacing pattern was not significantly different between competitions 1 and 2 (P>.18). -CV's for intra-individual differences in split times between heats and finals were small for all 200m races (<2.2%; CL 0.6-3.2%). In 400m freestyle, values increased in the course of the race up to 2.9% (CL 2.2-4.5%) in the last section.	-Pacing pattern is consistent between competitions in elite swimmers. -Elite swimmers showed a fast-start-even (freestyle, butterfly, backstroke) and positive pacing (breaststroke) during 200m and parabolic-shaped pattern during 400m freestyle. -Swimmers choose the same pacing pattern during heats and finals but with a lower average velocity during heats.
-Six simulated competitions (SC: 2x 200m, 2x 400m and 2x 800m. -Real competition races (RC) Measurements: -50m splits times (200m) and 100m splits (400m, 800m). -Peak blood lactate values (post-trial) -HR (post trial)	-2-way repeated measures ANOVA test*section of test -Cohen's d -Within-subject-variation by means of the SEM and log-transformed CV.	-Fast-start-even	-Fast-start profile during SC (p<0.002) and RC (p<0.001). -CV for test-retest small for first 3 sections (CV < 2.0%, for first 6 sections of 800m) and increased towards the end. -Pacing pattern SC = RC (p>0.22). -Pacing pattern for absolute velocities SC = RC (p>0.10), all section times faster during RC (p<0.001). -SEM in split times between SC and RC were small in the middle of the race during 800m (200m-600m) and 400m (200m-300m) (SEM <1.6s). The first section higher SEM in both distances (>1.8s). The last section of the during the 400m (300m-400m) and the 2 last sections during the 800m (600m-800m) showed higher SEM (>1.8s).	-Pacing profile (fast-start-even) is consistent during the first three quarters of the race (CV <2%). The absolute variability in split times in the last quarters was higher (CV= 2.2-2.9%). -Athletes show similar a pacing pattern in SC and RC -Race times faster in RC during all sections of the race.

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Mauger, Neuloh, & Castle. (2012)	400m[2]	Male (n=147), Female (n=117)	n/a	Elite	Freestyle	Real competition (finals)
Taylor, Santi, & Mellalieu (2016)	400m[2]	Male (n=489), Female (n=312)	n/a	Elite	Freestyle	Real competition (heats, semi-finals and finals)

Methods	Statistical analyses	Pacing profile	Main results	Main findings
Races collected at the EC, WC, British and Australian national championship and International Invitational Meets, CG and OG in period 2003-2010. Measurements: -Total race time -50m split times -Mean velocity of every lap (excluding first 10m after the start and first and last 5m of every lane). Pacing profiles were determined by an algorithm based on normalized velocity.	Data were analyzed using a three-way ANOVA (pacing strategy _ sex _ swimming suit) in an unrelated design (p=0.05).	-Parabolic -Fast-start-even -Positive -Negative -Even	-Fast-start-even and parabolic pacing profiles used the most, with parabolic profiles preferred by men. -Fast-start-even pacing profile performed at 96.08±2.12% of the (228.4±4.66s). -Parabolic pacing profile performed at 96.04±2.2% of the WR (228.7±4.84s) -Positive pacing profile performed at 95.4±2.19% of the (230.15±4.82s) -1.7s performance difference between fast-start-even and positive pacing ($F_{2,228}$ = 1.00, P>0.05).	-Fast-start-even and parabolic pacing profiles used more frequently -Profile preference regardless of sex -Functional difference between profiles during competition appears to be minimal. -No specific single profile had significant influence on performance.
Races collected at the WC, EC, OG between 2006 and 2012. Measurements: -50m split times -Normalized 50m split time	-*k*-means cluster analysis -One-way ANOVA -Cohen's d.	-Fast-start -Positive -Parabolic	-In males mean race time in parabolic pacing (mean race time = 230.57 s, 95% CL = 229.51–231.63) < fast-start-even pacing (mean race time = 235.91 s, 95% CL = 234.81–237.01),and positive (mean race time = 252.66 s, 95% CL = 249.26–256.06) -In females mean race time in parabolic pacing profile (mean race time = 249.59 s, 95% CL = 248.47–250.71) < fast-start-even (mean race time = 253.94 s, 95% CL = 252.87–255.01), positive (mean race time = 262.76 s, 95% CL = 260.05–265.47) -Fast-start-even and parabolic pacing profiles were most frequently observed. 220 and 182 for males (n=498) and 105 and 135 for females (n=312) respectively.	-In elite swimmer the parabolic pacing profile resulted in the lowest race times, followed by the fast-start-even profile. - Parabolic and fast-start-even profiles were most frequently chosen by the elite athletes.

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Mytton et al. (2015)	400m[2]	Male (n=48)	n/a	Elite .	Freestyle	Real competition (finals)
Skorski et al. (2014)	400m[2]	Male (n=10), female (n=5)	Male: 19.2±2.0 Female: 16.2±1.8	Sub-Elite	Freestyle	Simulated competition (without opponent)
Schnitzler, Seifert, & Chollet (2009)	400m[1]	Male (n=6), Female (n=6).	18.2±2.2	Sub-Elite	Freestyle	Simulated competition (without opponent)

Methods	Statistical analyses	Pacing profile	Main results	Main findings
Races collected at the EC 2006, 2010, 2012. WC 2007, 2010 and CG 2006. Measurements: -50m split times -Velocity per lap -Normalized velocity	-Mann Whitney test -Kruskal-Wallis test -Cohens *d* effect size: trivial (<0.2), small (0.2-0.6), moderate (0.6-1.2) and large (1.2-2.0).	-Fast-start-even -Parabolic	-Medallists: larger variation in velocity compared to non-medallists -Lap one: normalized velocity medallists < non-medallists (102.2±1.2%, 103.1±1.1%, p=0.03, *d* = 0.75). Gold medallists = others -Lap two: normalized velocity medallists < non-medallists (97.7±0.8%, 98.2±0.6%, p<0.001, *d* = 0.78). -Lap three: Normalized velocity medallists = non-medallists (98.5±1.0%, 98.4±0.6%, p=0.63). Gold medallist > 4th-8th place (p=0.04 to 0.002). -Lap four: Normalized velocity medallists > medallists (101.8±1.7%, 100.5±1.2%, p≤0.01, *d* = 0.93 moderate).	-Medallist, compared to non-medallists, swim a relatively slower first and second 100m. In the third 100m there is no difference and the final 100m is faster.
Self-paced trial (PP_{SS}), trial with first 100m paced 3% slower compared to PP_{ss} (PP_{SLOW}), trial with first 100m paced 3% faster compared to PP_{ss} (PP_{FAST}). Controlled for the dive start. Measurements: -Total racing time -50m split times -La (post-trial) -Normalized velocity	-One-way repeated-measures ANOVA -Two-way ANOVA SR and normalized velocity between trials (with and without start dive). -Post-Hoc (Scheffé) -Cohen d effect (0.2, 0.6, 1.2, 2.0, and 4.0 for trivial, small, moderate, large, very large, and extremely large, respectively)	-Parabolic	-Overall performance compared to PP_{SS}: < PP_{FAST} (278.5±16.4s) (P=.05). < PP_{SLOW} (277.5±16.1s) (P=.20). - 7 out of 15 subjects faster time in a manipulated race (3 in PP_{FAST}, 4 in PP_{SLOW}) -Pacing was different between conditions in the first 100m (P<0.001), not in the rest of the trial (P=0.45). -Including the dive start: in all conditions the first 50m were faster compared to the remaining sections of the trial (P<0.001). -Blood lactate (P=.33) and HR (P=.47) were not different between conditions.	-Manipulation during the initial 100m of a 400m freestyle event reduces overall performance (more than 2.5s) -7 out of 15 participant recorded their fastest time during a manipulated trial.
100m, 200m, 300m and 400m at 400m velocity. No dive start. Measurements: -HR -La (post-trial) -Mean speed every 50m (V50) -Workload (TWL). By the NASA-TLX questionnaire.	-Three-way ANOVA (fixed factors: swim, gender; random factor: subject) -Three-way ANOVA (fixed factors: swim distance, gender; random factor: subject) -Post-Hoc (Tukey HSD) -CV -One-way ANOVA	-Even	-HR, lactate values and TWL increased with distance for both genders (p<0.05). -HR: increased from 100m to 400m (p<0.05). 200m = 300m. -Lactate: increased from 100m to 400m (p<0.05). 200m = 300m. -Velocity: first 50m > other laps (p<0.05)	-The changes in HR, lactate values and TWL increased with race distance. -Velocity in the first lap was higher compared to other laps

Table 2. (Continued)

Study	Race distance	Gender and number of participants	Age (years)	Performance level	Stroke type	Competition type (stage of competition)
Lipinska, Allen, & Hopkins (2016]	800m[2]	Female (n=192)	17-34	Elite	Freestyle	Real competition (heats, semi-finals and finals)

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1. Short course (25m pool)
2. Long course (50m pool)

Abbreviation list:
Competitions: World Championship (WC), European Championship (EC), Olympic Games (OG), Pan-pacific championship (PPC), Commonwealth Games (CG), World record (WR).
Measurements: Heartrate (HR), Stroke rate (SR), Rate of Perceived exertion (RPE), Oxygen uptake (VO_2), Blood lactate peak value (La).
Statistical analyses: analyses of variance (ANOVA), coefficient of variation (CV), confidence limits (CL), confidence intervals (CI), the standard error of measurement (SEM).

Methods	Statistical analyses	Pacing profile	Main results	Main findings
Races collected during OG, WC, EC, PPC, Universiades, NC. Measurements: -50m split times -Pacing profiles: linear and quadratic coefficient for the effect of lap number, reductions in time for the first and last laps, and the residual standard error of the estimate.	-Reliability analyses	-Positive	-Mean values of the linear and quadratic coefficients represent a swim with a shallow negative curvature and a slowest lap time in the eleventh lap. -First and last laps were much faster than predicted by the quadratic curve (extremely large and very large reductions in time, respectively).	-The pacing profile described contained a fast initial and final lap. -The middle laps gradually decreased in velocity.

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Chapter 8

Pacing behaviour development in adolescent swimmers: a large-scale longitudinal data analysis

Adapted from:

Menting S.G.P., Post A.K., Nijenhuis S.B., Koning R.H., Visscher C., Hettinga F.J., Elferink-Gemser M.T. Pacing Behavior Development in Adolescent Swimmers: A Large-Scale Longitudinal Data Analysis. *Medicine & Science in Sports & Exercise. 2023;55(4):700-709.*

Abstract

Purpose: Use a large-scale longitudinal design to investigate the development of the distribution of effort (e.g., pacing) in adolescent swimmers, specifically disentangling the effects of age and experience and differentiating between performance levels in adulthood.

Methods: Season best times and 50m split times of 100m and 200m freestyle swimmers from five continents were gathered between 2000 and 2021. Included swimmers competed in a minimum of three seasons between 12-24 years old (5.3±1.9 seasons) and were categorized by performance level in adulthood (elite, sub-elite, high-competitive) (100m: n=3498, 47% female; 200m: n=2230, 56% female). Multilevel models in which repeated measures (level 1) were nested within individual swimmers (level 2) were estimated to test the effects of age, race experience, and adult performance level on the percentage of total race time spent in each 50m section ($p<0.05$).

Results: In the 100m, male swimmers develop a relatively faster first 50m when becoming older. This behaviour also distinguishes elite from high-competitive swimmers. No such effects were found for female swimmers. Conversely, more experienced male and female swimmers exhibit a slower initial 50m. With age and race experience, swimmers develop a more even velocity distribution in the 200m. Adolescent swimmers reaching the elite level adopt a more even behaviour compared to high-competitive. This differentiation occurs at a younger age in female (>13 years) compared to male (>16 years) swimmers.

Conclusion: Pacing behaviour development throughout adolescence is driven by age-related factors besides race experience. Swimmers attaining a higher performance level during adulthood exhibit a pacing behaviour which better fits the task demands during adolescence. Monitoring and individually optimizing the pacing behaviour of young swimmers is an important step towards elite performance.

Keywords: sport, race analysis, competitive swimming, future performance, talent, multilevel modelling.

1. Introduction

The goal-directed decision-making process regarding effort distribution (i.e., pacing) is a decisive factor for performance in exercise tasks (1, 2). The outcome of this process, the athletes' pacing behaviour, is commonly quantified by registering a measure of effort (e.g., power output or velocity) during sections of an exercise task (2, 3). Pacing seems to be learned through a cyclical acquisition process, in which experience gathered during a previous task is used to inform the athlete in future iterations of the task (4). The awareness of the benefits of distributing effort to reach a set exercise goal is first observed at 5-8 years old (5), and the capability to do this effectively continues to develop during adolescence and into adulthood (6, 7). With age, the pacing behaviour of children and adolescents develops to feature an increasing fit to the task demands (6, 7). Previous longitudinal studies considered the pacing behaviour exhibited by elite level adults as the endpoint of this development (6, 7). Moreover, it was revealed that athletes who reached a higher performance level in adulthood exhibited a pacing behaviour resembling that of adult athletes at an earlier stage of adolescence, compared to their less successful peers (6). Knowledge about the development of pacing behaviour is, therefore, of great interest for both scientists and practitioners. Unfortunately, the limited amount of available research into the pacing behaviour of children and adolescents consists mainly of cross-sectional studies with small sample sizes, often including individuals from one specific country, region, school, club or team (8, 9). To provide further insights into the development of pacing behaviour, more rigorous longitudinal studies with large sample sizes are needed.

One sport in which the topic of pacing behaviour has gained increasing scientific interest in the last few years is competitive swimming (8, 10). Given the highly resistive properties of water compared to air and the low mechanical efficiency of the swimming movement, it has been argued that adequate pacing might be more important in swimming compared to land-based sports (8, 10). Moreover, competitive swimming is a popular, global sport in which the gap between the gold medallist and the last finisher in international competitions is decreasing (11). In light of this, optimizing pacing behaviour plays an increasingly important role in elite swimming performance (8, 10). Systematic literature reviews have shown that the pacing behaviour of swimmers is primarily determined by the race distance and stroke type (8, 10). In races over a short distance (50-100m), elite swimmers adopt an all-out pacing behaviour, attempting to achieve a high velocity through rapid acceleration and trying to maintain this velocity throughout the race (12). During 200m races, elite swimmers adopt a fast start followed by an even pace (13). Comparing different strokes, it is evident that the butterfly and breaststroke events are characterized by a gradual decrease in velocity over the duration of the race, which is mostly attributed to the relative inefficiency of these strokes compared to front crawl or backstroke. Regarding pacing behaviour development in swimming, one study reported that adolescent swimmers performing a 200m front crawl trial started off too fast and therefore lacked in speed at the end of the trial (14). A second study reported that adolescent swimmers have difficulty in selecting the optimal pace, performing better in a 400m front crawl trial when executing an externally imposed pace compared to a self-selected pace (15). It was proposed that the difference between adolescent and adult swimmers was due to the disparity in task experience (13, 16, 17). This, however, seems to be an oversimplification as the shift of pacing behaviour during adolescence is thought to originate not only from increased exercise experience but also from age-related physical maturation and cognitive development (4, 9). Additionally, as the chronology of physical maturation and cognitive development processes differ between boys and girls (18, 19), it logically follows that the timeline of pacing behaviour development differs between sexes (20, 21). A profound understanding of the mechanisms behind the pacing behaviour of adolescent swimmers, including the influence of factors such as age, experience and sex, could help coaches to guide their athletes in developing a more optimal pacing behaviour.

The present study aimed to investigate the development of pacing behaviour in adolescent swimmers, specifically disentangling the effects of age and experience and differentiating between performance levels in adulthood. It was hypothesized that the pacing behaviour of swimmers would develop during adolescence, gradually exhibiting more resemblance to adult behaviour. The demands of the task would influence the direction of the development. In short tasks, the development would present itself as a change towards a more all-out pacing behaviour, characterized by a higher velocity during the initial stages. In longer tasks, the shift would be towards a more even effort distribution. Moreover, it was hypothesized that, independent of age, increased experience would facilitate a better fit with the task demands: a higher velocity in the initial stages in the shorter tasks and an overall more even distribution of effort in longer tasks. Adolescent swimmers who eventually reached a higher performance level in adulthood were hypothesized to exhibit a pacing behaviour more resembling that of adult swimmers, compared to adolescent swimmers who attained a lower performance level. As females generally exhibit puberty-related physical maturation and cognitive development at an earlier age compared to their male counterparts, it was hypothesized that the split between swimmers of different future performance levels would occur earlier in females compared to males.

2. Methods

All procedures used in the study were approved by the Local Ethical Committee of the University Medical Center Groningen, University of Groningen, The Netherlands (201900334) in the spirit of the Helsinki Declaration. The requirement for informed consent of the participants was waived given the fact that the study involved the analysis of publicly available data and analyses were group-based.

2.1. Data collection

All available 100m and 200m freestyle long course performance data (i.e., date of the race, total race time and available 50m split times) of both male and female swimmers performing between 2000 and 2021 were collected from Swimrankings' database (www.swimrankings.net). This resulted in 2,857,181 (100m freestyle) and 1,897,872 (200m freestyle) observations. The assumption was made that all swimmers chose the front crawl during the freestyle events. Performance data were collected from 113 countries across the world. The date of birth of all included swimmers was collected using the same database.

2.2. Data processing

Swim performances over 180s (100m freestyle) and 360s (200m freestyle) were excluded from the analysis to ensure a homogeneous dataset. Performance data were classified per swimming season, starting on the 1st of September and ending on the 31st of August of the next calendar year. Data from the 1st of January 2008-2010 were excluded from analysis because of the impact of full-body polyurethane swimsuits on swimming performance in that period (22-24). Performance data from the 2019-2020 season were excluded as competitions and training opportunities were disturbed because of the COVID-19 pandemic. A total of 2,773,387 observations (100m freestyle) and 1,842,992 (200m freestyle) observations remained. For each swimmer, the Season Best Time (SBT) per swimming season was used for further analysis. Age at SBT was determined using the swimmer's date of birth. Race experience was defined as the cumulative number of races of a specific event, which the swimmers had completed before SBT.

2.3. Inclusion criteria

For the purpose of this study, it was important to outline the development of pacing behaviour from a young age towards the age of peak performance. Peak performance in competitive swimming is on reached at 24 (±2) years for males and at 22 (±2) years for females (25). Therefore, only swimmers who had at least one swim performance in the age category of 22 years or older (male) or 20 years or older (female) were included. To ensure a dataset representing the developmental pathway of pacing behaviour towards peak performance, swim performances after the swimmer's career-best swim performance were excluded. To longitudinally study pacing behaviour development, included swimmers had to be between 12 and 24 years old and have performance data with 50m split times in at least three swimming seasons. To study pacing behaviour independent of current performance, split times of each 50m section were converted into relative section times (RST), representing the percentage of the total race time spent in one section. The inclusion criteria were conducted for the 100m and 200m events separately.

Swim performances of multiple generations (i.e., from 2000 through 2021) were included in the dataset, which necessitated the correction of evolution in competitive swimming. As such, swim performances were defined as a percentage of the prevailing world record (WR) of the corresponding sex, referred to as relative Season Best Time (rSBT) (26, 27).

World records from 2008 and 2009 were replaced by the prevailing fastest time in a textile swimsuit. According to the event, swimmers were allocated to the elite, sub-elite or high-competitive performance group by using their event-specific all-time rSBT after 20 (female) or 22 (male) years of age (see Table 1). The elite level was defined as the average rSBT of the 50th swimmer of the event-specific FINA World Ranking List between 2016 and 2021 (11). Sub-elite level and high-competitive level were defined as the average rSBT of the 8th and 50th swimmer of the event-specific National Ranking List of the Netherlands between 2016 and 2021 (11). Swimmers with a best rSBT outside the limits of the high-competitive group were excluded from further analysis. For the 100m event, this resulted in 3,498 swimmers (1,659 female) with 15,960 observations (7,384 female) with an average of 5.3 ± 1.9 observations per swimmer. For the 200m event, this resulted in 2,230 swimmers (1,252 female) with 10,309 observations (5,412 female) with an average of 5.3 ± 1.9 observations per swimmer.

Table 1. The total number of swimmers and observations according to sex, performance level and event included in the analysis.

	Performance level limits	*Individuals*	*Observations*
Male (100m freestyle)			
Elite	best rSBT ≤ 103.7%	145	756
Sub-elite	103.7% < best rSBT ≤ 107.4%	501	2.472
High-competitive	107.4% < best rSBT ≤ 114.7%	1.193	5.348
Total		1.839	8.576
Male (200m freestyle)			
Elite	best rSBT ≤ 104.1%	104	524
Sub-elite	104.1% < best rSBT ≤ 107.6%	314	1.548
High-competitive	107.6% < best rSBT ≤ 116.6%	650	2.825
Total		1.068	4.897
Female (100m freestyle)			
Elite	best rSBT ≤ 105.2%	175	940
Sub-elite	105.2% < best rSBT ≤ 107.5%	265	1.289
High-competitive	107.5% < best rSBT ≤ 115.0%	1.219	5.155
Total		1.659	7.384
Female (200m freestyle)			
Elite	best rSBT ≤ 104.2%	142	704
Sub-elite	104.2% < best rSBT ≤ 107.5%	315	1.455
High-competitive	107.5% < best rSBT ≤ 115.8%	795	3.253
Total		1.252	5.412

rSBT: relative Season Best Time

2.4. Statistical analysis

Following the methods introduced by Menting *et al.* (7), longitudinal multilevel models were created to describe pacing behaviour as a function of age, race experience and performance group. Multilevel modelling allows for the creation of models in which repeated measures (level 1) are nested within individual swimmers (level 2), allowing the use of longitudinal data with varying number of measurements between swimmers as well as a variety in temporal spacing between measurements. Analyses were performed using the lmer4 package in R (R version 3.6.0) (28, 29). Statistical assumptions (e.g., multicollinearity) were checked, and outliers were screened and removed (100m: 915, 200m: 1,006). The RST per 50m section were included as dependent variable. In contrast to split times, all RST must add up to 100%. With respect to this constraint, one out of two (100m freestyle) and three out of four (200m freestyle) multilevel models were created. The remaining, free section (RST 50-100m in both events) was calculated from these models. Following that the sum of 50m sections must add up to 100%, the same predictor variables (fixed part) and variance structure (random part) had to be incorporated into each model equation. Predictor variables age and race experience were included as continuous, time-varying factors, whereas the performance group was included as a categorical, time-invariant factor. The power law of practice states that the effect of experience on performance decreases as the level of experience increases (30). In addition, the age effect on performance decreases as swimmers are fully matured (26). As such, the effect of a 1-year increase at age 13 will be larger than a 1-year increase at age 19 (see Appendix). To account for this, the variables age and race experience were log-transformed, of which the latter transformation was needed to meet the assumption of normality. To represent the three performance groups in the statistical models, two dummy variables (sub-elite and high-competitive) were included, and the elite group functioned as the reference level. A random intercept model was selected as the most appropriate variance structure, allowing the inclusion of each swimmer's individual trajectory that randomly deviates from the average population trajectory. In sum, the following multilevel model was adopted:

$$
\begin{gathered}
RST_{is} = \alpha_i + \beta_1 \times \log(Age_{is}) + \beta_2 \times \log(RaceExperience_{is}) + \beta_3 \times SubElite_i \\
+ \beta_4 \times HighCompetitive_i + u_i + \varepsilon_{is} \\
u_i \sim N(0, \sigma_0^2) \\
\varepsilon_{is} \sim N(0, \sigma^2)
\end{gathered}
$$

RST_{is} was the relative split time of a 50m section for swimming season s of swimmer i, α the intercept assigned to the elite group, Age_{is} the corresponding age value, $RaceExperience_{is}$, the corresponding race experience value, $SubElite_i$ the dummy variable of swimmer i assigned to the sub-elite group and $HighCompetitive_i$ the dummy variable of swimmer i assigned to the high-competitive group. The unexplained information was the sum of u_i (between-subject variance) and ε_{is} (residual variance). The models were validated by using graphical tools to check violations of homogeneity, normality and independence.

Predictor variables were considered significant if the estimated coefficient is greater than twice the standard error of the estimate ($p<0.05$). Post-hoc analyses were performed for models with future performance groups as significant predictor variable. For this analysis, swimmers were classified in age categories based on their age on the 31st of December of the swimming season. Per age category, an independent sample t-test was conducted to examine from which age onward between-group differences in pacing behaviour occurred. These follow-up analyses were executed for age categories with at least 30 observations per performance group. For all tests, $p < 0.05$ (two-tailed) was set as significance.

3. Results

The models created can be found in Table 2. Using the fixed part of the models, predictions for the dependent variables can be made. For example, for the RST in the 100-150m segment of a 200m event performed by an 18-year-old male swimmer with 20 previous races and an adult performance level as high-competitive, the following value will be predicted as:

$$\begin{aligned} RST\ 150m &= 27.42 + (-0.55 \times \log 18) + (-0.03 \times \log 20) + (-0.00 \times 0) + (0.09 \times 1) \\ &= 25.83\% \end{aligned}$$

3.1. Age

The predicted effect of age on RST is visualized in Figure 1A (100m) and Figure 2A (200m). Older male swimmers were relatively faster in the first 50m of the 100m. No effect of age was indicated in female 100m swimmers. In the 200m, older male and female swimmers were predicted to start relatively slower, have a relatively faster middle section and, a relatively slower final 50m section, compared with their younger counterparts.

3.2. Race experience

Race experience significantly impacted RST in all segments except for the final segment in the male 200m event, as visualized in Figure 1B (100m) and Figure 2B (200m). In the 100m, more experienced male and female swimmers were relatively slower in the first half of the race. In the 200m, male swimmers with more race experience were relatively slower in the first 50m section, but faster in the 150m section. More experienced female swimmers were relatively slower in the first 50m section and relatively faster in the 150m and 200m sections.

3.3. Performance level

Elite male swimmers were faster in the first 50m of the 100m, compared to the high-competitive group. Post hoc analysis revealed that the male swimmers of the elite group started differentiating themselves at 17 years old ($t_{(99.6)} = -2.21$, $p<0.05$). No difference was found between female swimmers of differing performance groups. In the 200m, elite male swimmers were predicted to be relatively slower in the first 50m, but faster in the 150m section, compared to swimmers from the high-competitive group. Swimmers from the elite group differentiated themselves as early as 16 years old (RST50: $t_{(51.728)} = 3.10$, $p < 0.01$; RST150: $t_{(57.699)} = 3.11$, $p < 0.01$). Elite female swimmers were relatively slower in the first 50m section, but faster in the 150m and 200m sections, compared to the high-competitive group. The difference started at 13 years of age (RST50: $t_{(51.07)} = 2.36$, $p < 0.05$, RST150: $t_{(77,62)} = 4.62$, $p < 0.001$; RST200: $t_{(97,66)} = -3.065$, $p < 0.01$). In both the 100m and 200m, the model predicted no significant difference in RST between the elite and sub-elite groups (Figure 1C and Figure 2C).

4. Discussion

The present study aimed to investigate the pacing behaviour development of swimmers throughout adolescence, explicitly differentiating between the effects of age and experience as well as investigating its relationship to performance level in adulthood. As hypothesized, older male swimmers adopted a more all-out distribution of effort in the 100m event, although this development was not exhibited by female swimmers. In the 200m, male and female swimmers exhibited a more even distribution of effort as they became older. Both race experience and age independently impacted the pacing behaviour of adolescent swimmers, providing evidence that experience is not the sole driver of pacing behaviour development. Furthermore, adolescent swimmers who in adulthood reached the elite level (100m: male, 200m: male & female) exhibited a pacing behaviour more resembling adult swimmers compared to swimmers in the high-competitive group. As hypothesized, the distinction in pacing behaviour between swimmers of differing future performance level occurred earlier in female compared to male swimmers.

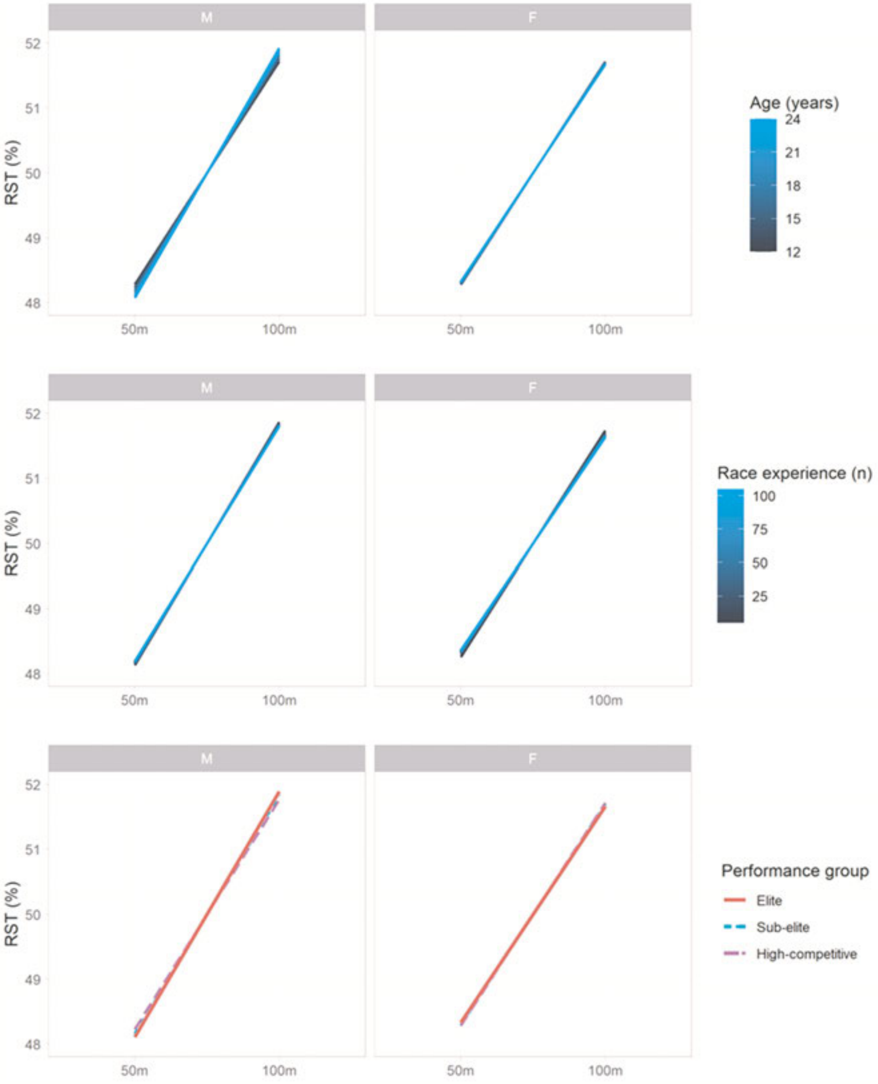

Figure 1. Predicted pacing behaviour for males and females in the 100m freestyle event according to age, race experience and performance level.

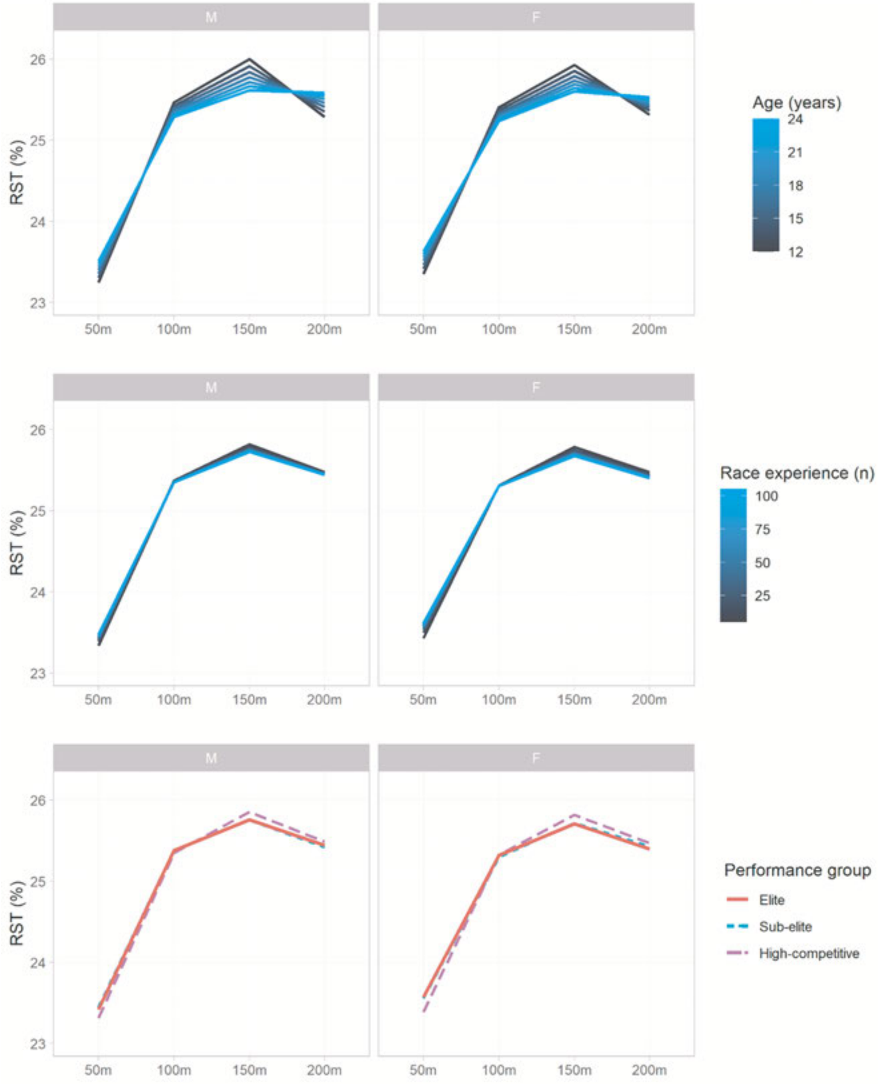

Figure 2. Predicted pacing behaviour for males and females in the 200m freestyle event according to age, race experience and performance level.

Table 2. Multilevel models predicting relative section time per 50m section, divided by sex and event.

Male (100m freestyle)	**50m**				**100m**			
	Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
Fixed Effects								
Intercept	48.90	0.15	48.61 – 49.19	<0.001	51.10	-	-	-
Age[a]	-0.30	0.05	-0.40 – -0.20	**<0.001**	0.30	-	-	-
Race experience[a]	0.02	0.01	0.01 – 0.04	**0.006**	-0.02	-	-	-
Elite vs. Sub-elite	0.05	0.04	-0.02 – 0.12	0.190	-0.05	-	-	-
Elite vs. High-competitive	0.12	0.03	0.06 – 0.19	**<0.001**	-0.12	-	-	-
Random Effects								
σ2	0.22					-	-	-
τ00	0.11					-	-	-
ICC	0.33					-	-	-
Marginal R2 / Conditional R2	0.011 / 0.334					-	-	-

Male (200m freestyle)	**50m**				**100m**			
	Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
Fixed Effects								
Intercept	22.20	0.14	21.94 – 22.47	<0.001	26.14	-	-	-
Age[a]	0.38	0.05	0.28 – 0.47	**<0.001**	-0.26	-	-	-
Race experience[a]	0.05	0.01	0.03 – 0.06	**<0.001**	-0.01	-	-	-
Elite vs. Sub-elite	0.03	0.03	-0.03 – 0.09	0.412	-0.00	-	-	-
Elite vs. High-competitive	-0.11	0.03	-0.16 – -0.05	**<0.001**	-0.03	-	-	-
Random Effects								
σ2	0.10					-	-	-
τ00	0.05					-	-	-
ICC	0.34					-	-	-
Marginal R2 / Conditional R2	0.011 / 0.334							

Note: [a] = the variables age and race experience were log-transformed. The p-value of significant predictor variables (α < 0.05) indicated in bold.

150m				**200m**			
Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
27.42	0.10	27.23 – 27.61	<0.001	24.24	0.16	23.92 – 24.55	<0.001
-0.55	0.03	-0.62 – -0.48	**<0.001**	0.43	0.06	0.32 – 0.54	**<0.001**
-0.03	0.01	-0.04 – -0.02	**<0.001**	-0.01	0.01	-0.03 – 0.01	0.240
-0.00	0.02	-0.04 – 0.04	0.858	-0.02	0.03	-0.09 – 0.04	0.495
0.09	0.02	0.06 – 0.13	**<0.001**	0.04	0.03	-0.02 – 0.10	0.150
0.06				0.17			
0.02				0.05			
0.23				0.22			
0.152 / 0.345				0.020 / 0.233			

Table 2. (Continued)

Female (100m freestyle)	**50m**				**100m**			
	Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
Fixed Effects								
Intercept	48.06	0.13	47.80 – 48.31	<0.001	51.94	-	-	-
Age^{a}	0.06	0.05	-0.03 – 0.15	0.215	-0.06	-	-	-
Race experience^{a}	0.04	0.01	0.02 – 0.05	**<0.001**	-0.04	-	-	-
Elite vs. Sub-elite	-0.03	0.03	-0.10 – 0.03	0.331	0.03	-	-	-
Elite vs. High-competitive	-0.05	0.03	-0.10 – 0.01	0.095	0.05	-	-	-
Random Effects								
σ2	0.17					-	-	-
τ00	0.08					-	-	-
ICC	0.33					-	-	-
Marginal R2 / Conditional R2	0.010 / 0.335							

Female (200m freestyle)	**50m**				**100m**			
	Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
Fixed Effects								
Intercept	22.24	0.12	22.01 – 22.46	<0.001	26.02	-	-	-
Age^{a}	0.40	0.04	0.32 – 0.49	**<0.001**	-0.24	-	-	-
Race experience^{a}	0.06	0.01	0.05 – 0.07	**<0.001**	-0.00	-	-	-
Elite vs. Sub-elite	-0.01	0.03	-0.07 – 0.04	0.616	-0.02	-	-	-
Elite vs. High-competitive	-0.18	0.02	-0.23 – -0.14	**<0.001**	0.00	-	-	-
Random Effects								
σ2	0.09					-	-	-
τ00	0.05					-	-	-
ICC	0.37					-	-	-
Marginal R2 / Conditional R2	0.142 / 0.463							

Note: ^{a} = the variables age and race experience were log-transformed. The p-value of significant predictor variables ($\alpha < 0.05$) indicated in bold.

150m				**200m**			
Estimates	Std. Error	CI	p	Estimates	Std. Error	CI	p
27.15	0.08	26.99 – 27.31	<0.001	24.60	0.12	24.36 – 24.84	<0.001
-0.47	0.03	-0.52 – -0.41	**<0.001**	0.30	0.05	0.22 – 0.39	**<0.001**
-0.04	0.00	-0.04 – -0.03	**<0.001**	-0.02	0.01	-0.04 – -0.01	**<0.001**
0.01	0.02	-0.03 – 0.04	0.719	0.03	0.03	-0.02 – 0.08	0.203
0.11	0.02	0.08 – 0.14	**<0.001**	0.07	0.02	0.03 – 0.12	**0.001**
0.05				0.12			
0.02				0.03			
0.26				0.21			
0.166 / 0.380				0.015 / 0.225			

4.1. Pacing behaviour development in swimming

In previous literature, the effect of experience and age has often been used synonymously (13, 16, 17). However, this seems to be an oversimplification. In the 100m, the behaviour of older male swimmers moves towards a fast first 50m, hereby paralleling the behaviour of the elite swimmers in adulthood. This resemblance, however, was not observed when comparing male swimmers based on race experience. It supports the notion that pacing behaviour development is driven by other age-related factors (e.g., physical maturation and cognitive development) alongside the increase in experience. Additionally, these findings suggest that race experience in itself may not be sufficient to explain the development of future elite performers. Further evidence for this view is provided by the finding that in the 200m event, age still impacts pacing behaviour in both male and female swimmers, even with a separate variable for race experience included in the model. Moreover, the results show that in line with the hypothesis, the separation between future performance levels occurs at a younger age in females (13 years old) compared to males (16 years old). The earlier onset of pacing behaviour development in females, which has previously been described in a cross-sectional study (20) is thereby confirmed by the current longitudinal study and is thought to be caused by the earlier onset of physical maturation and cognitive development (20, 21).

Based on previous literature, it was proposed that with experience and age, adolescent athletes adapt their pacing behaviour to better fit the task demands (6, 7). Indeed, within the present study, there is a difference in the development of pacing behaviour in the 100m and the 200m events. In the 100m event, older male swimmers adopt a more all-out pacing behaviour, characterized by a relatively faster first lap. The relatively faster initial 50m could be the result of an improved race start, including the dive and underwater phase. Alternatively, it has been established that in tasks of similar duration to the 100m freestyle event, better-performing athletes differentiated themselves by a relatively more all-out pacing behaviour (31, 32). De Koning *et al.* proposed that for shorter events (<2min), the advantage of a higher velocity in the first part of an exercise task and the lower amount of kinetic energy left at the end of the race, outweighed the disadvantage of higher frictional losses associated with the higher average velocity (32), which was further evidenced through modelling studies in speed skating and track cycling (33, 34), although differences between sports were visible (35). Indeed, elite swimmers competing in the 100m freestyle finals of international events exhibited an all-out pacing behaviour comparable to the one found in the current study (12). Moreover, it was reported that elite male swimmers adopted a more all-out pacing behaviour (RST50m: 47.91%, RST100m: 52.09%) compared to female swimmers (RST 50m: 48.29%, RST100m: 51.77%) (12). These findings are supported by the results of the present study, as adolescent male swimmers not only presented a more all-out pacing behaviour, but also continued to develop this behaviour with age. The reason behind the apparent difference in pacing behaviour between male and female swimmers could potentially be found in the physical and physiological differences between male and female swimmers (36). Alternatively, it has been reported that males engage more in risk-taking behaviour and therefore are expected to generally adopt a more all-out pacing behaviour (37).

Contrary to the 100m event, older male and female swimmers adopt a relatively more even distribution of velocity in the 200m event. This is achieved by a relatively slower first and last 50m section and a relatively faster middle section. Swimming is a head-to-head type event, as the winner of a race is the swimmer who covers the given distance before the other swimmers, independent of the time set by swimmers in previous races (8). Remarkably, the development of pacing behaviour in swimming does not resemble that of other middle-distance head-to-head events, such as short-track speed skating. Studies in these events have reported that the athletes' pacing behaviour develops towards a more conservative start and middle section of the race to facilitate the athlete to position themselves well and be relatively faster in the key final stages of the race (7, 20, 21). The development of pacing behaviour in the 200m more resembles the one found in time-trials of a similar duration (6, 38, 39). This development is characterized by a shift towards a more even distribution of effort, which allows for a minimization of energy loss due to acceleration and deceleration, resulting in better performance in middle- and long-distance time-trial based events (40). This resemblance to time-trials likely originates from the lane-based nature of competitive swimming (8). The lanes inhibit the interaction with other competitors, resulting in a less interactive competitive environment, as is also found in time-trial events. Taken together, coaches could expect to encounter sex- and age-related differences in pacing behaviour in adolescent swimmers of the same level of race experience. Additionally, as adolescent athletes get older, they adapt their pacing behaviour to fit the characteristics of the task, with male swimmers adopting a more all-out behaviour on the 100m and both male and female swimmers adopting a more even distribution of effort in the 200m event.

4.2. Future performance

The findings of the present study provide evidence that the swimmers who perform within 104% of the prevailing world record as adults (i.e., the elite group), exhibit pacing behaviour that differentiates them from other adolescent swimmers (i.e., the high-competitive group). It therefore establishes that adequate pacing behaviour development is an essential part of the developmental pathway towards elite swimming performance. In the 200m event, the effect of future performance level parallels the effects of age and race experience in both males and females. In other words, swimmers that achieve a higher level of performance in adulthood exhibited a pacing behaviour resembling that of older and more experienced swimmers during adolescence. This is different for the 100m event. Adolescent male swimmers who reach the elite level as an adult exhibit a pacing behaviour that is more resembling the pacing behaviour of the older swimmers (all-out pacing behaviour) compared to that of their peers who reach the high-competitive level. However, the current findings suggest that more race experience results in a more conservative first 50m in the

100m instead of going more all-out. The underlying mechanism for this converse effect of race experience on pacing behaviour in 100m event remains unclear and warrants further research. In females, no effect of either performance level or age was found, however, the effect of race experience was equal to males.

In the present study, no distinction could be made between elite and sub-elite swimmers. A possible reason for this could be the high performance level of all included swimmers in the present study. To place it into context, for a male 200m swimmer competing in 2022, the performance levels equal a time of <106.18s (elite), 106.18-109.75s (sub-elite) and 109.75-118.93 (high-competitive). The Olympic Qualifying Time for Tokyo 2021 was set at 107.02s (41). In comparison to the current study, a previous study did report a difference in pacing behaviour between three performance levels (6). However, Wiersma *et al.* determined adult performance using the season best performance at 18-19 years of age, whereas the present study used a more appropriate measure to indicate adult performance level: all-time peak performance after 20 (female) or 22 (male) years of age expressed as a percentage of the prevailing world record. Recalculating the performance level of the athletes in the previous study, using these methods results in a much wider spectrum of performance (elite: 113.8%, sub-elite: 120.6%, non-elite: 129.7%), could explain why the previous study did find a difference in pacing behaviour development between the performance levels.

4.3. Limitations and future directions

Although the models created in the present study provide novel insights into the relationship between age, experience and pacing behaviour, the models do not account for all the variance in a swimmers' pacing behaviour. Pacing is a complex, psychophysiological process, and even when the task characteristics are set, it is influenced by a multitude of factors relating to the individual (i.e., physical maturity, cognitive development, muscle fiber type distribution) and environment (i.e., coaching culture, training opportunities) (1, 9, 42, 43). The absence of these factors has potentially led to the lower explained variance of the models. For example, there was no effect of age or performance level on pacing behaviour in female swimmers competing in the 100m event. In males, the effect of age and performance group was also more pronounced in the 200m event compared to the 100m event. It could be that 100m freestyle performance is predominantly driven by the development of physical characteristics, such as muscle fibre type distribution, whereas in the 200m event, the distribution of effort is a stronger predicter of race performance. However, another reason might be that the 100m freestyle is often contested by both 50m and 200m specialists. The energetic system requirements between the 50m and 200m freestyle events differ significantly and therefore, swimmers who compete in these events are adapted to physiologically very different tasks (36), therefore exhibiting a different pacing behaviour. The coming together of these two types of specialized swimmers might have impacted the results of the present study. It should be pointed out that previous studies have evidenced that swimming performance is impacted by velocity in free swimming sections, but also by turns and underwater phases (44). This was demonstrated by investigating swimmers' velocity in 25m, 10m or even 5m sections (17, 44). These data have to be gathered using camera set-ups and specialized software, which drastically decreases practicality. Such an approach would have greatly reduced the sample size of the current study. In the end, the present study aimed to create models which could provide insight into the relation between age, experience and future performance level, not precisely predict each individual swimmers' pacing behaviour. The large sample size, consisting of swimmers from five continents, and the strong longitudinal nature of the data are of key importance to the rigidity of the present study's design, not in the first place because more large scale longitudinal studies on pacing behaviour development are needed (4, 21). Consequently, the decision was made to use publicly available 50m split times. The choice for this approach does allow for future studies, using more detailed quantifications of pacing behaviour and the inclusion of more individual and environmental factors to provide additional insights into the development of pacing behaviour in the 100m and 200m freestyle events.

4.4. Practical application

The effect of age and race experience on pacing behaviour as reported in the present study are relatively small compared to that of task defining characteristics such as race duration or stroke type (8). However, in a 200m freestyle, an average 0.16% difference in velocity distribution per 50m section (the difference between a 12 and 18-year-old male swimmer as calculated using the models in the present study) constitutes 0.20s. In a sport where 0.01 of a second can be the difference between winning and losing, a 0.20s difference in velocity distribution in every 50m section can indeed have a very real impact on competition performance. Using the formula provided in the present study, coaches could determine whether their swimmers are on track of developing the pacing behaviour necessary to achieve the elite performance level. One point of notice should be made to this approach: the road to elite performance is not always linear and pacing is only a part of the skillset necessary to reach the top (45). In addition, it has been established that to pace adequately, athletes need to match their personal performance capacities to the task demands. Seeing as there is variation in each swimmer's performance capacities, a slightly different pacing behaviour could be optimal for each swimmer. It is, therefore important to take the outcomes of the formula from the present study as a starting point and take an individualized approach to the development of each swimmer. Within this approach, coaches are advised to provide the swimmers with opportunities to experiment with variants of their established pacing behaviour (4). Introducing variability would provide swimmers with the opportunity to discover a more optimal match between their personal performance capacities and the task demands (46). Coaches could induce this variation by providing augmented feedback via tools such as a stopwatch, pacer clock, wearable metronome, underwater lights or smart goggles (47). In support of this method, a recent study reported that a three week training program in which adolescent swimmers were provided with feedback on their own pacing behaviour was effective in increasing 400m freestyle performance (48). Subsequently, practice of the new variation of pacing behaviour could be further increased by gradually taking away sources of feedback and adding environmental factors such as opponents, therefore training the swimmers to maintain their capability of decision-making regarding effort distribution in a more realistic competitive environment (9, 47).

5. Conclusion

The current large-scale study is the first in its kind in that it investigates the pacing behaviour of swimmers from five continents over a period spanning the last twenty years. The rigorous multilevel modelling approach with corrections for prevailing world records revealed insights on developmental patterns based on thousands of swimmers with on average five competitive seasons in adolescence. The pacing behaviour of swimmers develops during adolescence, as older swimmers adopt a pacing behaviour that better suits the task demands (100m: more all-out [males only], 200m: more even). Although swimming is a head-to-head type of competition, the development of pacing behaviour resembles that of time-trial events, most likely due to the lane-based nature of the sport. The persistence of the effect of age on pacing behaviour, when race experience was also included as predicting variable, supports the hypothesis that pacing behaviour development during adolescence is driven by other factors in addition to increased experience, such as physical maturation and cognitive development. Swimmers who reach the elite performance level in adulthood exhibit a pacing behaviour better suits the task demands, and that resembles that of adults (100m: more all-out [only males], 200m: more even) during adolescence. In the 200m, this differentiation occurs earlier in females compared to males, most likely due to the earlier onset of age-related physical maturation and cognitive development in females. Coaches are advised to take notice of the complex development of pacing behaviour which occurs throughout adolescence. Furthermore, coaches could use the data presented in the present study as a starting point for an individualized approach to optimize the pacing behaviour development in their swimmers and better guide them on the road towards elite performance.

6. Acknowledgements

The study conception and design were done in full collaboration with all authors. SGPM and AKP contributed equally to this manuscript. All authors critically revised the work. All authors read and approved the final manuscript. The authors do not have any conflict of interest. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The authors received no specific funding for this work.

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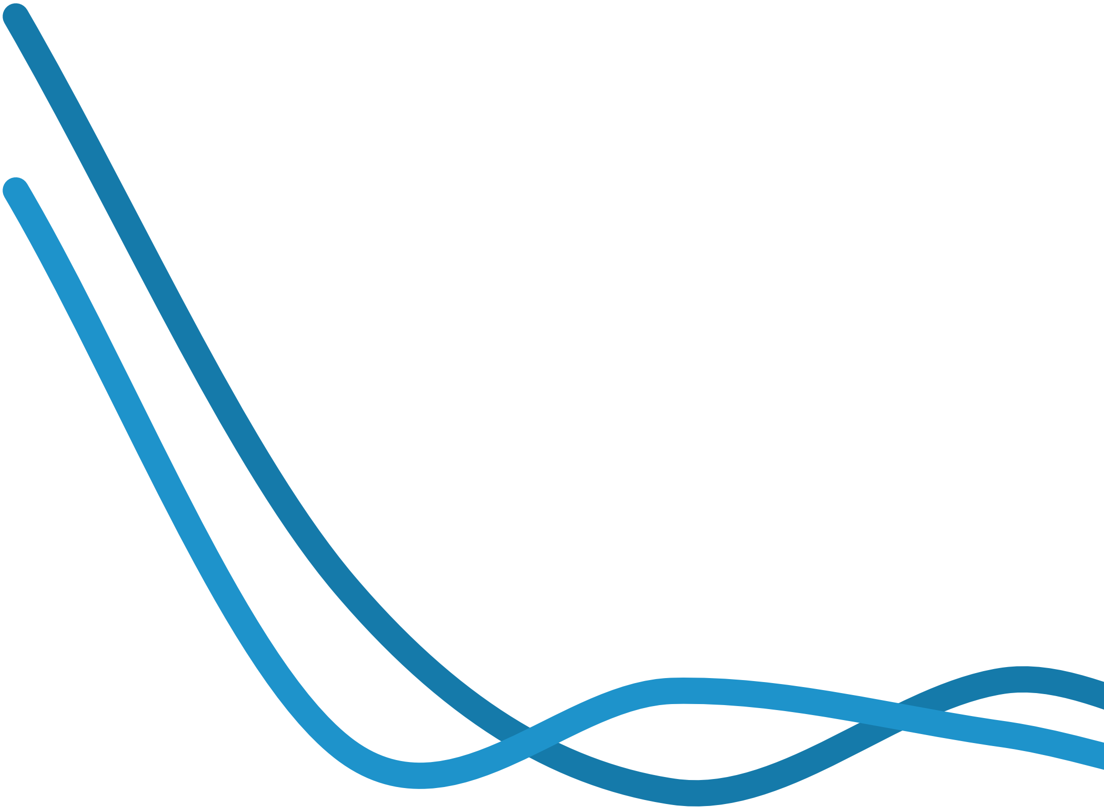
8. Appendix

To test whether the effect of age on pacing behaviour decreases as swimmers get older, the fit of the data to the models with a linear and log-transformed variable for age was compared using the Log Likelihood and Akaike information criterion (AIC). A better fit to the data is indicated in a higher value for Log Likelihood and a smaller value for AIC. As described in Table 3, the fit of the data is better to the log-transformed variable of age in all models. The one exception is the model for RST 50m in the male 100m event . To further investigate, a model with both a variable for Age and log (Age) was created. The measures for fit indicated that this third model fit the data better than either the linear or log-transformed model (Log Likelihood: -6698.47, AIC: 13406.94). Collectively, it can be concluded that the development of pacing behaviour in swimmers is most prominent during the early stages of adolescence and decreases towards early adulthood.

Table 3. Measure of fit with dataset for each model

		RST 50m		**RST 150m**		**RST 200m**	
		Log Likelihood	**AIC**	**Log Likelihood**	**AIC**	**Log Likelihood**	**AIC**
100m	Male						
	Age*	-6723.43	13454.87				
	log (Age)	-6724.74	13457.48				
	Female						
	Age	-4913.89	9835.78				
	log (Age)*	-4908.34	9824.67				
200m	Male						
	Age	-2018.36	4044.71	-624.539	1257.08	-2987.22	5982.45
	log (Age)*	-1993.31	3994.63	-588.228	1184.46	-2984.05	5976.10
	Female						
	Age	-1942.75	3893.50	-256.028	520.055	-2547.97	5103.94
	log (Age)*	-1917.98	3843.96	-221.306	450.613	-2542.80	5093.59

* = Best fit to the data: highest Log Likelihood & smallest AIC.



Chapter 9

Unravelling the role of (meta-) cognitive functions in pacing behaviour development during adolescence: planning, monitoring and adaptation

Menting S.G.P., Khudair M., Elferink-Gemser M.T., Hettinga F.J. Unraveling the Role of (Meta-) Cognitive Functions in Pacing Behavior Development during Adolescence: Planning, Monitoring and Adaptation. *Medicine & Science in Sports & Exercise (in press).*

Abstract

Purpose: To investigate whether (meta-) cognitive functions underpin the development of the self-regulated distribution of effort during exercise (i.e. pacing) throughout adolescence.

Methods: Participants included 18 adolescents (9 females, 15.6±2.5 years old) and 26 adults (13 females, 26.8±3.1 years old), all recreationally active but unfamiliar with time trial cycling. The (meta-) cognitive functions involved in pre-exercise planning were quantified by calculating the difference between estimated and actual finish time during a 4-km cycling time trial. The capability to monitor and adapt one's effort distribution during exercise was measured during a 7-min submaximal trial, in which the participants were tasked with adhering to a set submaximal goal velocity either with (0-5 min) or without (5-7 min) additional feedback provided by the researcher. Analyses included between-group comparisons (ANOVA) and within-group comparisons (correlation) ($p<0.05$).

Results: Adolescents were less accurate in their estimation of the task duration. The adolescents' overestimation of the task duration of the 4-km time trial was accompanied by pacing behavior characteristics resembling a longer trial (i.e. more even power output distribution, lower RPE, more pronounced end-spurt). Contrary to the adults, the adolescents deviated relatively more from the goal velocity during the 7-min submaximal trial, when no additional feedback was provided by the researcher. Within the adolescent group, the estimation of task duration accuracy ($r = 0.48$) and adherence to goal velocity ($r = 0.59$) correlated with age.

Conclusion: The (meta-) cognitive functions involved in the pre-exercise planning and the monitoring and adaptation of the distribution of effort during exercise underpin the development of pacing behavior during adolescence. Feedback from the (social) environment can be used to aid the monitoring and adaptation of effort expenditure in adolescents.

Keywords: exercise, cycling, performance, time trial, adolescence, cognition.

1. Introductions

Although humans are capable of staggering athletic performances, not even elite athletes are capable of endless sustained maximal effort (1). To perform optimally in a sports setting, individuals self-regulate the expenditure of effort over the exercise tasks' duration (2-4). Before starting the task, individuals make an assessment of the tasks' demands (e.g. task duration, sport-specific features, environmental factors), compare them to their performance capabilities, and plan their effort distribution accordingly (1, 3-6). During exercise, individuals monitor and adapt their effort expenditure in reference to the proximity to task goal achievement (3, 4). Brought back to its most rudimentary form, individuals continuously decide whether to increase, decrease or maintain their current level of effort expenditure to achieve the task goal (7). After task completion, individuals reflect on their pacing behaviour in relation to the resulting task performance, and use this as input for the next iteration of the task (3, 8). The goal-directed decision-making process regarding the self-regulated distribution of effort is termed pacing, and the outcome of this process is termed an individual's pacing behaviour (1, 5, 7-9). Following Newell's constraints-led approach (10), an individual's pacing behaviour is determined by a multitude of interacting factors (5), broadly falling into three main categories (8): the task (e.g. task duration or sport-specific characteristics (2, 11)), the environment (e.g. terrain or presence/behaviour of competitors (12, 13)) and the individual (e.g. muscle fibre distribution or level of experience (8, 14)). With regards to the individual, a recent series of robust longitudinal studies evidenced that the pacing behaviour of athletes is not innate, but rather develops throughout adolescence (15-17). It was ventured that with age, individuals gain an appreciation for their performance capabilities and how these fit the task demands (8). Emphasizing the importance of pacing behaviour development, it was noted that a long-term misdistribution of effort could not only lead to sub-optimal performance, which could decrease the individuals' feeling of competence and enjoyment during exercise, but could also result in overexertion, injury, and drop-out of sports and exercise (8, 18). Aiding the pacing behaviour of younger individuals could therefore aid their sense of competence and confidence, increasing their enthusiasm and engagement in sports and exercise (19). Following the principle of the constrained-led approach to skill acquisition, the impact of the individual factor of age on the pacing behaviour could be accounted for by the modification of the task characteristics or the environment (20). Edwards *et al.* (19) presented the example of younger individuals running or swimming shorter distance races to accommodate for the physical and physiological differences between younger individuals and adults. It was proposed that by gradually adapting the task characteristics (e.g. the race distance) with age, the pacing behaviour can be transferred to the version of the task as performed in adulthood (e.g. longer race distance). Furthermore, the social environment (i.e. coaches or parents) is also theorized to be able to support the pacing behaviour of younger individuals by helping them to set realistic task goals, plan an appropriate pacing strategy and reflect upon the pacing behaviour post-exercise (21). Yet, pacing is a complex process, involving a multitude of psychophysiological interactions (22). Unravelling which specific aspects are under development during adolescence, and therefore are different between adolescents and adults, could provide further direction in determining the modifications of exercise tasks presented to younger athletes, or inform appropriate guidance by their social environment.

Physical maturation, cognitive development, and an increase in exercise experience have previously been linked to pacing behaviour development (8, 23, 24). Focusing on cognitive development, Micklewright *et al.* reported that the pacing behaviour of schoolchildren was related to their scoring on tests for Piaget's stages of cognitive development (23). Theoretically, various cognitive functions, including decision-making (7, 25), the engagement in abstract, hypothetical, and prospective thoughts (23, 26), and executive functions such as retaining the task goal, inhibiting distractions, and shifting cognitive strategies (27), have been suggested to play a role in pacing. Elferink-Gemser and Hettinga (3) proposed a model for pacing behaviour development, in which repeated task exposure and the development of the pre-frontal cortex are the basis that allows younger individuals to develop the capability to think about their thoughts and actions. In succession, the development of these (meta-) cognitive functions allows for the self-regulation of effort distribution (3). In agreement with Brick *et al*. (4), (meta-) cognitive functions which were proposed to facilitate the development of pacing behaviour, included pre-exercise planning as well as the monitoring and adaptation of effort distribution during the task. An essential part of the pre-exercise planning of the effort distribution is the assessment of the task demands, including an accurate estimation of the tasks' duration (3, 7, 25). Manipulation of this estimation, by means of omitting or providing inaccurate performance feedback, has been shown to lead to the adoption of sub-optimal pacing behaviour (28-30). The estimation of task duration requires the individual to engage in (meta-) cognition, as well as consider thoughts of an abstract and prospective nature. Both of these capabilities are estimated to be developed between the ages of 11 and 20 (31, 32). It is therefore likely that adolescents experience difficulty with accurately estimating an exercise task's duration (8, 23). Menting *et al.* (33) demonstrated that adolescents with no prior cycling experience overestimated the time needed to finish a 2-km cycling time trial. Furthermore, Chinnasamy *et al*. (34) observed that children who were asked to perform a 750-m running task based on temporal feedback had difficulty estimating the remaining task duration compared to those who performed the same task based on spatial feedback. Interestingly, the authors put forward the question of whether this was due to an age-related inaccuracy in the perception of time in general or specifically in the metacognitive process of thinking about one's future performance in relation to the task's duration (34). During exercise, monitoring and adaptation of the current effort expenditure allows individuals to account for mistakes in initial planning or unexpected stimuli from the individual or the environment (3, 4, 6, 7, 26). Engagement in the (meta-) cognitive process of monitoring and adaptation of effort expenditure has been investigated by testing the capability to adhere to a submaximal goal pace. Athletes with a higher performance level were reported to be more proficient at this task (35). On the other hand, athletes with an intellectual impairment were found to struggle to maintain a pre-planned submaximal pace compared to athletes without an intellectual impairment (36). The athletes with an intellectual impairment specifically experienced difficulty with the task in the absence of external feedback provided by a coach (36). It has been suggested that aid from the (social) environment could reduce the cognitive load involved in the monitoring and adaptation of effort expenditure during exercise (20, 21). Given the (meta-) cognitive nature of the monitoring and adaptation of effort expenditure, is likely that adolescents will struggle to adhere to a goal velocity, specifically in the absence of feedback from the (social) environment. Indeed, adolescent swimmers experienced difficulty adhering to a submaximal swimming speed during an incremental step test (37). Yet, with the aid of an audio-pacing device providing sound signals, adolescent swimmers were able to adhere to the goal speed (38). Overall, there is precedent to propose that the (meta-) cognitive functions involved in the planning, monitoring, and adaptation of one's effort distribution develop throughout adolescence and underpin the development of pacing behaviour. Yet, there is a need for more structured testing of this proposition. A better understanding of how these (meta-) cognitive functions associated with pacing differ between adolescents and adults could provide further insight into the underlying mechanisms of the development of pacing behaviour, as well as offer practitioners a basis to support children and adolescents in their pacing behaviour development (3, 8, 20).

The overall aim of the current study was to investigate the differences in pacing behaviour between adolescents and adults. Initially, age-related differences were investigated by comparing the pacing behaviour of both groups during a 4-km cycling time trial. In addition, to investigate the hypothesized underlying mechanisms of pacing behaviour development as described by Elferink-Gemser and Hettinga (3), specific (meta-) cognitive functions related to pacing were tested. The pre-exercise planning of one's effort distribution was quantified by the accuracy of the estimation of a task's duration. The capability to monitor and adapt one's effort distribution was quantified by the capability to adhere to a submaximal goal pace, both with and without feedback from the (social) environment. It was hypothesized that: 1) the observed pacing behaviour during the 4-km cycling time trial differs between adolescents and adults, 2) adolescents are less accurate in their estimation of task duration, and 3) adolescents experience more difficulty adhering to a submaximal goal pace, specifically without additional feedback from the (social) environment.

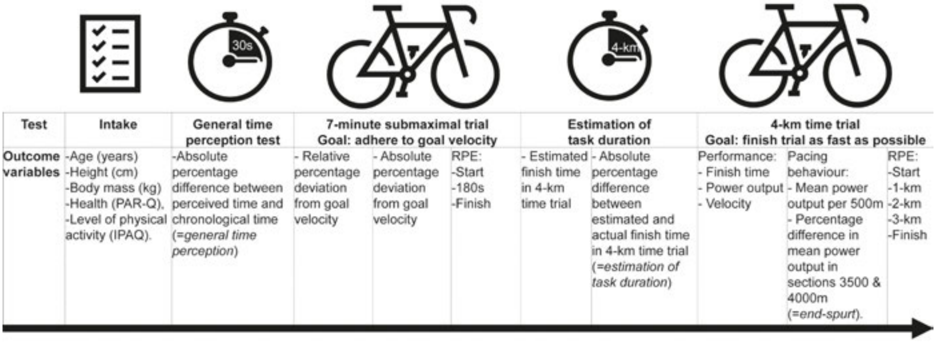
2. Methods

2.1. Participants

Two groups of adolescents (12-18 years old) and adults (20-35 years old) were recruited to participate in the study. Potential participants were excluded from taking part if they were not able to safely engage in physical exercise testing (as determined by the PAR-Q) (39), did not have moderate to high activity levels (IPAQ) (40), or had any prior experience with cycling time trials. A total of 18 adolescents (9 females, 15.6 ± 2.5 years old, height: 168.5 ± 15.8 cm, body mass: 60.2 ± 19.9 kg) and 26 adults (13 females, 26.8 ± 3.1 years old, height: 173.0 ± 8.7 cm, body mass: 72.0 ± 13.1 kg) participated in the study. Before starting the study, written informed consent was obtained from the participants. In the case of the adolescent group, written informed assent was obtained from the participants as well as written informed consent provided by their parents or legal guardians. Participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 hours, and from caffeine and food consumption, respectively, four and two hours before the start of the visit to the laboratory. The study was approved by the ethical committee of the local university in accordance with the Declaration of Helsinki (reference number: 15746).

2.2. Experiment proceedings

An integrated design of several measurements was used to test the hypotheses (Figure 1). The participants performed two cycling trials: a 7-min submaximal trial and a 4-km time trial. The cycling trials were performed on the Velotron cycling ergometer (Velotron Dynafit, Racermate, Seattle, USA). Using the Velotron 3D software, a straight 4-km track was created, which was used in both trials. The track, including an avatar which represented the participant, was projected on a screen in front of the ergometer. Power output, velocity, distance covered, and gear selection were gathered with a sampling rate of 25Hz and monitored by the experimenter during both cycling trials. Trials were conducted at ambient temperatures between 19°C and 21°C.



Test	**Intake**	**General time perception test**	**7-minute submaximal trial Goal: adhere to goal velocity**			**Estimation of task duration**		**4-km time trial Goal: finish trial as fast as possible**		
Outcome variables	-Age (years) -Height (cm) -Body mass (kg) -Health (PAR-Q), -Level of physical activity (IPAQ).	-Absolute percentage difference between perceived time and chronological time (=*general time perception*)	- Relative percentage deviation from goal velocity	- Absolute percentage deviation from goal velocity	RPE: -Start -180s -Finish	- Estimated finish time in 4-km time trial	- Absolute percentage difference between estimated and actual finish time in 4-km time trial (=*estimation of task duration*)	Performance: - Finish time - Power output - Velocity	Pacing behaviour: - Mean power output per 500m - Percentage difference in mean power output in sections 3500 & 4000m (=*end-spurt*).	RPE: -Start -1-km -2-km -3-km -Finish

Figure 1. Schematic overview of the experimental procedures and outcome variables (chronological from left to right).

The participants were asked to perform a general time perception task (before the submaximal trial) and provide an estimation of task duration for the 4-km time trial (between the 7-min submaximal trial and the 4-km time trial). During the general time perception task, the participants were instructed to read a section of a popular novel, which was the same across all participants, and provide the researcher with an audible "stop" when they thought 30 seconds had passed. The researcher would examine if the participant actually read the text by both watching the participants' eye movements and asking the participant general questions, including whether they recognized the text and to generally summarize what they just read. The accuracy of general time perception was defined as the absolute percentage difference between perceived time (i.e. when the participant thought the 30 seconds had passed) and chronological time on the stopwatch. A lower percentage represents a better general time perception. Before starting the 4-km time trial, participants were asked to provide an expected finish time ("In what time do you think you will complete the trial? The trial is 4-km, which equals 2.5 miles"). The estimation of task duration was calculated as the absolute percentage difference between the expected finish time and the actual finish time (a lower percentage representing a more accurate estimation).

The 7-min submaximal trial was an adaptation of the design described by van Biesen *et al.* (36). Participants were tasked with cycling at a set goal velocity for a duration of seven minutes. The exact goal velocity was unknown to the participants. Feedback on the goal velocity was provided by a combination of signs visible next to the virtual track (every 75m) and an audio track with distinct beeps at a set time corresponding to the goal velocity (e.g. when the goal velocity was 24.6 km/h, there would be a beep every 11.0 seconds). Participants were instructed to stay as close as possible to the goal velocity by matching the audio beeps to the participant's avatar passing the signs. Additional directions included: 1) when the audio beep was heard before passing the sign, the participant was cycling too slow, and 2) when the audio beep was heard after passing the sign, the participant was cycling too fast. The trial started with a "rolling start" at the goal velocity, facilitated by the researcher providing feedback in the form of vocal instructions to the participants ("you are going too slow, please speed up", "you are going too fast, please slow down"). During the first five minutes of the trial, the researcher assisted the participants to maintain the goal velocity by providing additional feedback on their current performance, using the same vocal instructions used to facilitate the rolling start. This additional feedback was provided every time the participants' avatar past a 75m sign. During the last two minutes of the trial, the additional feedback was not provided. The goal velocity was based on 70% of mean velocity during a 4-km time trial, using sex and age-matched normative data from previous studies (adolescent male: 23.2 km/h, female 21.0 km/h; adult male: 26.0 km/h, female: 23.5 km/h) (33, 41-43). The mean relative and absolute deviations from the goal velocity were calculated for each minute of the trial. The rate of perceived exertion (RPE) was measured just before the start, at 180 seconds into the trial, and immediately after completing the trial, using the OMNI 0-10 cycling scale (44, 45). The submaximal test also acted as the warm-up for the 4-km time trial. A period of approximately 2-3 minutes between the two trials was used for recovery and to provide participants with the instructions regarding the 4-km time trial. After the instructions were provided, the participants were asked to verbally indicate whether they felt ready to start the 4-km time trial.

Before starting the 4-km time trial, participants were instructed to "finish the 4-km cycling trial as fast as possible". Additionally, the participants were made aware that the finish line would be visible as a blinking line on the track, and that it would be called out to them by the researcher as soon as it appeared. The participants were unaware that the moment the finish line became visible was 250m before the end of the trial. To increase the impact of the estimation of task duration on pacing behaviour and performance, no numerical feedback (e.g. distance covered, power output, velocity) was provided to the participants before, during, or after the trial. Furthermore, participants were told that RPE was measured at random points in the trial. In reality, RPE was measured before the start, when the participants had covered 1, 2, or 3-km (for each trial, two of these points were chosen at random), and at the finish line.

2.3. Data analysis

The hypotheses were tested by means of a comparison of outcome variables between the groups of adolescents and adults. Additional analyses involved the exploration of the relations between outcome variables within each group.

The Shapiro-Wilk test, used to test for normality, revealed that the age of the participants within both groups violated the assumption of normality. Additionally, within the adult group, measures for general time perception, estimated finish time, and estimation of task duration also violated the assumption of normality. Testing whether the estimated finish time and actual finish time differed within adolescent and adult groups, was done using a paired sample t-test or a Wilcoxon signed rank test, respectively. Between age group differences in general time perception, estimated finish time, and the estimation of task duration were analysed using Mann-Whitney tests. If a difference between age groups was found, the relation between age, general time perception, and estimation of task duration was further investigated within the adolescent and adult groups, using Spearman's rho correlation.

Differences in 4-km time trial performance between the adult and adolescent groups were analyzed using independent t-tests of finish time, mean power output, and mean velocity. Differences in pacing behaviour between the two age groups were analysed using a two-way repeated measures analysis of variance (ANOVA), using mean power output during each 500m segment as within-subject factor and age group as between-subject factor. If a significant interaction effect was found, a post hoc analysis, using an independent t-test with Bonferroni correction of normalized power output for each 500m section, was used to determine in which section the difference between adolescents and adults occurred. In addition, the end-spurt was defined as the percentage increase (positive value) or decrease (negative value) in power output from the 3000-3500m to the 3500-4000m section. An independent t-test was used to study the difference in end-spurt between the age groups. If a difference in end-spurt between the age groups was found, the relation between the end-spurt and age was further explored within the adolescents and adult group, using Spearman's rho correlation. Additionally, the relationship between end-spurt and estimation of task duration would be investigated within the adolescent group (using Pearson's correlation) and adult group (using Spearman's rho correlation). Due to the randomization of the RPE measurement moments, a series of independent t-tests with Bonferroni corrections were used to test the difference in RPE between age groups, just before the start, at 1-km, 2-km, 3-km and at the completion of the race.

The participants' capability to adhere to the goal velocity during the 7-min submaximal trial was investigated by the visual representation of the mean relative and absolute deviation from goal velocity per minute, and per section (with or without additional feedback). The homogeneity of variance of the relative and absolute deviation from goal velocity for each minute of the trial, as well as the sections with (0-5 minutes) and without additional feedback (5-7 minutes), were analysed using the Brown–Forsythe test. Additionally, the mean absolute percentage difference from goal velocity during the sections with and without additional feedback was compared between the age groups. Mann-Whitney tests were used to make this comparison between the age groups, as the assumption of normality was violated. Within each age group, Wilcoxon signed rank tests were used to compare the absolute deviation from goal velocity between the sections with and without additional feedback. As a supplementary within-group analysis, Spearman's rho correlations were used to explore the relationships between the absolute deviation from goal velocity (with and without additional feedback), age, and estimation of task duration. A two-way repeated measures ANOVA was used to test differences in RPE at the start, at 180 seconds, and finish of the trial, between age groups.

In all analyses, statistical significance was set to 0.05. Tests for the significance of the correlations were one-tailed, following the direction as stated in the hypotheses. Linear regression equations were added to quantify the relation between variables. If the assumption of sphericity was violated for the ANOVA, the Greenhouse-Geisser correction was used. Cohen's d and Cohen's f were used to report the effect sizes of the t-tests and ANOVA's, respectively (46). Effect size and correlations were compared to set benchmarks and considered either small ($d = 0.2$, $f = 0.1$, $r = 0.1$), medium ($d = 0.5$, $f = 0.25$, $r = 0.3$), or large ($d = 0.8$, $f = 0.4$, $r = 0.5$) (46, 47).

3. Results

3.1. Time perception and estimation of task duration

Mean (±standard deviation) values of measures for general time perception, estimated finish time, and estimation of task duration are presented in Table 1. No differences between age groups were found in the absolute difference between perceived time and chronological time, indicating no difference in general time perception between age groups. The significant difference between the estimated and actual finish time indicated that both adults ($\Delta = 89.1$s, $U = 2.88$, $p<0.01$) and adolescents ($\Delta = 182.9$s, $t = 3.07$, $p<0.01$) overestimated the time it would take to finish the 4-km time trial. The estimation of task duration was higher in adolescents, indicating that adolescents were less accurate in their estimation of task duration. Within the adolescent group, a negative correlation was found between age and estimated finish time (Figure 2A), as well as between age and estimation of task duration (Figure 2B). No such correlations were found in the adult group.

Table 1. Means (±standard deviation) for performance variables, estimation of task duration, and end-spurt measures for adolescent and adult groups, including mean difference (±standard error) between age groups and outcomes of the statistical between-group tests.

	Adolescents	Adults	Δ age groups	Statistics
General time perception (%)	7.75 (±5.84)	7.92 (±8.52)	0.17 (±2.31)	U = 236.0, p = 0.96, d = 0.08
Estimated finish time (s)	717 (±286)	565 (±166)	-152 (±68)	U = 151.5, p < 0.05, d = 0.67
Estimation of task duration (%)	44.4 (±28.4)	27.7 (±26.5)	-16.7 (±8.4)	U = 130.0, p < 0.05, d = 0.63
Finish time (s)	534.15 (±85.60)	475.92 (±52.39)	-58.23 (±20.80)	t = 2.80, p < 0.01, d = 0.86
Power output (Watt)	136.7 (±52.2)	174.0 (±51.6)	37.3 (±15.9)	t = 2.34, p < 0.05. d = 0.72
Velocity (km/h)	27.60 (±4.32)	30.61 (±3.39)	3.01 (±1.16)	t = 2.59, p < 0.05, d = 0.79
End-spurt (%)	19.1 (±12.5)	9.9 (±10.2)	-9.2 (±3.5)	t = 2.67, p < 0.05, d = 0.82

3.2. 4-km time trial

Adults performed better in the time trial, indicated by a 21.4% higher mean power output, 9.8% higher mean velocity, and a 12.2% lower finish time (Table 1). Mean (±standard deviation) values of the velocity and normalized power output per 500m, for both adolescents and adults, are presented in Figure 3. Adolescents exhibited a lower normalized power output during 0-500m section and a higher normalized power output during sections 1500-2000m and 3500-4000m ($F_{1.80, 76.05} = 7.09$, $p < 0.01$, $f = 0.40$). Adolescents exhibited a 9.2% larger increase in power output during the last 500m of the trial (i.e. the end-spurt) compared to the adults. Both in the adolescent and adult groups, there was no significant correlation between age and end-spurt (Figure 2C). However, it should be mentioned that the regression equations in both groups indicate a trend towards a decrease in end-spurt with age. Within the adolescent group, there was a positive correlation between end-spurt and the estimation of task duration (Figure 2D). The RPE score at the start 4-km trial did not differ between the age groups. Furthermore, the low score indicates that both groups felt sufficiently rested before starting the 4-km trial. Adults reported a higher RPE at 1-km, 2-km, 3-km, and at the finish of the trial (Figure 4).

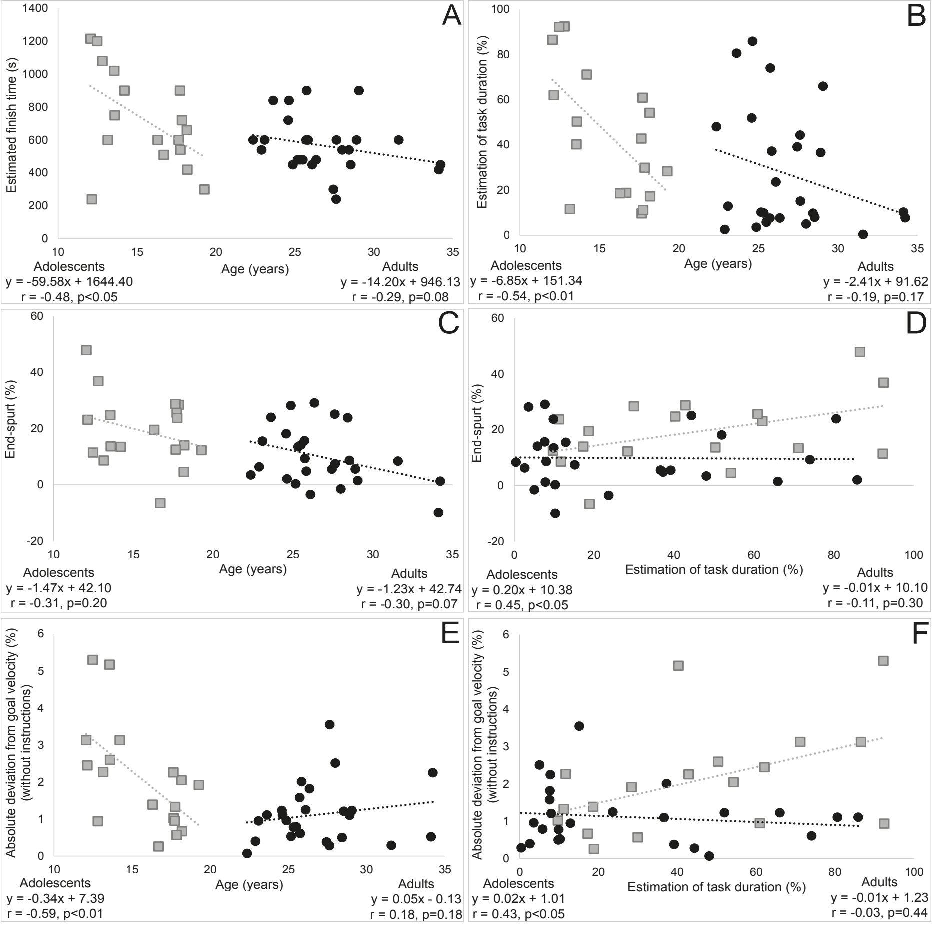


Figure 2. Scatterplots displaying data points of adolescents (grey squares) and adults (black circles), including linear trendlines and regression equations as well as outcomes of the statistical tests (correlations) of the following relations: A) age and estimated finish time, B) age and estimation of task duration, C) age and end-spurt, D) estimation of task duration and end-spurt, E) age and absolute deviation from goal velocity (without additional feedback), F) estimation of task duration and absolute deviation from goal velocity (without additional feedback).

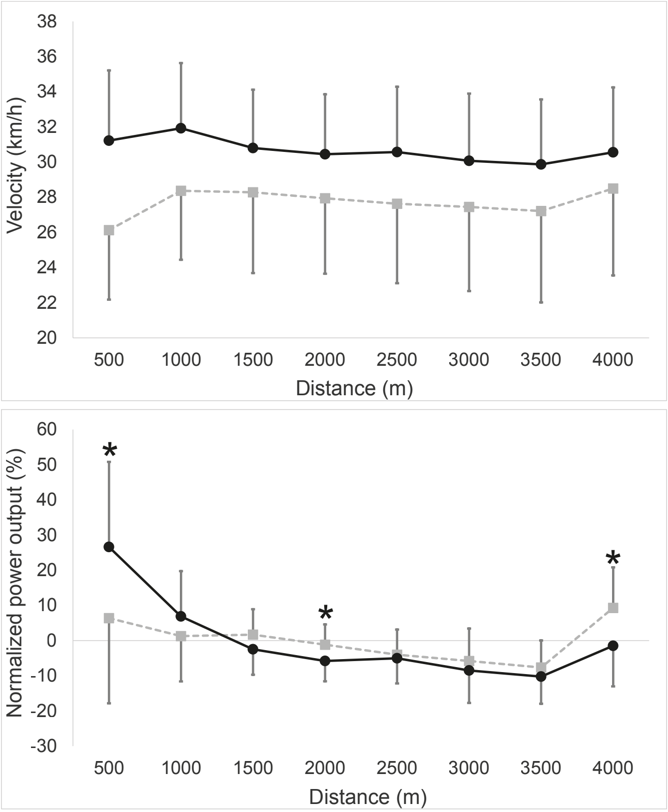


Figure 3. Pacing behaviour of adolescents (grey, squares) and adults (black circles) during the 4-km time trial, expressed as velocity and normalized power output over 500m sections. * = $p<0.01$, $d>0.80$.

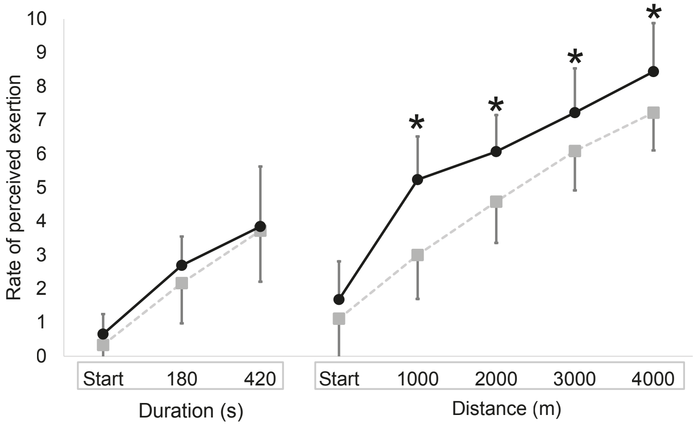


Figure 4. Rate of perceived exertion of adolescents (grey squares) and adults (black circles) per section during the 7-min submaximal trial and 4-km time trial. * = $p<0.05$, $d>0.90$.

3.3. 7-min submaximal trial

The mean (± standard deviation) and the variance of the relative and absolute deviations from goal velocity during the 7-min submaximal trial are presented in Figure 5. There was no difference in the variance of the relative deviation from goal velocity between age groups. Adolescents exhibited a larger variance in the absolute deviation from goal velocity in the section without additional feedback, specifically during 300-360s. No difference between age groups in the absolute deviation from goal velocity was found in the section with additional feedback (0-5 minutes). In the section without additional feedback (5-7 minutes), the adolescents' absolute deviation from goal velocity was higher compared to the adults (Δ0.87%, U = 2.46, $p<0.05$). Within the adolescent group, the absolute deviation from goal velocity was higher in the section without additional feedback, compared to with additional feedback (Δ0.87%, U = 2.59, $p<0.01$). No such difference was found in the adult group. Supplementary analysis within the adolescent group revealed a significant negative correlation between age and the absolute deviation from goal velocity in the section without additional feedback (Figure 2E). Furthermore, there was a significant positive correlation between the estimation of task duration and the absolute deviation from goal velocity in the section without additional feedback (Figure 2F). No such correlations were found in the adult group. No differences in RPE were found between the age groups during the submaximal trial ($F_{1.42, 59.80} = 0.65$, $p=0.47$, $f = 0.12$) (Figure 4).

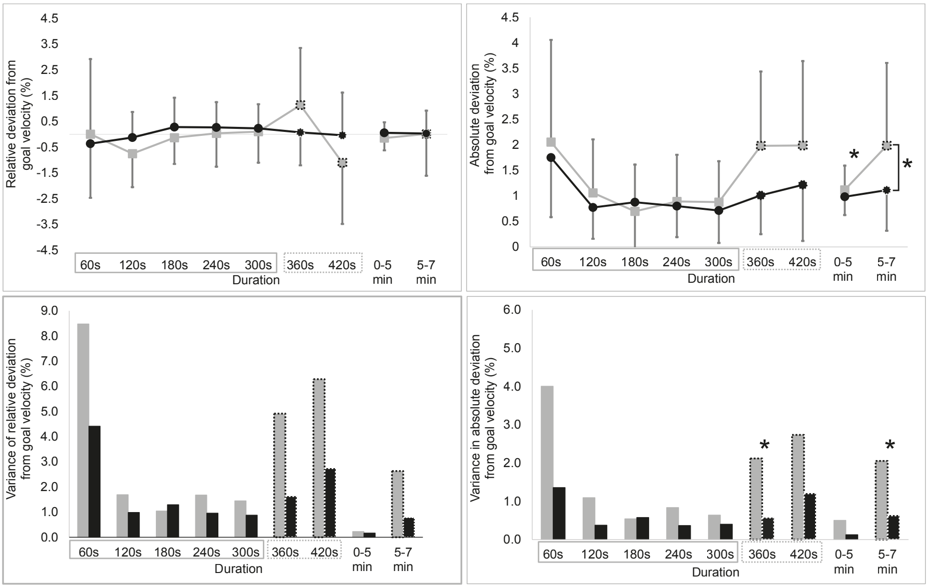


Figure 5. Mean (±standard deviation) and variance of the relative and absolute deviation from goal velocity for adolescents (grey squares) and adults (black circles) during each minute of the 7-min submaximal trial, as well as the full sections with additional feedback (solid border) and without additional feedback (dotted border). For relative deviation: positive value = faster than goal velocity, negative value = slower than goal velocity. * = $p<0.05$.

4. Discussion

The current study revealed a difference in pacing behaviour during the 4-km cycling time trial between adolescents and adults, providing further support for the view that pacing behaviour develops during adolescence. Furthermore, the findings that adolescents demonstrate an inaccuracy in the estimation of task duration as well as a struggle to adhere to a set submaximal velocity without additional feedback from the researcher provide novel experimental evidence for the theorized role of (meta-) cognitive functions in the development of pacing behaviour.

4.1. Pacing behaviour: adolescents and adults

Previous observational cross-sectional and longitudinal studies in the (elite) athlete population reported that pacing behaviour differs between adolescent and adult athletes (8). The current study, using a well-controlled laboratory design, corroborates these findings, as the pacing behaviour during the 4-km time trial differed between the age groups. Furthermore, the demonstrated difference in pacing behaviour between adolescents and adults who are recreationally active suggests that pacing behaviour development is not unique to the (elite) athlete population, but rather a more general aspect of development during adolescence. The capability to self-regulate the distribution of effort over an exercise task is thought to impact the individual's feelings of competence, confidence, and enjoyment during sports and exercise, and could contribute to the risk of injury, overexertion, and drop-out (8, 18, 19). Suitable support of the development of pacing behaviour in a younger population could therefore aid not only the feeling of enjoyment but also the sustained adherence to sports and exercise, with all associated health benefits.

4.2. Planning: estimation of task duration

An accurate estimation of an exercise tasks' duration forms the basis of the pacing process and requires individuals to engage in the metacognitive process of thinking about their future actions and behaviour (23, 26). These (meta-) cognitive functions are proposed to develop during late childhood and adolescence, and are theorized to underpin the development of pacing behaviour (3, 31). Conform to this proposition, the adolescents in the current study were less accurate in their estimation of task duration ahead of the time trial, compared to adults. Additionally, within the adolescent group, younger adolescents were less accurate in their estimation of task duration compared to their older counterparts. Previous studies have speculated that such an age-related improvement in the estimation of task duration could be due to a development of time perception in general (34). However, the current study found no relationship between age and general time perception. It, therefore, seems that it is specifically the (meta-) cognitive functions involved in considering one's performance capabilities in relation to the task demands that become more accurate during adolescence. The inaccuracy in the estimation of task duration provides evidence that adolescents are less capable at engaging in the metacognitive thought process regarding their future behaviour and actions, which forms the basis for planning one's effort distribution for upcoming exercise tasks (3, 28). It would therefore be expected that the differences between age groups in the estimation of task duration and pacing behaviour during the 4-km time trial are related. Especially as the participants received relatively few environmental stimuli (they knew at the start that the trial was 4-km long and that the finish line was marked the end of the trial) and were therefore required to rely on their assessment of the task demands as a basis for the pacing process before and during the trial. Both the adolescent and adults overestimated the duration of the 4-km time trial. Yet, this overestimation of the trial's duration was significantly larger in the adolescent group compared to the adults. Previous studies have proposed that individuals performing exercise trials of a longer duration adopt a more even distribution of power output and a lower RPE throughout the majority of the trial (2, 28). It is thought that this behaviour results from the notion that power output and velocity scale non-linearly in cycling, and therefore an uneven effort distribution negatively impacts performance (2). In addition, longer trials are believed to inherently include an increased level of uncertainty about the effort requirements in the remaining duration of the task (26, 28). The individuals, therefore, are thought to maintain a greater energetic reserve to respond to unforeseen factors (26, 28). Taken together, the adolescents in the current study expected the duration of the trial to be relatively longer, and also demonstrated a more even distribution of power and lower RPE, which has been deemed optimal for a task of a longer duration. It could therefore be speculated that the estimation of task duration influenced the pacing behaviour during the 4-km time trial. Corroborating this notion are the findings related to the end-spurt. The adolescents adopted a relatively larger end-spurt during the last 500m of the trial, compared to the adults. Furthermore, in both groups the regression equations indicated a trend towards a decrease in the end-spurt with age. Within the adolescent group a larger estimated task duration significantly correlated with a larger end-spurt. It has previously been proposed that the presence of the finish line provides individuals with a relatively solid point of reference to the remaining task duration, negating the need for an energetic reserve and enabling the individual to spend the remaining energy to optimize performance (28, 30). Individuals who possess a larger energetic reserve in the final sections of the trial, due to a lower level of effort in the other parts of the trial, would therefore be capable of demonstrating a more pronounced end-spurt (48). Taking this all into account, the view arises that adolescents' overestimation of the task duration led them to adopt a lower power output during the trial, maintaining a larger energetic reserve. When the end-point of the trial became apparent at an earlier point than expected based on the inaccurate estimation of task duration, more reserved energy was available, which allowed for a more pronounced end-spurt. Overall, the current study demonstrates that the age-related difference in the estimation of task duration is paralleled by an age-related difference in pacing behaviour during exercise. Furthermore, based on our current findings it could be argued that it is the (meta-) cognitive process of accurately establishing a pre-exercise pacing plan which develops with age, and not the capability to execute this plan. In other words, although adolescents seem to struggle with the accurate formation of a pre-exercise plan for effort distribution, this population seems to have no difficulty in executing this plan. These findings, therefore, provide experimental evidence to support the framework of Elferink-Gemser and Hettinga, which proposed that throughout adolescence, individuals improve the capability to engage in the assessment of their performance capabilities and the task demands, resulting in the adoption of a pacing behaviour which fits these demands (3, 8).

4.3. Monitoring and adaptation: adherence to goal velocity

During exercise, individuals are proposed to engage in the monitoring of their effort expenditure and are thought to adapt this expenditure in response to internal and environmental stimuli (4). In the framework of Elferink-Gemser and Hettinga, the (meta-) cognitive functions of monitoring and adaptation were hypothesized to underpin the development of pacing behaviour during adolescence and would therefore differ between adolescents and adults. Additionally, previous studies have provided evidence suggesting that additional feedback from the (social) environment, in the form of vocal instructions from a coach, could aid the monitoring and adaptation of effort expenditure during exercise (36). Conform to previous studies (35, 36), these hypotheses were tested by analysing the capability to adhere to a goal velocity during a submaximal cycling trial, both with and without additional feedback from the researcher. When both age groups received additional feedback, there was no difference in adherence to the goal velocity. In the adult group, the adherence to the goal velocity remained the same in the absence of the additional feedback provided by the researcher. On the contrary, in the adolescent group, removing the additional feedback led to a decrease in adherence to the goal velocity. More specifically, without additional feedback from the researcher, the adolescent group initially started to cycle faster than the goal velocity. After a certain time, the deviation from the goal velocity likely reached a critical point, as in the second half of the section without additional feedback the adolescents made an effort to correct the error by cycling relatively slower than the goal velocity. Furthermore, compared to the adult group, the adolescent group exhibited a larger variance in adherence to goal velocity in the absence of additional feedback from the researcher. Further analysis within the adolescent group revealed that the younger adolescents experienced relatively more difficulty cycling at the pre-set pace when additional feedback from the researcher was absent. Collectively, the capability to adhere to the goal velocity seems to develop during adolescence, with younger adolescents specifically experiencing difficulty when additional feedback was absent. These findings support the framework proposed by Elferink-Gemser and Hettinga, as the (meta-) cognitive functions of monitoring and adapting one's effort expenditure during exercise seem to develop during adolescence. In addition, the finding that the age-related difference in adherence to the goal velocity only occurs in the absence of additional feedback from the researcher provides further evidence that the (social) environment could support specifically the (meta-) cognitive functions of monitoring and adaptation of effort expenditure during self-regulated exercise (21, 36) . Feedback regarding adherence to the pacing strategy from the (social) environment seems to be a viable way to support populations who struggle with the self-regulation of effort during exercise.

It should be pointed out that the additional analysis within the adolescent group revealed that the adolescents with a less accurate estimation of task duration experienced more difficulty in adhering to the goal velocity in the absence of additional feedback. This would suggest that the capability to monitor and adapt one's effort expenditure during exercise is related to the capability to accurately estimate a task's duration. There is evidence that links these two (meta-) cognitive functions, as both are associated with areas in the pre-frontal cortex (4, 32). Furthermore, the current study provides evidence that both (meta-) cognitive functions develop during adolescence. Moreover, the accurate assessment of the task demands has been pointed out to play a role not only in the planning of the distribution of effort pre-exercise but also in the monitoring and adaptation of effort expenditure during exercise (3, 4). Yet, additional experiments would be needed to confer the nature of the relationship between these (meta-) cognitive functions and the development of pacing behaviour.

4.4. Practical applications and future directions

The findings of the current study provide evidence that adolescents experience relatively more difficulty in the planning, monitoring, and adaptation of the effort distribution over an exercise task. This could have negative implications for both training (e.g. misinterpreting training dose) and competition (e.g. failure to stick to a pre-planned strategy). Fortunately, it has been proposed that modification of the task characteristics and the social environment (e.g. competitors, coaches, spectators) could increase engagement in (meta-) cognitive functions and positively influence skill acquisition and development (19-21, 49). The social environment could aid the individuals in setting realistic, achievable goals and selecting an appropriate pacing strategy, before the start of the exercise task (21). Coaches could aid individuals to engage in pre-exercise planning by asking questions such as: "how much time do you think the exercise task is going to take you?", "are you going to start fast?" or "are you going to try to save some energy for the end?". Additionally, coaches could prompt individuals to engage in the monitoring and adaptation of their effort expenditure by providing them with questions such as "can you describe how you are feeling at the moment?" or "do you think this pace will get you to the finish line?". Building a question-and-answer relationship also provides the coach with a way of monitoring the individuals' meta-cognitive capabilities and potentially intervening when necessary. One method of intervention is the provision of additional feedback, which the results of the current study demonstrated to be effective in aiding adolescents tasked with the monitoring and adaptation of their effort expenditure during exercise. Timely intervention in this manner could help prevent repetitive sub-optimal distribution of effort and the associated risks of injury, burn-out, and drop-out of sport and exercise (18, 20). Through the building of a dialog with the athlete, the coach could therefore nurture the acquisition of (meta-) cognitive functions underlying the development of pacing behaviour.

It should also be noted that the pacing process is thought to be cyclical in nature (4). After participating in an exercise task, individuals reflect and evaluate their pacing behaviour, as well as match their pacing behaviour to their task performance (4). Repeated task exposure leads individuals to adapt their pacing behaviour to better suit the task demands (12). The current study provided evidence that the development of (meta-) cognitive functions related to pacing develop during adolescence. It could therefore be hypothesized that the capability to accurately reflect upon one's pacing behaviour and integrate this in anticipation of a future task, could be another (meta-) cognitive function which is associated with the development of pacing behaviour during adolescence. Future studies are warranted to enlighten whether younger individuals might need additional aid in these reflective and adaptive aspects of pacing behaviour.

5. Strengths and limitations

The current study used an original and elegant design, combining multiple tests and outcome variables, to test multiple theory-informed hypotheses with practical relevance. However, additional insight into the pre-exercise planning could have been gained by questioning the participants on their methods of determining their estimated finish time and whether they used this information to determine their effort distribution. In addition, the tests in the current study were intentionally devised as a method of testing the concepts of meta-cognition (planning, monitoring and adaptation) in the specific process of effort distribution during exercise. Yet, the inclusion of more general tests of (meta-) cognition, such as the Self-Regulation of Learning Self-Report Scale (50), could have provided valuable additional insights.

6. Conclusion

The current study investigated the development of pacing behaviour during adolescence, by studying the planning, monitoring and adaptation of effort expenditure during exercise in a group of adolescents and adults. The adolescents demonstrated a larger overestimation of the time needed to finish the 4-km time trial, which was paralleled with this group demonstrating a pacing behaviour associated with tasks of a longer duration, and a more pronounced end-spurt. The adolescents experienced relatively more difficulty adhering to a goal velocity when in the absence of additional feedback, in comparison to the adults. Yet, when provided with additional feedback by the researcher, the adherence to the goal velocity did not differ between the age groups. The current study not only corroborates the view of pacing behaviour developing during adolescence but also differentiates specific (meta-) cognitive functions involved in the complex pacing process which underpin this development. In addition, the positive effect of additional feedback on the monitoring and adaptation of effort distribution in the adolescent group provides evidence for the supporting role of the (social) environment in the self-regulation of effort distribution in this population. Collectively, these findings provide a foundation for the design of interventions aimed at engaging individuals in sports and exercise, by supporting their development of pacing behaviour.

7. Acknowledgements

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Chapter 10

Pacing behaviour development: the role of task experience and the presence of competitors

Menting S.G.P., Khudair M., Elferink-Gemser M.T., Hettinga F.J. Pacing behaviour development: the role of task experience and the presence of competitors. *Medicine & Science in Sports & Exercise (under review).*

Abstract

Introduction: Self-regulation of effort during exercise (i.e. pacing) is a determinant of exercise performance, which develops during childhood and adolescence. Yet, the (meta-) cognitive functions underpinning this development, such as the capability to use task experience and retain the task goal in the presence of competitors, have remained relatively unexplored.

Methods: 9 adolescents (14.9 ± 2.1 years old) and 14 adults (24.2 ± 3.2 years old) completed four 4-km cycling trials in a well-controlled laboratory setting. After one familiarization visit, trials were performed randomly: alone, with the goal to finish the trial as fast as possible (AloneTime), with a competitor and the same goal (CompTime), or with a competitor and the goal to finish first (CompFirst). Within each age group, repeated measurement ANOVAs ($p<0.05$) examined the differences in the estimated task duration, pacing behaviour (distribution of mean power output per 500m) and performance (finish time) between visits (4) or conditions (3).

Results: In contrast to adults ($p<0.05$, $\eta^2p>0.20$), adolescents did not exhibit a change in estimation of task duration, pacing behaviour or performance over repeated visits ($p>0.05$, $\eta^2p<0.10$). Adolescents altered their pacing behaviour in the presence of a competitor independent of the task goal (CompTime & CompFirst), whereas adults only demonstrated this alteration when instructed to finish first (CompFirst).

Conclusion: Adolescents are still developing the capability to 1) use experience from previous tasks to adjust their pacing behaviour, and 2) inhibit the intuitive action of engaging with the competitor to retain the more abstract task goal of finishing the trial as fast as possible. These findings establish novel experimental evidence for the theorized link between (meta-) cognitive functioning and pacing behaviour development.

Keywords: acquisition, learning, adolescence, exercise, cycling, opponents.

1. Introduction

A decisive factor for success in sports is the athletes' capability to match the distribution of their available energy to the task demands (1). Before and during exercise, individuals continuously decide whether to increase, decrease or maintain the current level of effort, in order to reach the task goal (2). This goal-directed decision-making process regarding the self-regulation of effort distribution is termed pacing (2-4). The overall outcome of this process has been termed the individual's pacing behaviour (5) and is generally quantified by expressing a measure of effort over time (1). Following Newell's constraints-led approach (6), the multitude of interacting factors that influence an individual's pacing behaviour can broadly be categorized as the task (e.g. task duration (7)), the environment (e.g. behaviour of competitors (8)) and the individual (e.g. previous experience (5)). Focusing on the influence of the individual, a series of longitudinal studies established that pacing behaviour is not innate, but rather develops during childhood and adolescence (9-11). As a result, children and adolescents experience difficulty in adopting a pacing behaviour which best suits the task demands (including both task characteristics and environmental factors) (12, 13). Suboptimal pacing behaviour could have negative implications for competition, but also for training (e.g. misinterpreting training dose) (14, 15). Long-term misdistribution of effort could decrease the individuals' feeling of competence and enjoyment during exercise and contribute to overexertion, injury and drop-out of sports and exercise (5, 16). A better understanding of the factors underlying the differences in pacing behaviour between adolescents and adults could expose the mechanisms underpinning pacing behaviour development and provide a basis for the design of interventions aimed at aiding the self-regulation of effort distribution in children and adolescents (4, 5, 15).

The development of pacing behaviour has been linked to the processes of physical maturation and cognitive development, characteristic of late childhood and adolescence (4, 5). Focusing on the cognitive aspect, Micklewright *et al.* demonstrated the link between test scores indicating Piaget's stages of cognitive development and the distribution of effort during a 4-min running task in schoolchildren (12). Elferink-Gemser and Hettinga (2017) theorized that is was the development of the capability to consider one's thoughts and actions (meta-cognition) that facilitates the self-regulation of effort distribution during late childhood and adolescence (4). It should be pointed out that, as of yet, the role of (meta-) cognition within exercise regulation is not fully understood. More detailed research into which (meta-) cognitive functions underpin pacing behaviour, and its development, is therefore needed. One recurrent observation in literature is the influence of task experience on pacing behaviour (5, 17, 18). Through repeated task exposure, individuals use their experience to inform the assessment of task demands and the planning of a fitting distribution of effort in future iterations of the exercise task (4). This cyclical process has been proposed to underpin the recalibration between task demands and the individual's performance characteristics (3), and the formation of a pacing template (18). For example, the estimation of an exercise task's duration is a key factor in the pre-exercise planning of effort distribution (19) and has previously been demonstrated to improve with task experience (20). Furthermore, manipulation of this estimation by means of providing inaccurate performance feedback has been reported to lead to the selection of a sub-optimal pacing behaviour (17). The cyclical process of adjusting one's pacing behaviour to fit the task demands of a novel and unfamiliar exercise task through repeated task exposure has been consistently demonstrated in the adult population (5, 18). Yet, Chinnasamy *et al.* (21) documented that there was no between-trial difference for average speed or pacing behaviour in a group of children repeating a 750m running trial. Lambrick *et al.* (22) reported that when children were tasked with repeatedly running an 800m trial, there was no change in pacing behaviour. Similarly, Menting *et al.* (23) observed that adolescents performing a 2-km cycling trial did not adjust their pacing behaviour throughout the repeated visits. These results provide support for the notion that children and adolescents might experience difficulty in the (meta-) cognitive process of using previous experience to inform the planning of effort distribution in future iterations of the exercise task. However, more rigorous testing, including direct comparison with a control group of adults in a well-controlled laboratory environment, is needed to provide further evidence for this hypothesis.

Recent literature has provided convincing evidence for the consideration of stimuli from the social environment as an important factor in pacing (8). Smits *et al.* (3) proposed that the decision-making process regarding effort distribution emerges from the competition between different stimuli that invite opportunities for action (i.e. *affordances*). During an exercise task, individuals can stick to their pre-exercise planning, adapt their effort expenditure based on internal stimuli, or adapt their effort expenditure in reaction to external stimuli (e.g. a competitor) (8). It is the inhibition of some stimuli and the acting upon others, which determines the individual's pacing behaviour (3). For example, elite athletes in highly interactive sports, such as short-track speed skating, differentiate themselves through their capability to successfully balance their pre-planned effort distribution with adapting their effort expenditure in reaction to the behaviour of competitors (24). In the pacing process, individuals are theorized to use two types of decision-making (2, 3, 25). Deliberative decision-making allows for the considerations of abstract, hypothetical prospective consequences resulting from decisions made in the present but requires considerable cognitive effort (25). Intuitive decision-making requires less cognitive effort and allows individuals to deal with complex situations by making decisions based on association and a small number of cues (25). It was proposed that the presence of a (virtual) competitor introduced affordances which invite individuals to engage in more intuitive decision-making regarding effort distribution ("just keep up with the competitor") as an alternative to the more cognitively effortful deliberative approach involving the monitoring and adaptation of one's effort expenditure in relation to an abstract pacing plan and potential environmental factors (8, 26). Given that the regions of the brain involved in goal-directed decision-making are still under development during adolescence (27), it could be expected that children and adolescents would prefer the less cognitively effortful intuitive decision-making afforded by engaging with a competitor. Further supporting this proposal is the notion that the capability to actively retain the task goal (i.e. working memory) and deliberately inhibit dominant, automatic, or prepotent responses (i.e. inhibition) develops during adolescence (27, 28). These cognitive functions are known to play an important role in the pacing process, as they allow individuals to remain focused on achieving the prospective task goal while in the presence of distracting stimuli, such as those originating from competitors (28). Given that these cognitive functions are under development during childhood and adolescence (27, 29), it was proposed that the integration of stimuli originating from competitors into one's pacing behaviour could be another aspect of pacing behaviour development (4, 5, 10, 30). More specifically, it was theorized that children and adolescents would experience directly perceptible competitors to be more inviting than the abstract and hypothetical notions of future task goal achievement (5, 8). In other words, children and adolescents will likely prefer the more intuitive action of engaging with a competitor. Unfortunately, experimental studies investigating the impact of the presence of competitors on the pacing behaviour of children and adolescents are scarce (5). Lambrick *et al.* (22) asked children to run the distance of 800m in the fastest possible time, either on their own or in groups of four or five. Although no statistically significant difference in the pacing behaviour was reported, the children's performance was negatively impacted by the presence of the competitors as evidenced by an increase in finish time (7.4%, $p=0.06$) and average 200m split times (4.5%, $p<0.01$). The authors speculated that the possibility of beating the other competitors might have overruled the abstract and prospective task goal of finishing the given distance in the fastest time possible (22). Unfortunately, previous studies investigating the pacing behaviour of children or adolescents in the presence of a competitor did not feature a control group of adults (22, 23). Furthermore, to determine whether children and adolescents are indeed more prone to engage with competitors as opposed to achieving a more abstract and hypothetical task goal, a comparison should be made between trials with different task goals (e.g. finish the task as fast as possible vs. finish ahead of the competitor). Laboratory studies in adults have demonstrated the effect of coupling the task goal to a competitor on pacing behaviour (31). With the goal of completing a given distance in the fastest time possible, adults adopted a fast-start followed by a relatively evenly distributed power output, with a significant end-spurt (26, 31). When tasked with finishing the trial ahead of the competitor, the adults still adopted a fast-start-even approach, but the end-spurt became less pronounced (31). The end-spurt was no longer deemed to contribute to goal achievement, as participants were either far ahead or far behind the competitor (31). It would be expected that such as difference in pacing behaviour would be absent in children and adolescents, as they are expected to engage with the competitor, regardless of whether the task goal was to beat the competitor or to complete the trial in the fastest time. To further study the role of (meta-) cognition in pacing behaviour development, there is a need for a more rigorous well-controlled laboratory approach to investigate the influence of competitors on the pacing behaviour of adolescents and adults.

Although previous large-scale observational studies have been successful in mapping out the characteristics of the development of pacing behaviour during competition (9-11), questions remain regarding the role of specific (meta-) cognitive functions potentially underpinning this development (4, 5). The current study aimed to experimentally investigate the role of several (meta-) cognitive functions theorized to underpin pacing behaviour development by investigating the influence of 1) repeated task exposure and 2) the combined effect of the presence of competitors and whether these competitors are coupled to the task goal, on the estimation of task duration, pacing behaviour and performance of adolescents and adults performing a 4-km cycling trial, in a controlled laboratory environment. It was hypothesized that in comparison to adults 1) adolescents will experience more difficulty in adjusting their assessment of the task demands and their pacing behaviour over repeated iterations of an exercise task, and 2) adolescents will demonstrate a pacing behaviour aimed at finishing ahead of the competitor, regardless whether this is the task goal.

2. Methods

2.1. Participants

Nine adolescents (14.9 ± 2.1 years old, 22% female, height: 167.9 ± 9.7 cm, body mass: 66.0 ± 9.2 kg) and fourteen adults (24.2 ± 3.2 years old, 36% female, height: 171.9 ± 8.6 cm, body mass: 72.7 ± 13.5 kg) participated in the study. All participants were healthy (PAR-Q) (32) and moderately to highly active (IPAQ) (33). None of the participants had previous experience with cycling time trials. Before starting the study, written informed consent was obtained from the participants, and the parents or legal guardians if participants were under 18 years old. Participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 hours, and from caffeine and food consumption, respectively, four and two hours before the start of the visit to the laboratory. The study was approved by the ethical committee of the local university (reference number: 15746) in accordance with the Declaration of Helsinki.

2.2. Experiment proceedings

Participants visited the laboratory a total of four times, with a minimum of one week and a maximum of two weeks between visits. Each visit was completed around the same time of the day (±2 hours) to minimize circadian variation. Each visit consisted of a warm-up and a 4-km cycling trial. The Velotron cycling ergometer was used for all cycling, measuring power output, velocity and distance covered (25Hz) (34). Using the Velotron 3D software, a straight 4-km track, including an avatar which represented the participant, was projected onto the wall in front of the ergometer. Before starting the 4-km cycling trial, the participant performed a warming-up consisting of seven minutes of cycling at 70% of the mean velocity achieved during a 4-km trial. During the first visit, this was based on sex and age-matched normative data. During the second, third and fourth visits, it was set individually for each participant, based on the 4-km trial of the first visit. During the 4-km trial in visit one, only the participants' avatar was visible and the participants received the instruction: "finish the 4-km cycling trial as fast as possible". During visits two, three and four, the participants performed the trial in any of three following conditions on the time-trial to head-to-head spectrum (in a randomized order): 1) only the participants' avatar was visible and the goal was to complete the task as fast as possible (AloneTime), 2) alongside the participants' avatar, a competitor avatar was visible and the goal was to complete the task as fast as possible (CompTime), or 3) alongside the participants' avatar, a competitor avatar was visible and the goal was to complete the task before the competitor (finish first: CompFirst). To accommodate for the increase in performance following familiarization (23), the competitor was individualized for each participant using 105% of their finish time during the first visit. As the competitors were constructed manually by the researcher, the finish time of the resulting competitors was 105.1% (±0.3) of the participants. When asked, the participants were told the competitor was of a similar performance level as the participants. The competitor avatars were created to gradually increase velocity over the first 250m towards a mean velocity which then was constant until the end of the trial, representing the theoretically most optimal pacing behaviour for a 4-km cycling time-trial (35). When all instructions were given, participants were asked to provide an expected finish time for the 4-km cycling trial ("In what time do you think you will complete the trial? The trial is 4-km which equals 2.5 miles"). The estimation of task duration was calculated as the absolute percentage deviation between the predicted and actual finish time. As numerical feedback could impact participants' estimation of task duration throughout the four visits, no numerical feedback (i.e. finish time, power output, velocity, distance covered) was provided before, during or after the trials. The participants thought the rate of perceived exertion (RPE) was measured at random moments. In reality, the RPE was measured before the trial, during the trial at 1, 2 or 3-km (two were chosen at random for each trial), and immediately after completion, using the OMNI 0-10 cycling scale (36, 37). Trials were conducted at an ambient temperature between 19°C and 21°C.

2.3. Data analysis

The effect of repeated visits (4) or conditions (3) was investigated separately for adolescents and adults. As the assumption of normality was violated, Friedman's one-way analysis of variance by ranks was used to investigate the estimation of task duration between repeated visits or conditions. Performance was analysed by using a set of one-way repeated measures ANOVA's, with mean power output, velocity and finish time as independent variables and repeated visits or conditions as within-subject factors. On an individual basis, the finish time of the participant in the CompTime and CompFirst conditions was compared to the finish time of the competitor, in order to establish whether the participants finished the trial ahead of the competitor. To investigate pacing behaviour, a set of two-way repeated measures ANOVA's was used, in which mean power output during each 500m segment was the independent variable and repeated visits or conditions the within-subject factor. Additionally, a variable for end-spurt was defined as the percentage change in power output from the 3000-3500m to the 3500-4000m section. A set of one-way repeated measurement ANOVAs, using end-spurt as the independent variable and repeated visits or conditions as within-subject factors, was performed. Due to the randomization of the RPE measurement moments, a series of one-way repeated measures ANOVA's was used to test the difference in RPE between visits or conditions, at the start, 1-km, 2-km, 3-km and completion of the trial.

In all the above tests, if a significant effect was found, a post-hoc analysis of a pairwise comparison with Bonferroni correction was used to differentiate between the visits or conditions. A statistical significance of 0.05 was used. In the t-test analysis, Cohen's d was used to report effect size (small: d = 0.2, medium: d = 0.5, large: d < 0.8). In the analysis of variance, if the assumption of sphericity was violated, the Greenhouse-Geisser correction was used. Additionally, partial eta squared (η2p) was used to report effect sizes (small: η2p = 0.01, medium: η2p = 0.06, large: η2p < 0.14).

3. Results

Mean (± standard deviation) values of measures for expected finish time, estimation of task duration, performance, and end-spurt, are presented in Table 1. The outcomes of the statistical tests are presented in Table 2, with the results of the post-hoc test in Table 1.

3.1. Repeated visits

Over the course of the repeated visits, the adolescents did not become more accurate in their estimation of task duration. The pacing behaviour (Figure 1), end-spurt and performance (finish time, mean power output and mean velocity) of the adolescent group did not change over repeated visits. Contrary, over the repeated visits, the adult group gradually became more accurate in their estimation of task duration. Additionally, adults gradually altered their pacing behaviour by increasing their power output in the 1500-4000m section (Figure 1), yet there was no change in the end-spurt. The adults' finish time and mean velocity, but not mean power output, improved over repeated visits. The RPE throughout the trial did not differ between repeated visits, for both adults and adolescents (Figure 2).

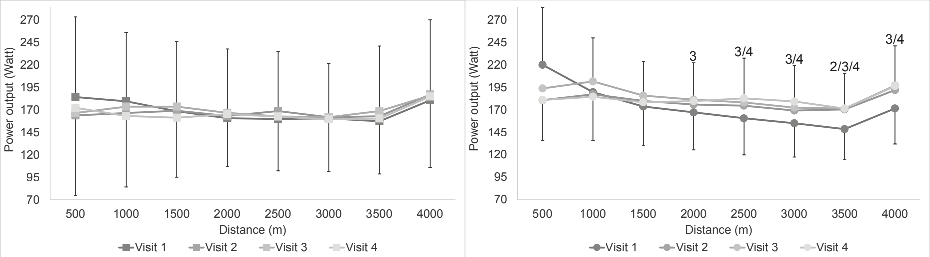

Figure 1. Pacing behaviour of adolescents (squares, left) and adults (circles, right) over repeated visits expressed as power output over 500m sections. Difference between Visit 1 and Visit 2, Visit 3 or Visit 4 (p<0.05, d>0.80).

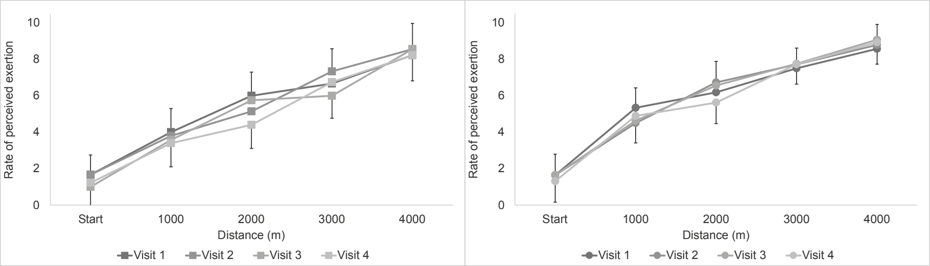

Figure 2. Rate of perceived exertion of adolescents (squares, left) and adults (circles, right) per section during repeated visits. Difference between Visit 1 and Visit 2, Visit 3 or Visit 4 (p<0.05, d>0.80).

3.2. Conditions

Neither adolescents nor adults altered their estimation of task duration before the different conditions. The adolescents altered their pacing behaviour between conditions, evidenced by a higher power output in sections 0-500m (CompTime) and 500-1000m (CompTime, CompFirst) compared to AloneTime (Figure 3). Furthermore, the adolescents exhibited a less pronounced end-spurt in CompTime and CompFirst compared to AloneTime. The adolescents performed best in the CompTime condition, achieving a 5.1% better finish time and 4.5% higher mean velocity compared to AloneTime. Of the adolescent group, 44.4% finished ahead of the competitor in the CompTime condition and 22.2% in the CompFirst condition. The adult group did not exhibit a statistical difference in pacing behaviour between conditions. However, the adult group adopted a 7.3% higher mean power output during the first 2000m of the CompFirst, compared to the AloneTime condition (Figure 3). Additionally, the adults adopted a less pronounced end-spurt during CompFirst, compared to AloneTime and CompTime. The adults exhibited the best finish time in CompFirst, completing the trial 1.9% faster compared to AloneTime or CompTime. This was accompanied by a 2.0% and 1.8% higher mean velocity, respectively. In the CompTime and CompFirst conditions, respectively, 35.7% and 50% of adult participants finished the trial ahead of the competitor. The RPE did not differ between conditions in both adolescents and adults (Figure 4).

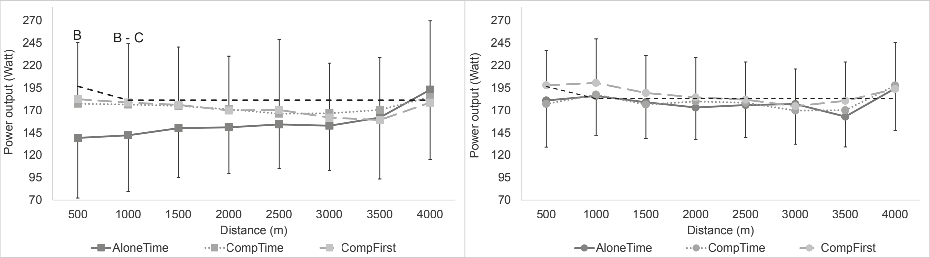

Figure 3. Pacing behaviour of adolescents (squares, left) and adults (circles, right) in different conditions expressed as power output over 500m sections. Virtual competitor visualized by the dotted line. Difference between conditions: A = AloneTime, B = CompTime, C = CompFirst (p<0.05, d>0.80).

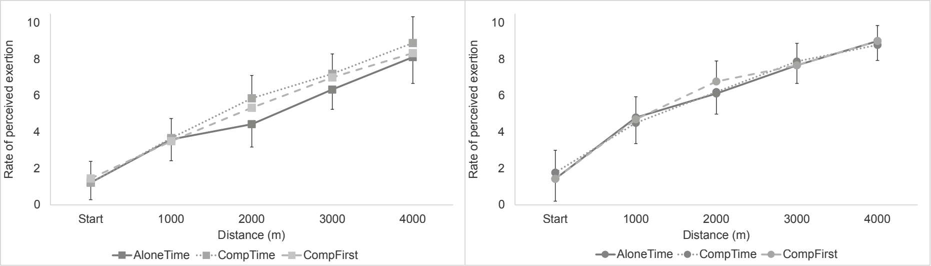

Figure 4. Rate of perceived exertion of adolescents (squares, left) and adults (circles, right) per section in different conditions. Difference between conditions: A = AloneTime, B = CompTime, C = CompFirst ($p<0.05$, $d>0.80$).

Table 1. Mean (± standard deviation) of power output, velocity, finish time, estimated finish time, estimation of task duration and end-spurt per age group.

		Power output (W)	Velocity (km/h)	Finish time (s)	Expected finish time (s)	Estimation of task duration (%)	End-spurt (%)
Adolescents	Visit 1	169.1 (±64.3)	29.9 (±4.6)	492.9 (±84.8)	443.3 (±229.4)	34.2 (±29.1)	13.5 (±9.7)
	Visit 2	168.0 (±62.9)	30.0 (±4.3)	489.3 (±74.7)	506.7 (±185.8)	22.8 (±24.6)$^{\text{Visit 3}}$	14.2 (±9.1)
	Visit 3	170.1 (±69.9)	29.9 (±5.4)	497.1 (±98.3)	583.3 (±267.1)	44.4 (±26.1)$^{\text{Visit 2}}$	9.9 (±11.3)
	Visit 4	166.3 (±67.2)	29.5 (±5.2)	502.7 (±97.0)	616.7 (±314.3)	44.9 (±35.2)	16.7 (±11.8)
	AloneTime	155.6 (±58.8)	29.0 (±4.8)$^{\text{CompTime}}$	509.7 (±91.6)$^{\text{CompTime}}$	643.3 (±295.1)	43.7 (±37.7)	19.7 (±12.1)$^{\text{CompTime, CompFirst}}$
	CompTime	175.8 (±64.0)	30.4 (±4.5)$^{\text{AloneTime}}$	483.8 (±76.4)$^{\text{AloneTime}}$	543.3 (±239.3)	38.5 (±27.9)	9.1 (±11.6)$^{\text{AloneTime}}$
	CompFirst	169.9 (±73.5)	29.8 (±5.4)	498.5 (±99.0)	520.0 (±240.5)	29.2 (±24.8)	11.7 (±7.3)$^{\text{AloneTime}}$
Adults	Visit 1	173.4 (±38.9)	30.7 (±2.8)$^{\text{Visit3}}$	472.1 (±42.3)$^{\text{Visit 3}}$	537.9 (±267.0)	40.0 (±30.5)$^{\text{Visit 4}}$	15.9 (±11.8)
	Visit 2	178.9 (±40.5)	31.1 (±2.7)	466.4 (±41.2)	520.5 (±194.3)	31.3 (±28.6)	13.4 (±12.6)
	Visit 3	185.3 (±37.7)	31.7 (±2.5)$^{\text{Visit1}}$	457.8 (±37.3)$^{\text{Visit 1}}$	510.0 (±179.2)	23.6 (±27.5)	15.3 (±16.8)
	Visit 4	181.8 (±37.1)	31.4 (±2.5)	461.3 (±37.2)	465.0 (±123.8)	20.0 (±13.0)$^{\text{Visit1}}$	15.3 (±11.5)
	AloneTime	178.6 (±34.8)	31.1 (±2.4)$^{\text{CompFirst}}$	464.8 (±35.2)$^{\text{CompFirst}}$	520.7 (±184.4)	29.1 (±24.4)	19.3 (±14.8)$^{\text{CompFirst}}$
	CompTime	179.6 (±39.6)	31.2 (±2.8)$^{\text{CompFirst}}$	464.7 (±41.7)$^{\text{CompFirst}}$	471.3 (±129.1)	21.0 (±14.3)	16.9 (±13.8)$^{\text{CompFirst}}$
	CompFirst	187.8 (±40.3)	31.8 (±2.7)$^{\text{AloneTime, CompTime}}$	456.0 (±38.5)$^{\text{AloneTime, CompTime}}$	503.4 (±187.2)	24.4 (±32.9)	7.9 (±9.3)$^{\text{AloneTime, CompTime}}$

$^{\text{Visit 1, 2, 3, 4}}$ = significantly different from visits 1, 2, 3 or 4 (d>0.70). $^{\text{AloneTime, CompTime, CompFirst}}$ = significant difference from conditions: alone, set the fastest time (AloneTime), with a competitor, set the fastest time (CompTime), with a competitor, finish first (CompFirst) (d>0.60).

Table 2. Outcome of the statistical tests for the effect of repeated visits or conditions in both adolescents and adults.

Age group	**Variable**	**Visits**			**Conditions**		
		Statistics	Significance	Effect size	Statistics	Significance	Effect size
Adolescents	Power Output (W)	$F_{3,24} = 0.07$	$p = 0.97$	$\eta^2 p = 0.01$	$F_{2,16} = 3.09$	$p = 0.07$	$\eta^2 p = 0.28$
	Velocity (km/h)	$F_{3,24} = 0.31$	$p = 0.82$	$\eta^2 p = 0.03$	$F_{2,16} = 3.74$	$p < 0.05$	$\eta^2 p = 0.32$
	Finish time (s)	$F_{3,24} = 0.75$	$p = 0.54$	$\eta^2 p = 0.09$	$F_{2,16} = 4.43$	$p < 0.05$	$\eta^2 p = 0.36$
	Estimation of task duration (%)	$\chi^2_3 = 9.40$	$p < 0.05$		$\chi^2_2 = 0.90$	$p = 0.64$	
	Pacing behavior (power output per 500m)	$F_{3.22,25.73} = 0.69$	$p = 0.58$	$\eta^2 p = 0.08$	$F_{2.67,21.5} = 3.63$	$p < 0.05$	$\eta^2 p = 0.31$
	End-spurt (%)	$F_{3,24} = 0.90$	$p = 0.46$	$\eta^2 p = 0.10$	$F_{2,16} = 5.68$	$p < 0.05$	$\eta^2 p = 0.42$
	Rate of perceived exertion (RPE per 1-km)	$F_{12,203} = 0.94$	$p = 0.51$	$\eta^2 p = 0.05$	$F_{8,152} = 0.45$	$p = 0.89$	$\eta^2 p = 0.02$
Adults	Power Output (W)	$F_{3,39} = 3.11$	$p = 0.12$	$\eta^2 p = 0.14$	$F_{2,26} = 2.98$	$p = 0.07$	$\eta^2 p = 0.19$
	Velocity (km/h)	$F_{3,39} = 3.40$	$p < 0.05$	$\eta^2 p = 0.21$	$F_{2,26} = 3.90$	$p < 0.05$	$\eta^2 p = 0.23$
	Finish time (s)	$F_{3,39} = 3.90$	$p < 0.05$	$\eta^2 p = 0.23$	$F_{2,26} = 3.76$	$p < 0.05$	$\eta^2 p = 0.22$
	Estimation of task duration (%)	$\chi^2_3 = 10.87$	$p < 0.05$		$\chi^2_2 = 1.86$	$p = 0.40$	
	Pacing behavior (power output per 500m)	$F_{3.44,44.75} = 3.57$	$p < 0.05$	$\eta^2 p = 0.22$	$F_{2.92,38.0} = 1.01$	$p = 0.40$	$\eta^2 p = 0.07$
	End-spurt (%)	$F_{3,39} = 0.12$	$p = 0.95$	$\eta^2 p = 0.01$	$F_{2,26} = 5.22$	$p < 0.05$	$\eta^2 p = 0.29$
	Rate of perceived exertion (RPE per 1-km)	$F_{12,124} = 0.56$	$p = 0.87$	$\eta^2 p = 0.05$	$F_{8,93} = 0.48$	$p = 0.87$	$\eta^2 p = 0.04$

4. Discussion

To investigate the role of several (meta-) cognitive functions in the development of pacing behaviour, the current study investigated the influence of 1) repeated task exposure and 2) the combined effect of the presence of competitors and whether these competitors are coupled to the task goal, on adolescents and adults performing a 4-km cycling trial in a well-controlled laboratory environment. First, it was hypothesized that adolescents would experience more difficulty in adjusting their assessment of the task demands and their pacing behaviour over repeated iterations of an exercise task. When repeatedly exposed to the same exercise task, the adults improved their accuracy in the estimation of task duration, adjusted their pacing behaviour and improved their performance. In contrast, the adolescents provided with the same level of task experience did not exhibit a change in their estimation of task duration, pacing behaviour or performance. The adjusting of one's pacing behaviour to the demands of a novel exercise task seems to occur at a slower rate in adolescents compared to adults. Given these findings, the (meta-) cognitive function of using task experience to inform pacing behaviour in future iterations of an exercise task, therefore, seems to be an aspect of pacing behaviour which is under development during adolescence. Second, it was hypothesized that adolescents would demonstrate a pacing behaviour aimed at finishing ahead of the competitor, regardless of whether this was the task goal. The adults only adjusted their pacing behaviour when they were tasked with finishing ahead of the competitor (CompFirst). Yet, adolescents adjusted their pacing behaviour in the presence of the competitor, both when the goal was to finish before the competitor (CompFirst) or to set the fastest time (CompTime). The adolescents, therefore, seem disposed to a more intuitive approach to their decision-making regarding effort distribution by focusing on the (virtual) competitor, whereas the adults are able to retain focus on the more abstract and prospective task goal of finishing the trial as fast as possible. The confirmation of both hypotheses provides novel experimental evidence supporting the view that the development of (meta-) cognitive functions underpins the development of pacing behaviour during adolescence.

4.1. Task experience

When novice individuals are faced with a new and unfamiliar exercise task, there is a need to select a fitting pacing behaviour (5). Through repeated task exposure, individuals are theorized to reassess the task demands as well as recalibrate the match between the task demands and their performance capabilities (5). This allows them to adjust their pacing behaviour and increase exercise performance in future iterations (5). Whereas evidence for this cyclical process has been consistently reported in the adult population (5, 17, 18), previous studies in children and adolescents demonstrated no adjustment of their pacing behaviour through repeated task exposure (21-23). The current study was the first to test whether there was indeed a difference in the effect of task experience on the pacing behaviour of adolescents and adults performing the same task in well-controlled laboratory conditions. Confirming the findings of previous studies, the adult group in the current study adjusted their pacing behaviour and improved their performance (finish time) over repeated trials. Contrary, the adolescent group did not demonstrate an adjustment of pacing behaviour, or performance, over repeated visits. The absence of change in pacing behaviour over the repeated visits in the adolescent group confirms that adolescents need relatively more experience with a new exercise task to adjust their pacing behaviour to match the task demands. Furthermore, it should be pointed out that the adolescents, in contrast to the adults, were unable to improve their accuracy of the estimation of task duration over repeated visits. The estimation of task duration is part of the meta-cognitive process of assessing the task demands in relation to one's performance capabilities and is important in the pre-exercise planning of effort expenditure. A previous study demonstrated that the accuracy of the estimation of task duration improved throughout adolescence, and linked it to resulting differences in pacing behaviour between adolescents and adults (15). The current results expand upon these findings by providing evidence that the capability to adjust the assessment of the task demands using task experience, also differs between adults and adolescents. It, therefore, seems that the meta-cognitive process of reflection upon one's own (pacing) behaviour is another aspect of pacing behaviour under development during adolescence. The findings of the current study parallel those of a series of previous studies investigating the effect of age on behaviour in a series of complex, goal-directed decision-making tasks (27, 38). These studies demonstrated that the rate at which individuals learned to differentiate what behaviour is advantageous or disadvantageous was linked to the development of the prefrontal cortex during adolescence (27, 38). The adult participants needed a relatively low amount of trials to be able to determine what behaviour resulted in a reward or punishment, adolescents needed considerably more trials, and younger children did not seem to be able to recognize this relationship at all (27). Similarly, in the current study, the adults seem to be able to recognize that an adjustment in their pacing behaviour might provide them with a reward (e.g. increased performance), whereas this process seems to occur at a slower rate in the adolescents. These findings provide further experimental evidence for the proposed framework by Elferink-Gemser and Hettinga, in which the development of (meta-) cognitive functions underpins the pacing behaviour development during adolescence (4).

Applying the findings of the current study more broadly, it was recently demonstrated that adolescent swimmers and speed skaters who eventually progressed towards the elite level in adulthood differentiated themselves by demonstrating a pacing behaviour that better fits the task demands (9, 11). Likewise, studies have demonstrated that in adolescent athletes performing those same sports, the more successful athletes also score higher on measurements for self-reflection (39, 40). In light of the results of the current study, it could be hypothesized that these athletes' higher level of self-reflection provides them with an increased capability to recognize whether or not their pacing behaviour optimally matches the task demands, and if they might need to adjust their pacing behaviour to improve performance during future iterations of the task. These athletes might therefore be able to better adjust their pacing behaviour to the task demands, even when provided with a similar amount of task experience as their peers. The higher capability of self-reflection could therefore be the reason why some athletes differentiate themselves from their less successful peers through their pacing behaviour. Although potentially holding value for talent identification and development, further research is needed to further establish the hypothesized link between self-reflection and pacing behaviour development in talented athletes.

4.2. Competitors and the task goal

The current study is the first to compare the effect of introducing a (virtual) competitor as well as the relation of this competitor to the task goal between adolescents and adults. A contrast between the age groups occurred when the competitor was present, but the goal of the task was to finish the trial as fast as possible (CompTime). The pacing behaviour of the adults in this condition is similar to when they were cycling alone (AloneTime), with an even distribution of effort and a significantly more pronounced end-spurt. Yet, the adolescents adopted a pacing behaviour more resembling the trial in which they were tasked with finishing ahead of the competitor (CompFirst), with a relatively higher power output during the initial section and a less pronounced end-spurt. Conform the hypothesis, the current results show that in the presence of a competitor, adolescents seemingly set finishing ahead of the competitor as a primary goal, regardless of the instructions provided by the researcher (e.g. finish the trial as fast as possible). More evidence for this notion is provided by the finding that, in contrast to the adults, the adolescents finished the trial faster when they were instructed to finish the trial as fast as possible (CompTime), compared to when they were tasked with finishing ahead of the competitor (CompFirst). This observation is likely due to the notion that when the adolescents felt like they were unable to stay ahead of the competitor in the CompFirst condition, they had already failed the task goal, and considerable effort expenditure was therefore not needed (31). Yet, in the CompTime condition, even if it was not deemed possible to finish ahead of the competitor (i.e. the primary goal as set by the adolescents), it was still possible to cover the distance in the fastest possible time (i.e. the original goal as set by the researcher). A continuation of effort exertion was, therefore, still required, resulting in a relatively lower finish time in the CompTime condition. Collectively, these results provide experimental evidence for the view that adolescents are more inclined to engage with competitors, whereas adults are better able to retain the focus on achieving the task goal (5).

Applying the findings of the current study to the affordance competition framework as theorized by Smits *et al.* (3), these findings confirm the notion that age impacts which affordances are considered inviting by the individual (41). More specifically, it can be stated that engaging with a competitor seem to be particularly inviting to adolescents. In explaining this age-related difference, it should be reiterated that the goal of finishing the task as fast as possible requires the participants to engage in self-regulation and deliberative decision-making, including abstract and hypothetical considerations, as they need to make decisions in the present, which determine their goal achievement in the future. Contrary, trying to finish ahead of the competitor allows for more intuitive decision-making, as it encapsulates the complex task of self-regulating the distribution effort over the duration of the task into a more concise task ("keep up with the competitor"). Intuitive decision-making uses relatively fewer cognitive resources, in comparison to deliberate decision-making (2, 25). It was, therefore, proposed that intuitive decision-making is favoured by individuals who possess a lower level of (meta-) cognitive functioning (16). The finding of the current study that adolescents place engaging with the (virtual) competitor ahead of achieving the task goal provides experimental evidence to support this view. The preference for engaging with the competitor could also result from the notion that (meta-) cognitive capability for the self-monitoring and adaptation of effort expenditure during exercise is still under development during adolescence (4). Given that the participants were told that the competitor was matched to their performance level, it provided a visual representation of their performance (42). By engaging with the competitor, the adolescents were able to alter their effort expenditure in relation to the competitor, instead of having to rely on the still developing (meta-) cognitive processes of self-monitoring and adaptation. In addition, goal-directed behaviour is known to be supported by the cognitive capability to actively retain the task goal (i.e. working memory) and deliberately inhibit dominant, automatic, or prepotent responses (i.e. inhibition) (28), which develops during adolescence (29). These cognitive functions are known to play an important role in the self-regulation of effort distribution, as they allow individuals to remain focused on achieving the prospective task goal while in the presence of distracting stimuli, such as those originating from competitors (41). Provided that these cognitive functions are still under development during adolescence, children and adolescents would be more prone to engage with stimuli that are immediately rewarding (27). This would explain why, for adolescents, engagement with a directly perceivable competitor would overrule the abstract and prospective task goal of finishing the trial in the fastest time (5). The finding that adolescents, in comparison to adults, perceive engaging with competitors as more inviting thus confirms the important role of cognition in exercise regulation and supports the view of the development of (meta-) cognitive functions underpinning pacing behaviour development as theorized by Elferink-Gemser and Hettinga (4).

In the current study, the adolescents' more intuitive approach to effort distribution, as afforded by the presence of the competitor, resulted in faster completion of the trial. Yet, this approach could also lead to sub-optimal performance, as previously demonstrated by Lambrick *et al.* (22). It would, therefore, be valuable to familiarize athletes with the unique invitations for actions afforded by competitors (43). This could, for example, be done through the introduction of a competitive aspect in training exercises or participation in (lower level) competitions (43). Furthermore, it should be recognized that although differences between the age groups became evident, there was considerable variation in the response to the presence of the competitor in both age groups. This variation could be explained by the notion that both the processes of pacing and the interaction with a competitor are complex, and multiple factors aside from age impact how an individual integrates the presence of a competitor into their pacing behaviour (8). Factors such as the level of self-efficacy and mental fatiguability have been recognized to impact the interaction with competitors (31, 44). A combination of these factors could have influenced the reaction to the competitors in the current study, resulting in variation within both age groups.

4.3. Practical applications

The finding that specifically the (meta-) cognitive process of using previous experience to inform future pacing behaviour is under development during adolescence, provides practitioners with a specific aspect to which to focus when aiming to support the effort distribution in children and adolescents. Previous studies have provided evidence that the social environment can aid the process of acquiring skilled behaviour (42, 45). Tijani *et al.* demonstrated that providing adolescent swimmers with details about their pacing behaviour and exercises based on their race pace resulted in an adjustment of their pacing behaviour and improved 400m freestyle performance (46). Making individuals aware of their pacing behaviour and designing practice sessions to engage with this behaviour seems to positively impact the acquisition process (47). More generally, practitioners can also aid this process by using questions such as: “what worked well and/or did not work well for you in the last task?” or “what will you do differently next time?”, to engage children and adolescents in the (meta-) cognitive process of reflection as well as the planning of their pacing behaviour (42, 45). By building a question-and-answer dynamic, practitioners could engage children and adolescents to reflect upon their pacing behaviour, engaging them to find new ways to possibly adjust this behaviour to better fit the task demands.

Building upon this, the finding that adolescents are especially prone to engage with a (virtual) competitor could also be used to improve the acquisition of pacing behaviour. In general, the presence of a competitor could improve motivation and the willingness to engage in sports and exercise (48), keeping individuals engaged in the acquisition process for longer. In addition, a recent systematic review established that the acquisition process of pacing behaviour shares similarities with the same process in other skilled behaviour (5). Just as with other skilled behaviour, individuals do not always exhibit the pacing behaviour that is the best fit for the task demands, even when supplied with ample task experience (5, 13). In this case, exploring variations of the exercise task constraints could lead to the discovery of pacing behaviour that better fits the task demands (5). Earlier research has stated that when firmly established through experience, pacing behaviour is robust, and externally imposing a goal velocity or distribution of power output leads to sub-optimal performance (49). Yet, the results of the current study provide further evidence that the presence of a (virtual) competitor can impact pacing behaviour and performance (19, 26, 47, 50). This could be because the (virtual) competitor is a relatively easy to interpret, visual representation of the desired behaviour and allows for a degree of natural oscillation in the effort expenditure (47, 49). When translated into practice, the presence of (virtual) competitors could allow individuals to explore actions that were not thought of as possible when exercising alone (47, 50). Including competitor-induced variation could therefore provide individuals with a repertoire of actions which they can use in order to successfully react to various environmental stimuli and reach the task goal (5, 6). Yet, it should be pointed out that the acquisition process is (partly) facilitated by internal stimuli such as pain and fatigue experienced during the exercise task (5, 18). The attention given to these stimuli could be reduced through the inclusion of competitors (51). Practitioners should therefore be aware that an overreliance on competitor-induced variation could hamper the pacing skill acquisition process. In addition, an opposite form of competitor-induced variation is also valuable in sports like short-track speed skating, where athletes train and race with competitors (30). Coaches could explore the self-regulatory capabilities of these athletes by integrating training exercises where the athletes perform their competitive events alone. These exercises would thus force the athletes to explore the variation within their pacing behaviour by shifting towards more deliberative decision-making regarding effort distribution and an engagement of the underlying (meta-) cognitive functions.

5. Conclusion

The current study aimed to investigate various (meta-) cognitive functions theorized to underlie the development of pacing behaviour during adolescence. This was achieved by analysing the estimation of task duration, pacing behaviour and performance of adolescents and adults during repeated 4-km cycling trials, with or without a competitor that was coupled to the task goal. In contrast to adults, adolescents struggle to improve their accuracy in the estimation of task duration, and alter their pacing behaviour or improve their performance over repeated tasks. This finding establishes the (meta-) cognitive process of using the reflections upon a past exercise task as the basis for the planning of effort distribution in future iterations as an aspect of pacing behaviour development. Children and adolescents are therefore expected to need more task experience, feedback and instructions from the social environment (e.g. coaches, teachers, instructors) in order to adjust their pacing behaviour in novel exercise tasks. Furthermore, in contrast to the adults, the adolescents altered their pacing behaviour in the presence of a competitor, regardless of whether the goal of the task was to finish ahead of the competitor or to finish the task as fast as possible. In the adolescent group, external stimuli originating from the presence of a competitor seemed to have overruled the more abstract and prospective notions related to the original task goal (i.e. finish the trial as fast as possible). These observations suggest that adolescents perceive external stimuli originating from the competitor as more inviting and that this population seems to favour intuitive decision-making. This is likely due to their still developing (meta-) cognitive capabilities, including retaining the task goal and inhibiting prepotent responses. Familiarizing athletes with the more intuitive approach to decision-making uniquely afforded by the presence of competitors in training could aid in preparation for competition. Overall, the current study provides experimental evidence which confirms previous speculations and theorized notions regarding the role of (meta-) cognitive functions underlying pacing behaviour development. Detailing this relationship provides a basis for the design of interventions aimed at supporting the self-regulation of effort distribution in children and adolescents.

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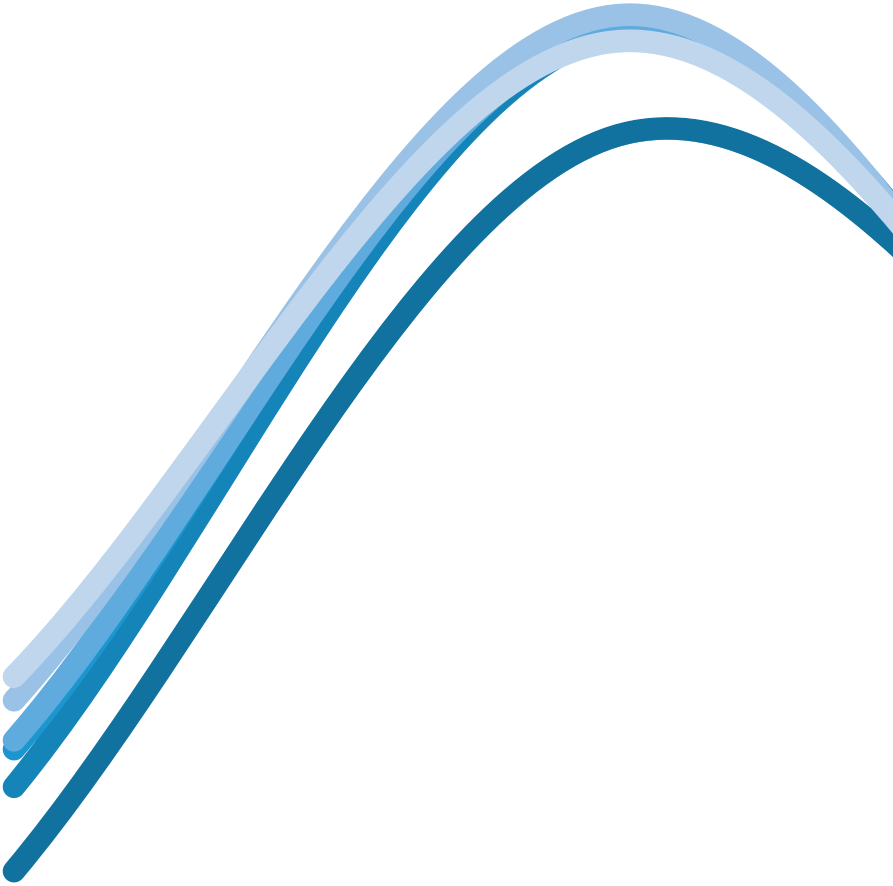

Chapter 11

General discussion

The goal-directed decision-making process regarding the self-regulation of effort distribution (i.e. pacing) is a key determinant of physical activity and athletic ability (1). Improving pacing can increase performance and create a positive attitude towards sports and exercise (2). Contrary, repeated suboptimal pacing can over time lead to overexertion, injury and drop-out of sports and exercise (3). Yet, preparatory to design interventions aimed at supporting the self-regulation of effort distribution, there is a need for a better understanding of how individuals develop their pacing behaviour. The aim of this thesis, therefore, was to investigate what characterizes the development of pacing behaviour during adolescence and to study the factors underpinning this development. In pursuit of these goals, it was first investigated whether or not the development of pacing behaviour exists uniformly across exercise tasks with different task characteristics and environmental factors.

1. General proof of the existence of pacing behaviour development

Prior to the current research project, studies investigating the pacing behaviour of children and adolescents were scarce, specifically when considering the breadth of research on the topic in the adult (athlete) population (4, 5). Only two studies directly investigated the effect of age (< 18 years old) on pacing behaviour. Micklewright *et al.* reported a difference in the velocity distribution between schoolchildren in different age groups (5-14 years old) tasked with performing a ~4 minute running task (6). Wiersma *et al.* determined a difference in the pacing behaviour of a group of talented male long-track speed skaters performing 1500-m races at 15, 17 and 19 years old (7). Although providing initial evidence for the influence of age on pacing behaviour, these studies featured observatory data of a relatively small group of individuals, from a selected school or sports team. Considerably more structured research was needed to establish that pacing behaviour develops during adolescence.

Given that pacing is a complex psychophysiological process (8), investigating the influence of age on the process requires the control of a substantial amount of other influential factors. This can be achieved in a well-controlled laboratory study or an observational study with a sufficiently large sample size (9). In Chapters 9 and 10, the differences in pacing behaviour between adolescents and adults were compared in a well-controlled laboratory environment. In these chapters, it was demonstrated that the pacing behaviour in both submaximal and maximal intensity exercise differs between recreationally active adolescents and adults. Taking the second approach, Chapter 3 was the first study to investigate the effect of age on pacing behaviour in a large, international sample of athletes. The use of publicly available recordings of lap times and positioning data made it possible to analyse the pacing behaviour of a large group (n=9715) of short-track speed skaters performing 1500-m races. A cross-sectional comparison of age groups (U17, U19, U21 and adults) confirmed that pacing behaviour indeed differed between the age groups, with the largest differences occurring between the youngest and oldest athletes. Further confirmation was provided in chapter 5, as the systematic collecting and reviewing of all the available literature on the pacing behaviour of individuals under 18 years old revealed that in various exercise tasks (e.g. running, swimming, cross-country skiing) adolescents demonstrated a different pacing behaviour from adults.

Although these studies provided evidence for a difference in pacing behaviour between age groups, the use of cross-sectional comparisons made it difficult to formulate definitive statements about behaviour development (10). Furthermore, even though the use of publicly available competition data provides an ecologically valid method of analysing the pacing behaviour of athletes (9), it also provides complications (11). One such complication is the fact that due to a wide range of factors, there is considerable variability in the number of times athletes will perform at the international level of competition (e.g. world cups or international championships). This is especially true for junior athletes, as their road towards elite performance is known to be dynamic, non-linear and characterized by periods of rapid progression (12, 13). An equal number of measurements per subject is a prerequisite for the statistical analysis of longitudinal data as used in previous studies analysing pacing behaviour over time (e.g. repeated measures analysis of variance (7)). The variability in competition attendance between athletes, therefore drastically limits the data available for longitudinal analysis. Resolving this problem, Chapter 6 introduced the use of multilevel modelling to study the development of pacing behaviour in a large sample of athletes competing at an international level. Multilevel modelling makes it possible to perform a more rigorous study of athlete competition data, as both the number of measurements and temporal spacing between measurements may vary among athletes. Using this approach, longitudinal data of 140 adolescent male short-track speed skaters were used to analyse the development of pacing behaviour between 15 and 20 years old. It was confirmed that the pacing behaviour of short-track speed skaters develops during adolescence and into adulthood. Furthermore, it was revealed that the most notable shift in behaviour occurred between the age of 15 and 16, after which the development became more gradual towards adulthood. Further expanding the use of multilevel modelling, Chapter 8 analysed a large-scale, worldwide, longitudinal dataset (n=5728) of swimmers between the ages of 12 and 24, competing in the 100-m and 200-m freestyle events. The analysis revealed that the pacing behaviour of the swimmers developed during adolescence. Additional analysis demonstrated that the rate of pacing behaviour development was highest at the early stages of adolescence and gradually decreased as athletes reached adulthood (Chapter 8, appendix). Furthermore, adolescent swimmers who in adulthood reach the elite level differentiated themselves from their peers at the age of 13 (female), or 16-17 (male) years old. This finding supports the notion, introduced in Chapter 3, that the development of pacing behaviour occurs at a younger age in females compared to males. Additional supporting evidence was provided by a study in which multilevel modelling was used to compare the pacing behaviour development of male and female talented Dutch long-track speed skaters performing 1500-m races (14). Whereas the rate of development in the female skaters seemed to decrease during late adolescence (16-17 years old), the male skaters demonstrated a more gradual continuation of pacing behaviour development towards early adulthood (19-20 years old) (14).

Collectively, the well-controlled laboratory studies and large-scale database studies in this thesis consistently demonstrated the influence of age on pacing behaviour across a range of exercise tasks of various durations, sport-specific features and environmental factors, as well as in samples of both the (elite) athlete and the recreationally active population. The collective evidence allows us to confidently state the following: 1) the development of the capability to self-regulate the distribution of effort over an exercise task is a universal feature of human development, 2) this development starts in childhood, is most pronounced at the early stages of adolescence, and becomes more gradual towards early adulthood, and 3) this development occurs at a younger age in females, compared to males.

2. Influence of constraints on pacing behaviour development

The consistently reported effect of age on pacing behaviour across a range of different sports and events supports the notion of pacing behaviour development as universal within the adolescent (athlete) population. Yet, it has been established that the task demands, including the constraints originating from the task characteristics and the environment, have a considerable influence on an individual's pacing behaviour (11, 15). Due to the lack of research into the pacing behaviour of adolescents, it was previously unknown whether or not the development of pacing behaviour was similar across exercise tasks with differing demands. The various studies included in this thesis allow for a comparison of pacing behaviour development between exercise tasks with different demands. This comparison could expand our knowledge of the impact of the interacting constraints originating from the individual (i.e. age), task (i.e. duration) and environment (i.e. competitors) on pacing behaviour.

Based on the results of Micklewright *et al.* and Wiersma *et al.*, it could be proposed that the development of pacing behaviour is characterized by a conservation of effort during the initial section of an exercise task (6, 7). The findings of Chapters 3 and Chapter 6 seem to support this proposition, as both reported that older short-track speed skaters demonstrated a relatively lower velocity in the initial phase of the 1500-m race (duration: ~140-160s). However, Chapter 8 presented new evidence that was contradictory to earlier observations. Although in the 200-m freestyle (~110-130s), the older swimmers were relatively slower during the first 50-m, in the 100-m freestyle (~50-60s), the older male swimmers were relatively faster during the first 50-m. In other words, in the 100-m freestyle, the older male swimmers expended relatively more effort during the opening stages of the exercise task. It should be noted that both modelling studies and observations of (elite) athletes have demonstrated that in tasks shorter than ~80 s, individuals benefit from an all-out pacing behaviour (15-17). A maximal acceleration at the start of the task ensures the optimal conversion of the available energy into realising a high mean velocity over the whole exercise task. Yet, in tasks with a duration over ~120 s, an even pacing behaviour balances the conversion of available energy into velocity with minimizing power loss, resulting in optimal performance. It, therefore, seems that throughout adolescence, athletes develop their pacing behaviour to improve performance under the constraints originating from the task's duration. In shorter tasks (<80s) the development of pacing behaviour is characterized by the adoption of a relatively faster start aimed at maximizing the acceleration at the start of the exercise task. In longer tasks (>120s), the development constitutes a conservation of effort during the initial stage of the trial, aimed at achieving a more even distribution of effort.

In addition to the constraints originating from the task characteristics, the task demands also include constraints originating from the environment. Pacing behaviour results from the continuous decision to act upon certain possibilities for actions above others (18). One important environmental factor influencing pacing behaviour is the presence of competitors, as they provide unique social invitations for action, including drafting and overtaking (11). Indeed, Chapter 2 demonstrates this concept as it was reported that in interactive, head-to-head competition, athletes perform at an unsustainable level of effort in an endeavour to stay with the race leaders. Additionally, the comparison between fast and slow races in Chapter 6 illustrates how much the interaction between competing athletes can impact the pacing behaviour of a collective of individuals performing the same exercise task. Comparing the pacing behaviour development of athletes performing tasks with a variation of interactivity with their competitors could further enlighten whether the interaction with competitors is an aspect of pacing behaviour under development during adolescence.

Figure 1 depicts the relative section times of adolescent male athletes performing: A) long-track speed skating, which is categorized as a time-trial sport, B) swimming, which is a head-to-head sport but due to the lane-based set-up, the interaction with other competitors is limited (Chapter 7), and C) short-track speed skating, which features a highly interactive competitive environment. The data represents the highest performing group in each study (long-track: 'elite group'(7), swimming: 'male, elite group', short-track: 'fast races, finals'). The athletes included in the studied cohort completed the tasks within 110-160 seconds. These events are considered of particular interest in pacing research, as they are too long for an all-out sprint effort but too short to be approached as an aerobic effort (15, 16, 19-22). Athletes are therefore tasked with balancing contributions from both the anaerobic and aerobic energy systems in order to perform optimally.

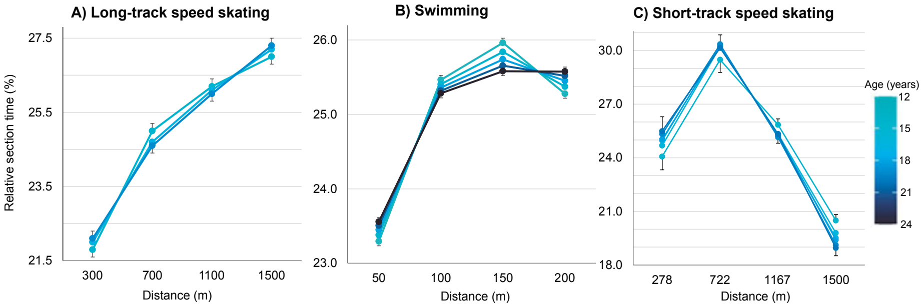

Figure 1. Mean relative section times (±SD/SE) for adolescent athletes performing A) 1500-m long-track speed skating (adopted from Wiersma *et al*), B) 200-m freestyle swimming (Chapter 8), and C) 1500-m short-track speed skating (Chapter 6). Gridlines equal 1.0%.

In all three exercise tasks, older athletes adopt a conservation of effort during the initial phase of the task. This fits with the previous description of pacing behaviour development as dictated by the task duration. Yet, the consecutive use of the energy conserved during the initial stages differs between the tasks. In swimming and long-track speed skating, the development moves towards a theoretically optimal, even distribution of effort (15-17). The conservation of effort during the initial phase is used to facilitate an increase in velocity during the middle section of the task. Contrary, in the head-to-head sport of short-track speed skating, the conservation of effort during the initial phase enables a higher velocity in the final section. Furthermore, Chapter 3 establishes that, in comparison to younger peers, adult short-track speed skaters also reach the position of their final ranking at a later point in the race. It seems that in a more interactive competitive environment, younger athletes are prone to engage with their competitors at an early point in the race, whereas older athletes distribute their efforts to beat their competitors at the finish line. This idea was further explored in Chapter 10, in which adolescents and adults performed a 4-km cycling trial in a well-controlled laboratory environment. In contrast to adults, adolescents were prone to engage with a virtual competitor at the start of the trial, whether the goal was to beat the competitor (head-to-head) or to finish the trial in the fastest time possible (time-trial). Collectively, these studies demonstrate that age influences an individual's interpretation of the opportunities for action originating from the social environment. With age, individuals come to discover new social invitations for action, including the use of drafting and overtaking later in the race. It is the discovery of these new opportunities for action that results in the development of pacing behaviour differing between tasks with various levels of interactivity. The interaction with environmental stimuli (e.g. competitors) should therefore be considered an aspect of pacing behaviour under development during adolescence.

The evidence originating from this thesis provides novel evidence that advocates that the development of pacing behaviour is characterized by individuals gaining the capability to match their effort distribution to the task demands, including the constraints originating from the task characteristics (e.g. task duration) and environment (e.g. competitors). Throughout adolescence, individuals develop their way of interpreting which stimuli constitute an opportunity for action. As a result, they are able to better determine how to distribute their effort and achieve the exercise task goal.

3. Underlying factors of pacing behaviour development

The investigation of the general effect of age on pacing behaviour, as described in the previous section, expanded our understanding of the development of pacing behaviour. Yet, the maturation process towards adulthood is known to be complex and multifaceted (23). The observed effect of age on pacing behaviour could be caused by a multitude of age-related subfactors, such as physical maturation, cognitive development and the gathering of exercise experience. Further insight could be gained by disentangling these factors and their relation to the development of pacing behaviour.

3.1. Cognitive functioning and the influence of the social environment.

Given the psychophysiological nature of the pacing process (8, 24), it can be argued that the development of pacing behaviour is linked to cognitive development and physical maturation, processes unique to childhood and adolescence (4). It has been established that various physical and physiological maturation processes, as well as structural and functional development of the brain, occur at a younger age in females in comparison to their male counterparts (23, 25). Likewise, studies in this thesis have demonstrated that the development of pacing behaviour occurs at a younger age in females compared to males (Chapters 3 and 8). Focussing on cognitive functioning, Micklewright *et al.* established an initial link between cognitive functioning and pacing behaviour development by reporting differences in the pacing behaviour in a sample of schoolchildren when grouped by their score on tests measuring Piaget's stages of cognitive development (6). These stages, among other things, index the capability to consider abstract, prospective and hypothetical concepts, and ponder ideas outside one's own experience (23). It was proposed that the contemplation of these concepts provides individuals with the aptitude to appreciate that making goal-directed decisions regarding effort distribution in the present could improve their future exercise performance (6). If this proposal is correct, adolescents will struggle to engage in deliberative decision-making, which requires continuous self-monitoring and adaptation of behaviour based on the consideration of hypothetical future scenarios (26). Instead, adolescents would be more likely to engage in intuitive decision-making, which requires less cognitive effort and uses association to make decisions based on a reduced number of stimuli (26). As a result, adolescents would be prone to monitor and make adaptations to their effort expenditure based on representations of performance provided by the (social) environment. Studying the interaction between age, pacing behaviour and the (social) environment could therefore provide more insight into the role of cognitive functioning in pacing behaviour development.

The proprioceptive nature of the pacing process determines that before the start of the exercise task, individuals need to assess the task demands and plan their distribution of effort accordingly (1). It was reported in Chapter 9 that, in comparison to adults, adolescents experienced relatively more difficulty in estimating how long it would take them to finish a set cycling time trial. It should be pointed out that there was no reported difference in a general test for time perception between the age groups, and that although the adolescents overestimated the duration of the task, they demonstrated a pacing behaviour fitting a longer task. From this, it was concluded that it was specifically the capability of contemplating the prospective task demands in accordance with one's own performance capabilities which differentiated the two age groups. Furthermore, in Chapter 9 it was demonstrated that adolescents were better able to adhere to a submaximal goal velocity when a researcher provided them with oral feedback ('speed up/slow down'). This finding suggests that adolescents struggle to engage in the self-monitoring and adaptation of their effort expenditure and are more prone to make decisions regarding their effort distribution based on an external source of feedback. Similarly, the collective findings of the observatory studies in Chapters 3 and 6 revealed that in comparison to adults, adolescent athletes are more prone to engage with competitors, specifically in the initial stages of a race. Contrary to the observatory studies, Chapter 4 did not find a significant difference in the pacing behaviour or performance between adolescents performing cycling time trials with or without a virtual competitor. Though it should be mentioned that the competitors in this study were based on 102% of the participants' finish time during a familiarisation visit. Additionally, the participants demonstrated a 5.1% reduction in the finish time in all the visits following familiarisation. It could be speculated that the adolescents did engage with the competitor, and aimed to finish ahead of them, but that this was achieved by an increase in total power output instead of an alteration of the distribution of effort (27). It was for this reason that in Chapter 10, the virtual competitor was set to 105% of the participants' finish time during the 4-km cycling trial performed during the familiarisation visit. Moreover, to more accurately test whether the adolescents engaged with the competitors, participants were either tasked with finishing the trial as fast as possible or finishing ahead of the virtual competitor. In contrast to the adults, the adolescents tried to finish ahead of the virtual competitor, whether this was the goal of the task or not. The adolescents' eagerness to engage with a competitor verifies that adolescents are searching for an external source of feedback to validate their decision-making regarding effort distribution. It further demonstrates that this population struggles to engage in the self-monitoring aspect of the self-regulation of effort distribution. Moreover, the adolescents' tendency to engage in intuitive decision-making based on external stimuli, confirms the notion that this population is still developing the capability of contemplating abstract and prospective considerations to anticipate different scenarios that might transpire during the course of the exercise task. Collectively, these findings provide experimental evidence to further establish cognitive functioning as an important factor underpinning pacing behaviour development.

3.2. *The role of task experience: is practice all you need?*

In Chapter 5 it was established that pacing behaviour, alike other skilled behaviour, develops during childhood and adolescence and is acquired through exercise experience. Indeed, both age and task experience seem to increase the capacity of individuals to match their pacing behaviour to the task demands. It should be noted that throughout adolescence, athletes increasingly gain exercise experience, as organized sports shift their focus more towards competition. It could be proposed that the effect of age on pacing behaviour, as described in Chapters 3 and 6, is (partly) due to the fact that older athletes have more exercise experience (28-30). Chapter 8 aimed to untangle the processes of development (i.e. the general effect of age) and acquisition (i.e. the specific effect of task experience) on pacing behaviour. It was demonstrated that independently, both age and task experience (i.e. the cumulative number of races performed) significantly impacted the pacing behaviour of swimmers, aged 12-24. It can therefore be stated that the influence of age on pacing behaviour is not solely due to an increase in task-specific experience, as previously suggested (28-30). Instead, the acquisition of pacing behaviour through exercise experience should be considered as another factor in the larger process of pacing behaviour development.

Furthermore, it should be noted that exercise experience also plays a pivotal role in general cognitive development (23). It has been established that children base their behaviour on similar experiences and physical activity is an opportunity to test whether their behavioural strategies should be retained or adapted (23). It is proposed that these processes of assimilation and adaptation form the basis for general cognitive development. Paradoxically, one aspect of the development of cognitive functioning is the improvement of the capacity to use reflection on past experiences to inform future behaviour (31). As Chapter 10 demonstrated, adolescents need relatively more task experience to adjust their pacing behaviour to a novel exercise task. Part of the cognitive development afforded by the processes of assimilation and adaptation is therefore the increased effectiveness of this very same process. Given the importance of the process of assimilation and adaptation in general cognitive development, it could be reasoned that sufficient opportunity to experience a wide variety of exercise tasks facilitates the development of various cognitive functions, including planning, self-monitoring and self-reflection, which in turn facilitate the self-regulation of effort distribution. In other words, it is important to expose children to a varied exercise environment, as this facilitates the development of cognitive functions underpinning pacing behaviour development. These findings fit well within the emerging viewpoint in sport science which claims that engagement in a variety of sports facilitates a better development of athletic ability (32).

4. Practical applications

The role of pacing behaviour in athletic performance (1) has piqued not only the interest of sports scientists but also of athletes, coaches and other practitioners. Previously, the main focus has been on studying and optimizing the pacing behaviour of adult (elite) athletes

(22). Yet, this thesis demonstrates that a broader view might yield valuable knowledge for practitioners. Through multiple studies, it was established that pacing behaviour develops throughout adolescence and is acquired through extensive experience. Longitudinal research into the pacing behaviour development of athletes that reach the elite level could therefore provide novel insights into this unexplored aspect of the pathway to sport excellence. Furthermore, the identification of factors underpinning the development of pacing behaviour in tasks with differing demands allows for the design of training exercisers which optimally support the development of pacing behaviour in young athletes. Additionally, it also allows us to provide practical advice regarding the design of exercise environments that aid the self-regulation of effort distribution of a wider population, providing them with a feeling of competence, confidence and a positive outlook on sports and exercise.

4.1. Pacing behaviour: a marker for talent

In Chapter 8 it is reported that adolescent swimmers who in adulthood reach the elite level, differentiate themselves from their less successful peers by demonstrating a pacing behaviour more like that of adult swimmers. Similarly, Wiersma *et al.* reported that in a sample of talented long-track speed skaters, the skaters with the highest level of performance at 19 years old differentiated themselves at an earlier age through their pacing behaviour (7). Considering these findings, it could be stated that the development of pacing behaviour could be a marker for performance in adulthood. In exploring the reason why more successful athletes seem to develop their pacing behaviour at a younger age than their peers, it should be reiterated that the pacing process can be considered a self-regulatory process (4, 33). Recognizing this, Elferink-Gemser and Hettinga emphasised the importance of the capability to think about one's own thoughts and actions (i.e. meta-cognition) in the self-regulation of effort distribution (4). Literature across a broad range of sports has previously evidenced that high-performing adolescent athletes outscore their peers on (meta-) cognitive functions, such as planning, self-monitoring, adaptation and self-reflection (34-36). It was proposed that these (meta-) cognitive functions allowed the high-performing athletes to be engaged in their own learning process, take responsibility and acknowledge which of their performance characteristics needed further improvement (4). Chapters 9 and 10 established the important role of these same (meta-) cognitive functions in the development of pacing behaviour. These (meta-) cognitive functions allow athletes to make a better assessment of the task demands and recognize when to make adaptations to their effort expenditure during exercise. In addition, an increased capability for self-reflection will allow athletes to recognize whether an adjustment of their pacing behaviour is needed to improve performance in future tasks. In other words, these (meta-) cognitive functions will not only allow athletes to be better at distributing their efforts during competition but also enable them to better adjust their pacing behaviour to (changing) task demands, even when provided with the same task experience as their peers. It could therefore be reasoned that these (meta-) cognitive functions could facilitate the earlier development of pacing behaviour observed in the athletes eventually making it to the elite level. Continuing this line of reasoning, it would be expected that these (meta-) cognitive functions would allow athletes to also excel in other aspects of sport and exercise in which the self-regulation of effort distribution plays a role. One such aspect is the correct interpretation and monitoring of intensity during a training session. The capability to self-monitor one's effort expenditure allows an athlete to recognize the limits of their performance capabilities and the need to reduce their effort expenditure to prevent overexertion or injury. Indeed, Van der Sluis *et al.* demonstrated that adolescent athletes who scored higher on tests for self-monitoring reported less time loss due to overuse injuries (37). Subsequently, the (meta-) cognitive functions of reflection and planning also enable athletes to appreciate the future rewards afforded by decisions made in the present. This could make them realize that overexertion to reach a goal in the short-term (e.g. training or less important competitions) might prevent them from reaching their long-term goals (e.g. season) (5, 38). These athletes' improved capability for the self-regulation of effort distribution would therefore enable them to effectively use training sessions to improve their performance and make them less prone to overexertion and injury.

4.2. Supporting the development of pacing behaviour.

Although some athletes might be naturally more predisposed to develop their pacing behaviour, studies have provided evidence that coaches and other practitioners can positively influence the pacing behaviour of athletes (2). One way in which the social environment can help athletes' pacing behaviour development is by engaging them in the meta-cognitive processes of planning, self-monitoring and self-reflection (2, 39). Through questions such as "how much time do you think the exercise task is going to take you?" or "do you think this pace will get you to the finish line?", coaches can prompt athletes to engage in the meta-cognitive process of thinking about their own actions and behaviour. By making athletes consider their own pacing behaviour, they will become more aware of what they doing and how they might change their behaviour in the future (39, 40). Moreover, establishing this type of question-and-answer relationship allows coaches the opportunity to monitor their athletes' meta-cognitive capabilities and potentially intervene when necessary.

Second, the self-regulation of effort distribution can be aided by the provision of feedback. It should be noted that because the cognitive development is still ongoing in younger athletes, this population will have difficulty interpreting more abstract forms of feedback (e.g. power output) (41). The use of easily interpretable feedback could allow individuals to engage in more intuitive decision-making, lowering the cognitive load associated with the self-regulation of effort distribution. To illustrate: before late childhood (7-10 years old), it is unlikely that children will be able to pace their efforts over an exercise task without additional aid, given that the (meta-) cognitive functions needed for the self-regulation of effort distribution have not yet developed. It is therefore most appropriate to provide this population with a few sources of easily interpretable feedback. An example is the use of a pacemaker, which provides a clear visual representation of the desired behaviour. In practice, this could be an adult athlete whose pace the younger athletes need to match until the final section of the exercise task when the younger athletes are free to distribute their effort as they see fit. As the development of the (meta-) cognitive functions underpinning pacing behaviour development starts during early adolescence, athletes are able to grasp more abstract notions and realize that they might perform better when they distribute their effort over the task. Yet, these (meta-) cognitive functions, including pre-exercise planning (e.g. estimation of task duration) as well as the self-monitoring and adaptation of effort expenditure during exercise, are still developing (Chapter 9). The self-regulation of effort in this group can be aided by feedback that provides more context to the task duration and their current performance. One example of this feedback is the use of visual indications of the remaining task duration. In an 800m run on a 200m track, one could include cones marking every 25m, a different cone marking at 200m and a clear indication of the finish line (41). Another is the provision of simple feedback regarding their current performance, such as providing vocal prompts ('speed up' or 'slow down') (Chapter 9). As athletes further develop their cognitive functioning and pacing behaviour, the more intuitive forms of feedback can be gradually replaced by feedback based on more abstract concepts, such as lap times, speed or velocity data and indications of power output.

As athletes reach young adulthood, the majority of the cognitive development will have concluded and further change in the established pacing behaviour will be mainly achieved through task experience. In practising relatively new events, a continuum of intuitive to abstract forms of feedback can be used to facilitate the optimal task difficulty and facilitate peak rate of learning (42). Furthermore, just as with other skilled behaviour, athletes are not always able to master the pacing behaviour that is the best fit for the task demands, even when supplied with ample task experience. In this case, manipulating the task constraints could compel athletes to explore variations of their established pacing behaviour, which could lead to the discovery of behaviour that better fits the task demands (43). Alas, multiple studies have demonstrated that externally imposing a strict pattern of effort distribution negatively affects performance, especially when compared to a self-paced approach (22, 44, 45). One of the main reasons for this observation is the need for a degree of natural oscillation of the effort expenditure, which is hindered by a strictly imposed distribution of effort (44). Fortunately, several studies, including Chapter 10, showed that the social environment (e.g. virtual avatars or pace-makers) facilitates unique social invitations for action that can successfully impose adjustments of pacing behaviour and improvements of performance across various populations (11, 18, 46-49). Implementing this form of intuitive feedback in a training session, Hofmann *et al.* demonstrated that when novice rowers followed an eight-week training program, the group whose training included a virtual avatar representing the desired velocity distribution elicited a larger change in pacing behaviour and improvement in performance, compared to the group who repeatedly performed the exercise task (2000-m rowing time trial) (50). The use of a visual representation of the social environment seems to be a viable way to explore the variation in an individual's pacing behaviour and discover different matches between their performance capabilities and the task demands.

Third, throughout this thesis, it has been reported that interactivity with competitors is an aspect of pacing behaviour development. Familiarizing younger athletes with the unique social invitations for actions afforded by the presence of competitors, and other environmental stimuli which they will face during competition, could be beneficial in competition preparation (2, 5, 18). By introducing a degree of variability within training sessions, a coach could prepare athletes for the scenario where they might need to amend their pre-exercise planning to accommodate the behaviour of competitors. This could, for example, be achieved by providing athletes with a variety of competitors (e.g. fast starters, stayers, fast finishers) or a variety of instructions (e.g. finish ahead of the competitor, only overtake the competitor once per race, set the fastest time). On the other hand, individuals who usually train and compete with other competitors could explore variations of their pacing behaviour by performing their competitive events alone.

4.3. The self-regulation of effort distribution: a broader view.

It should be pointed out that a focus on pacing can not only be valuable for athletes, but also for the general population and in a clinical setting (2, 5, 51). Improving an individual's self-regulation of effort distribution could aid their athletic ability, positively impacting their attitude towards sports and exercise. Furthermore, aiding one's pacing could help prevent negative experiences associated with exercise-induced fatigue which might have otherwise led to a drop-out from physical activities. Collectively, these processes could positively influence an individual's attitude towards physical activity and promote a healthy lifestyle. The findings in this thesis could be applied in programs supporting populations who struggle with the self-regulation of effort distribution, whether due to the cognitive effort associated (e.g. people with an intellectual impairment) or a change in their performance capabilities (e.g. high fatiguability due to illness) (2, 51). Practitioners could support the engagement in physical activity by designing an exercise environment which features the form of feedback that best supports the cognitive functioning and pacing capabilities of their pupils. In addition, practice sessions can be used to explore the variability within one's pacing behaviour and familiarize oneself with the unique invitations for action afforded by the social environment. Furthermore, practitioners could engage their pupils in the meta-cognitive processes of planning, self-monitoring, adaptation and self-reflection, by building a question-and-answer relationship focussed on these aspects. Using these methods, individuals familiarize themselves with their own performance capabilities, learn to anticipate the exercise task demands and feel more confident in their athletic ability.

Key points for practitioners:

Pacing: a marker for talent.

- Athletes who reach the elite level in adulthood differentiate themselves through their pacing behaviour in adolescence.
- The capability for the self-regulation of effort distribution, is linked to the engagement in the meta-cognitive processes of planning, self-monitoring, adaptation and self-reflection.
- In addition to differentiating themselves in competition, the self-regulation of effort distribution also provides athletes with a better capability to adjust their pacing behaviour based on the reflection upon past task experiences, interpretation of the intensity of a training session, as well as a reduction of the risk of overuse injuries caused by overexertion.

Supporting pacing behaviour.

- Feedback can aid the self-regulation of effort distribution, but should be tailored to individuals' cognitive functioning, starting with a few sources of feedback that are easy to interpret (e.g. pace-makers or avatars) and gradually progressing to more abstract feedback (e.g. lap times, power output).
- Individuals could be made more aware of their pacing behaviour by engaging in a question-and-answer dialog focused on the pre-exercise planning, the self-monitoring and adaptation of effort expenditure during exercise, and reflection upon the previous iterations of the exercise task.
- When an athlete's pacing behaviour is acquired through extensive experience, there could still be room for optimalisation by exploring variations of the established behaviour. Pacemakers or virtual avatars can be used to discover better matches between each individuals' performance capabilities and the set task demands.
- Athletes should be prepared to manage the influence of competitors on their pacing behaviour by using practice sessions to familiarise themselves with the unique invitations for action afforded by competitors.

5. Future directions

The current thesis explored the relationship between age, cognitive functioning and pacing behaviour, as well as the implications of this relationship for the acquisition of pacing behaviour. The novel insights from this thesis provide an excellent basis for the informed design of interventions and practical tools aimed at supporting an individual's self-regulation of effort distribution to improve athletic ability and enhance physical health. Such tools might be of specific interest when tackling a change in the task characteristics (e.g. transfer to a different sport or event), the competitive environment (e.g. moving to international level competition) or the performance capabilities of the individual (e.g. due to injury, medical condition or ageing).

One suggested method of intervention centres around the idea of making individuals more aware of their own pacing behaviour. This could be done through coaching tools aimed at discussing an individual's current pacing behaviour, arranging training exercises based on their behaviour and asking individuals questions related to the (meta-) cognitive process underlying pacing behaviour (39, 40). As determined in this thesis, these interventions should focus on the pre-exercise assessment of the task demands and planning of effort distribution, the self-monitoring and adaptation of effort expenditure during exercise, as well as reflecting upon past experiences to aid pacing in the future. Yet, more work is needed in translating these findings into practical tools which practitioners can use in practice. One promising path is the design of a validated set of questions, which could be provided to individuals (e.g. through a smartphone application) in practice or before and after completing the goal exercise task. A second method of intervention is the exploration of one's pacing behaviour through feedback. The inclusion of virtual avatars seems to be able to improve task performance by influencing the self-regulation of effort distribution (46-50), in contrast to other methods such as monetary rewards (52) or the restricting of velocity or power output (44, 45). The presence of a virtual avatar can afford the individual to engage in more intuitive decision-making, lowering the cognitive load associated with self-monitoring and adaptation of effort expenditure during exercise. In addition, the introduction of an avatar can lead individuals to explore variations of their pacing behaviour and discover new ways of overcoming the task demands. Although promising, more research needs to be done into the instructions and expectations relating to the virtual avatar. Depending on the population, introducing an avatar without instruction elicits a different stimulus compared to instructing individuals to follow or beat this same avatar (Chapter 10). Another important point of note is that the virtual avatars' performance level is linked to the individual's self-efficacy: the belief that they are able to keep up with the avatar (53, 54). Research into the presence of multiple avatars, potentially with differing performance levels (e.g. fast/slow) or instructions (e.g. beat at least one avatar), could provide interesting further insights into these aspects of decision-making during exercise. In designing the virtual avatar, establishing a reliable base performance level and an accurate expected rate of improvement is of the essence, specifically considering that the rate of acquisition is dependent on the individual's age-related (meta-) cognitive functioning (Chapter 10). Furthermore, to prevent the individual from becoming dependent on the virtual avatar, the presence of the avatar should be gradually decreased. This would also enable the individual to progressively engage more in the planning, self-monitoring and adaption of their effort expenditure.

Given the importance of the self-regulated distribution of effort in all forms of physical activity (24), it would be appropriate to broadly split testing and application of these interventions into two streams: sports and public health. In the sports stream, the aim of the interventions is optimizing exercise task performance and improving athletic ability by supporting pacing behaviour acquisition and exploring variations of athletes' established pacing behaviour. This thesis used the analysis of competition data to demonstrate the importance of pacing behaviour development in various sports, including running, short-track speed skating, and swimming (Chapters 2, 3, 6 and 8). Yet, the gained knowledge and proposed interventions can be applied to a much wider variety of sports, as most require athletes to self-regulate the distribution of effort to optimize performance (24). Of specific interest would be athletes that compete in an interactive environment, be it due to a highly interactive relation with competitors (e.g. short-track speed skating) or because they are tasked with finding a synergy of effort distribution within a team (e.g. team pursuit) (55, 56). These athletes require a highly variable and adaptive pacing skillset, given that they need to take into account the behaviour of competitors in their regulation of effort expenditure (18). Another population that would be interesting to study are the competitive rowers. In many countries, including the Netherlands, there are two distinct moments at which individuals pick up the sport of rowing, either during adolescence or at the start of their college or university degree. Comparing the effectiveness of the proposed interventions between these two age groups would provide exciting new insights into the interaction between age, cognitive functioning, experience and pacing behaviour. In the public health stream, interventions should be aimed at keeping people physically active and enabling them to perform all desired activities of daily living. One population of interest would be people whose conditions are associated with fatigue complaints or sudden changes in performance capabilities, such as patients with multiple sclerosis. Research has already pointed out that this population often does not possess a clear strategy to effort distribution (57). Yet, interventions providing tailored activity pacing have been found to help manage fatigue and improve physical activity (58). It could be possible that these interventions could be further improved by the inclusion of a focus on the (meta-) cognitive processes underlying the self-regulation of effort distribution or the inclusion of practice sessions, including guidance using virtual avatars.

In the design of future studies, it should be noted that within the literature, skill acquisition is defined by the relatively permanent change in skilled behaviour, and the effectiveness of an intervention is often measured by means of a test for retention and transfer to similar tasks (59). Remarkably, none of the studies investigating the effect of repeated task exposure on pacing behaviour included in a systematic review of the literature (Chapter 5) reported on these forms of tests. Future studies testing the effectiveness of the proposed interventions and practical tools aimed at supporting the self-regulation of effort distribution should include tests for the transfer of the desired pacing behaviour to real-world activities and retention over a longer time. Virtual home-based fitness software, such as Zwift, has been found to be a reliable way of testing pacing behaviour and exercise performance (60). The fact that participants can perform standardized tests without having to travel to a laboratory presents an exciting opportunity for the inclusion of retention and transfer tests in study designs.

6. Concluding remarks

The self-regulation of effort distribution plays a key role in facilitating athletic success and exercise participation. Yet, remarkably little was known about how individuals come to attain the capability to pace their efforts during exercise. By studying the development of pacing behaviour during adolescence, it was possible to gain further insight into the factors underpinning this complex psychophysiological process. Based on the findings of this thesis, it can be stated that as individuals age, they become better at assessing a task's demands and distributing their efforts to overcome the constraints of the task at hand. It was established that the capability to reflect upon past experiences is a key determinant in both the acquisition and development of pacing behaviour. Moreover, exploring variabilities of established behaviour can lead to discovering an even better fit between one's capabilities and the task demands. Lastly, this thesis reemphasizes the vast extent to which other people influence our own behaviour, and that some possibilities for action are only discovered in the presence of others.

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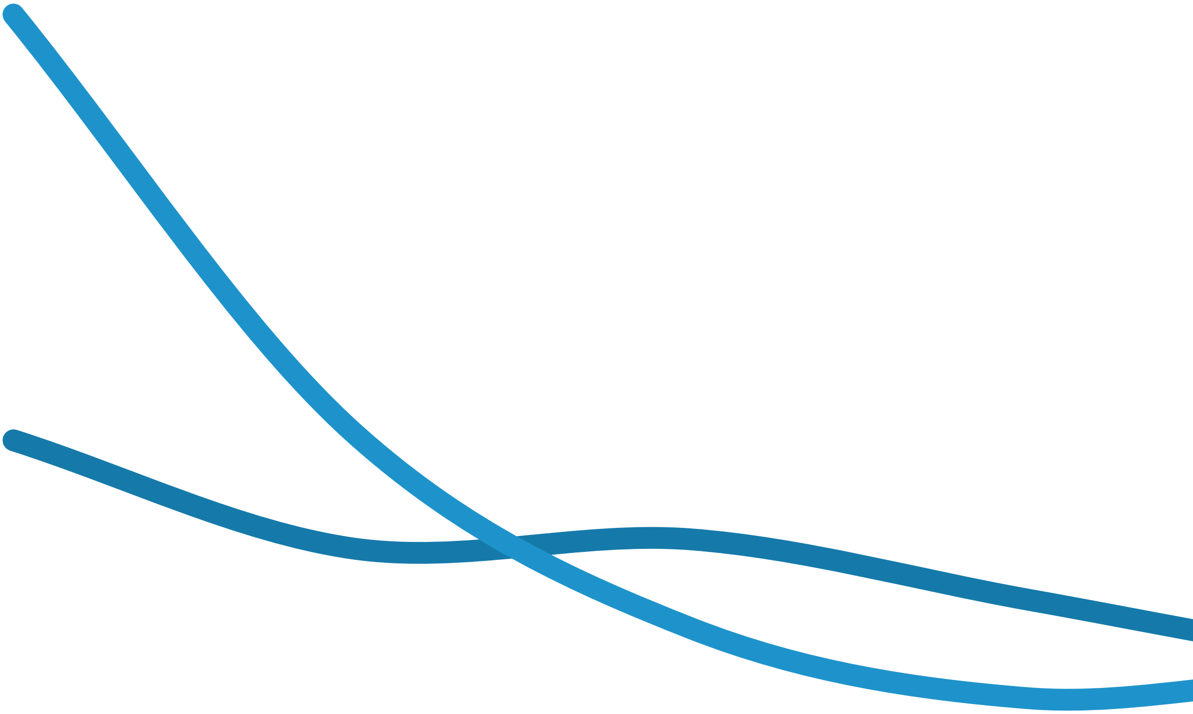

Appendices

Summery

The self-regulation of effort distribution (i.e. pacing) plays a key role in facilitating sports performance and exercise participation. Yet, literature about how individuals come to develop the skill of distributing their efforts is remarkably scarce. This thesis aims to investigate what characterizes the development of pacing behaviour during adolescence and study the factors underpinning this development. As a collective, the studies in this thesis provide the first structured investigation of pacing behaviour development during adolescence.

Initial explorations: the pacing behaviour of adolescents

The goal of the research in **Chapters 2-5** was to gain insight into the pacing behaviour of adolescents through observational field studies and laboratory-based experimental research. In **Chapter 2**, the pacing behaviour of male (n=153) and female (n=116) athletes competing in the middle-long distance running (3000m, 5000m and 10,000m) and race walking (5000m and 10,000m) events of the IAAF Under 18 and Under 20 World Championships between 2015 and 2018, was studied. The distribution of velocity per 1000m and the correlation between intermediate position and final ranking were compared between medallists, top 8/12 and the rest of the field. It was demonstrated that adolescent athletes attune their pacing behaviour to the behaviour of their competitors, as the non-medallists attempted to stay with the medallists as long as possible and therefore performed at an unsustainable level of effort.

Further studying the impact of age and the presence of competitors on pacing behaviour, **Chapter 3** observed a large number of short-track speed skaters performing 1500m races (n=9715). Relative section times (lap time as a percentage of total race time) and positioning data were compared between age groups (U17, U19, U21, adult), sex (female, male), and stage of competition (finals, non-finals). Younger short-track speed skaters were relatively faster during the initial phase of the race, relatively slower during the final phase and demonstrated a moderate-to-high correlation ($0.5 > T_b$) between intermediate positioning and final ranking at an earlier point of the race, compared to older speed skaters. The difference in pacing behaviour was largest between the youngest and oldest group, suggesting a development of pacing behaviour throughout adolescence. The pacing behaviour of the youngest group of female speed skaters more resembled the behaviour of adult speed skaters, compared to their male peers.

In **Chapter 4**, the effect of task experience and the presence of competitors on the pacing behaviour of adolescents was studied in a controlled laboratory environment. The participants (n=10, F=3; M=7, 15.8 ± 1.0 years old) performed four 2-km cycling time trials. After a familiarisation trial (visit 1), the trials included the following conditions, in randomized order: no competitor, a virtual competitor starting slow and finishing fast or a virtual competitor starting fast and finishing slow. The competitor was programmed to finish the trial

2% faster than the participant during visit 1. Before starting each trial, the participants were asked to provide an indication of the expected duration of the cycling trial. After gaining experience with the task in the familiarisation visit, the adolescents improved their expectation of the task duration (66.2%), mean power output (8.1%) and finish time (5.1%), but retained the same pacing behaviour. The introduction of a competitor did not impact pacing behaviour or performance.

Chapter 5 explored the resemblance between pacing behaviour and other skilled behaviour, hypothesizing that pacing behaviour would adhere to the same processes associated with the effect of task experience (i.e. acquisition) and age (i.e. development) on skilled behaviour. A systematic search of the Pubmed, Web of Science and PsychINFO databases resulted in 64 empirical studies reporting on the effect of age (<18 years old) (n=33), repeated task exposure (n=29) or differing levels of experience (n=13) on the distribution of effort during exercise. The collective evidence indicated that pacing behaviour development starts in childhood and continues throughout adolescence. This development resembles that of other skilled behaviour as it is characterized by an increasingly better fit to the task demands, encompassing the task characteristics (e.g. duration) and environment factors (e.g. opponents), and is likely driven by age-related physical maturation and cognitive development. In resemblance to established processes in skill acquisition literature, the collected empirical studies demonstrated that exercise task experience improves one's capability to match stimuli (e.g. task demands and afferent signals) and actions (i.e. continuing, increasing or decreasing the exerted effort) with the resulting exercise task performance. These findings suggest that established concepts in the skill acquisition and development literature (e.g. intervention-induced variability and augmented feedback) could be used to improve pacing behaviour and exercise performance.

Longitudinal research: studying development

The initial explorative studies established evidence for an age-related change in pacing behaviour during adolescence. However, to formulate definitive statements about behaviour development, individuals should be monitored over a prolonged period of time. This form of longitudinal research is complicated by the considerable variability in the number of events (junior) athletes compete in, specifically at the international level. In **Chapters 6 and 8**, a method of working within these restrictions was introduced. Multilevel modelling allows for the analysis of longitudinal data with inter-individual variation among the number of measurements and temporal spacing between measurements. It therefore enables the use of competition data to study the development of pacing behaviour in athletes. To better understand the role of the individual-competitor interaction in the development of pacing behaviour, this research method was used to study both swimmers and short-track speed skaters. In **Chapter 6**, data of male short-track speed skaters performing in 1500-m races of at least two Junior World Championships between 2010 and 2018, were collected (140 skaters, 573 race performances). The effect of age (15-20 years old), race type (fast, slow) and stage of competition (final, non-final) on the absolute and relative section times in four sections of the race was analysed using multilevel models, in which the repeated measures were nested within the individual athletes. With age, the athletes were relatively slower during the initial section of the race, in order to achieve a higher velocity in the critical final sections resulting in a decrease of total race time. The rate of development was most pronounced around 15-16 years old, and more gradual between 17 and 20 years old.

To gain insight into the factors influencing the pacing behaviour of swimmers, in **Chapter 7** the PubMed and Web of Science databases were systematically searched for relevant empirical literature (n=16). It was gathered that the pacing behaviour of swimmers is primarily determined by race distance (100m-1500m) and stroke type (freestyle, backstroke, breaststroke, butterfly). The observed pacing behaviour in swimming shared more resemblance with time-trial events than head-to-head events, most likely due to lane-based set-up inhibiting competitor interaction. The limited number of empirical studies on the pacing behaviour of adolescent swimmers (n=3) indicated that younger swimmers had difficulty in selecting the most appropriate distribution of effort for a specific event as well as consistently maintaining their pacing behaviour throughout multiple races. In **Chapter 8**, a large-scale longitudinal study design was used to investigate the pacing behaviour of swimmers competing in the 100m and 200m freestyle, across five continents between 2000-2021 (100m: n=3498, 47% female; 200m: n=2230, 56% female). Multilevel models in which repeated measures were nested within individual athletes, were used to analyse the influence of age (12-24 years old), race experience (cumulative number of races) and performance level in adulthood (elite, sub-elite, high-competitive) on the 50m relative section times. With age, swimmers develop their pacing behaviour to fit the constraints of the task, indicated by a faster initial 50m in the 100m and a shift towards a more even distribution of effort in the 200m event. The rate of development decreases towards adulthood. Moreover, adolescent swimmers reaching the elite level in adulthood demonstrate a pacing behaviour more resembling that of older swimmers. This differentiation occurs at younger age in females (>13 years) compared to males (>16 years).

Experimental research: factors underpinning development

The findings of the observational studies, in combination with the established theoretical rationale of Elferink-Gemser & Hettinga (2017), formed the basis of the experimental studies in **Chapters 9 and 10**. The aim of these studies was to gain a better understanding of the factors underpinning pacing behaviour development. In **Chapter 9**, a group of adolescents (n=18, F=9; M=9, 15.6 ± 2.5 years old) and adults (n=26, F=13; M=13, 26.8 **±** 3.1 years old) were tasked with a) performing a 7-minute submaximal cycling trial with the goal of maintaining the goal velocity either with (0-5 minutes) or without (5-7 minutes) additional feedback, and b) a 4-km cycling time trial. Before starting the time trial, the participants were asked to give an estimation of the duration of the 4-km trial. The adolescents were considerably less accurate in their estimation of the task duration and their overestimation was paralleled by a pacing behaviour fitting a longer task (i.e. a more even power output distribution, lower rate of perceived exertion and more pronounced end-spurt). In addition, in the 7-minute task the adolescents struggled to adhere to the goal velocity when no additional feedback was provided. Within-group analysis revealed that younger adolescents had relatively more difficulties in estimating the task duration and adhering to goal velocity. From this experiment it was gathered that the (meta-) cognitive functions involved in the pre-exercise planning as well as the self-monitoring and adaptation of effort expenditure during exercise underpin the development of pacing behaviour during adolescence. This results in adolescents being more prone to search for sources of feedback from the (social) environment to verify their decision-making regarding effort distribution.

In **Chapter 10**, a group of adolescents (n=9, F=2; M=7, 14.9 ± 2.1 years old) and adults (n=14, F=5; M=9, 24.2 ± 3.2 years old) were tasked with completing four 4-km cycling trials. After a familiarization visit, trials were performed randomly: alone, with the goal to finish the trial as fast as possible, with a competitor and the same goal, or with a competitor and the goal to finish first. Based on the findings from **Chapter 4**, the competitor was programmed to finish 5% faster than the participants during their familiarisation trial. Before each trial, the participants were asked to give an estimation of the task duration. In contrast to adults, adolescents did not demonstrate a change in their estimation of task duration, pacing behaviour or performance over repeated tasks. Furthermore, adolescents altered their pacing behaviour in the presence of a competitor, regardless of the task goal. Yet, adults did this only when instructed to finish before the competitor. It was gathered from these findings that adolescents are still developing the use of task experience to adjust their pre-exercise planning, pacing behaviour and performance. In addition, the adolescents' eagerness to engage with a competitor further verifies this populations' search for external sources of feedback to validate their decision-making regarding effort expenditure during exercise.

Concluding statements

As a collective, the studies in this thesis demonstrate that the development of pacing behaviour 1) starts in late childhood, is most prominent during adolescence and becomes more gradual towards adulthood, 2) occurs at an earlier age in females compared to males, and 3) results in a distribution of effort that better fits the constraints associated with task characteristics (e.g. task duration) and the environment (e.g. competitors). Moreover, the studies reveal the important role of the (meta-) cognitive functions associated with: a) assessing the task demands in relation to one's performance capabilities, b) the self-monitoring and adaptation of one's effort expenditure during exercise, and c) the capability to reflect on past experiences to inform the pre-exercise planning. As these (meta-) cognitive functions are still under development during adolescence, children and adolescents are prone to more intuitive decision-making as demonstrated by their tendency to validate their decision-making regarding effort distribution on stimuli originating from the (social) environment. The findings from this thesis allow for the informed design of interventions and practical tools aimed at supporting the self-regulation of effort distribution. These tools could not only be useful to optimize the performance of athletes, but also to enable children and adolescents to engage in exercise, and promote a healthy lifestyle.

Nederlandse samenvatting

Het indelen van de mate van inspanning tijdens een fysieke taak (*pacing*) is een belangrijke factor bij lichamelijke activiteit en sportprestaties. Er is echter weinig literatuur beschikbaar die beschrijft hoe individuen deze vaardigheid ontwikkelen. Dit proefschrift heeft als doel te bestuderen hoe ons pacing gedrag zich ontwikkelt tijdens de adolescentie en om te onderzoeken welke factoren ten grondslag liggen aan deze ontwikkeling. De studies in dit proefschrift vormen het eerste gestructureerde onderzoek naar de ontwikkeling van pacing gedrag tijdens adolescentie.

Initieel onderzoek naar het pacing gedrag van adolescenten

Het doel van **hoofdstukken 2-5** was het in kaart brengen van het pacing gedrag van adolescenten. Dit is gedaan door middel van het observeren van atleten tijdens wedstrijden en experimenteel onderzoek in het laboratorium. In **hoofdstuk 2** is het pacing gedrag onderzocht van atleten (153 mannen, 116 vrouwen) die deelnamen aan de finales van het hardlopen (3000m, 5000m en 10,000m) en snelwandelen (5000m en 10,000m) tijdens de IAAF wereldkampioenschappen onder 18 en onder 20 jaar. Pacing gedrag werd gekwantificeerd aan de hand van de snelheid in 1000m secties. Daarnaast werd de correlatie van de positie op de tussentijdse doorkomsten en de uiteindelijke wedstrijduitslag berekend. Deze variabelen werden vervolgens vergeleken tussen de medaillewinnaars, de top 8/12 en de rest van het veld. Uit de analyse kwam naar voren dat deze laatste twee groepen zo lang mogelijk probeerden de medaillewinnaars bij te houden, zelfs als ze hiervoor een tempo moesten aanhouden dat ze niet de gehele race konden volhouden. Dit wijst erop dat atleten in de adolescentie hun pacing gedrag aanpassen aan hun concurrenten.

Het effect van leeftijd en de aanwezigheid van concurrenten op pacing gedrag is verder onderzocht in **hoofdstuk 3**. Van een groot aantal shorttrack schaatsers (n=9715) werd de relatieve sectietijd (ronde tijd als percentage van de totale duur van de race) van een 1500 m race berekend. Daarnaast werd de correlatie van de positie op de tussentijdse doorkomsten en de uiteindelijke wedstrijduitslag berekend. Deze variabelen werd vervolgens vergeleken tussen leeftijdsgroepen (U17, U19, U21, volwassenen), geslacht (vrouw, man) en competitie ronde (voorrondes, finales). In vergelijking met oudere schaatsers waren jongere schaatsers relatief sneller tijdens het eerste stuk van de race en relatief langzamer tijdens het laatste gedeelte van de race. De positiedata wezen uit dat, in vergelijking met oudere schaatsers, jongere schaatsers relatief minder van positie wisselden tijdens het laatste deel van de race. Deze verschillen in relatieve snelheid en positionering waren het grootst tussen de jongste en oudste groep. Als collectief wekken deze resultaten de suggestie dat het pacing gedrag van shorttrack schaatsers zich ontwikkelt tijdens adolescentie. Daarnaast viel op dat in de U17 groep de vrouwelijke schaatsers meer overeenkomsten in pacing gedrag vertoonde met de volwassen schaatsers dan de mannelijke schaatsers.

In **hoofdstuk 4** is het effect van ervaring en de aanwezigheid van concurrenten op pacing gedrag getest in een gecontroleerde laboratorium omgeving. In dit experiment reden de proefpersonen (n=10, F=3; M=7, 15.8 ± 1.0 jaar oud) vier 2-km tijdritten op een fietsergometer. De eerste rit werd gebruikt om ervaring op te doen met de taak. De daaropvolgende ritten werden, in willekeurige volgorde, verreden in de volgende condities: a) zonder concurrent, b) met een virtuele concurrent die snel startte en langzaam finishte, en c) met een virtuele concurrent die langzaam startte en snel finishte. De virtuele concurrenten waren geprogrammeerd om de 2-km af te leggen in een tijd die 2% sneller was dan de tijd waarin de proefpersoon deze afstand had afgelegd tijdens de eerste rit. Voor elke rit werd de proefpersonen gevraagd om een inschatting te maken van hoeveel tijd ze nodig dachten te hebben om de rit te voltooien. Na het opdoen van ervaring tijdens de eerste rit verbeterden de adolescenten hun inschatting van de duur van de rit (66.2%), gemiddelde vermogen (8.1%) en eindtijd (5.1%). Er was echter geen aantoonbaar verschil in pacing gedrag. De aanwezigheid van een concurrent zorgde niet voor een aantoonbaar verschil in prestatie of pacing gedrag.

In **hoofdstuk 5** zijn de overeenkomsten tussen pacing en andere aangeleerde vaardigheden onderzocht. In het verwerven van deze aangeleerde vaardigheden spelen de processen van leren (de invloed van ervaring) en ontwikkeling (de invloed van leeftijd) een belangrijke rol. Als hypothese werd gesteld dat de processen van leren en ontwikkeling ook belangrijk zijn in het verwerven van pacing gedrag. Het systematisch doorzoeken van de Pubmed, Web of Science en PsychINFO databases resulteerde in 64 empirische studies die verslag deden van de invloed van leeftijd (<18 jaar oud) (n=33), herhaling van de taak (n=29) of taakervaring (n=13) op pacing gedrag. Als collectief gaven deze studies het beeld dat de ontwikkeling van pacing gedrag start tijdens de kindertijd en zich doorzet tijdens de adolescentie. In overeenstemming met andere aangeleerde vaardigheden, ontwikkelen individuen tijdens de kindertijd en adolescentie een pacing gedrag dat beter past bij de eisen van de taak. Dit omvat onder andere de kenmerken van de taak (zoals de duur van een activiteit) en de omgevingsfactoren (bijvoorbeeld concurrenten). Daarnaast is het aannemelijk dat de ontwikkeling van pacing gedrag voortkomt uit de fysieke rijping en cognitieve ontwikkeling die kenmerkend zijn voor deze leeftijd. Vanuit de verzamelde studies blijkt ook dat het verkrijgen van ervaring met een taak ervoor zorgt dat individuen een betere associatie kunnen maken tussen de stimuli (de eisen van de taak en afferente signalen), de gemaakte acties (het verhogen, verlagen of gelijk houden van de mate van inspanning) en de uiteindelijke taakprestatie. Dit proces komt overeen met de invloed van ervaring op het uitvoeren van andere aangeleerde vaardigheden. Als collectief benadrukt deze studie de overeenkomsten tussen pacing gedrag en andere aangeleerde vaardigheden. Dit leidt tot de suggestie dat de gevestigde concepten voor het verbeteren van aangeleerde vaardigheden waarschijnlijk ook kunnen worden toegepast voor de verbetering van pacing gedrag.

Longitudinaal onderzoek: het bestuderen van ontwikkeling

In de voorgaande studies werd al bewijs geleverd van de verschillen in pacing gedrag tussen adolescenten en volwassenen. Echter, om gefundeerde uitspraken te kunnen doen over ontwikkeling, is longitudinaal onderzoek nodig waarin het gedrag van dezelfde individuen over een langere tijd wordt gemonitord. Een methode hiervoor is de analyse van publiekelijk beschikbare wedstrijddata van dezelfde groep atleten tijdens opeenvolgende seizoenen. De aanzienlijke variabiliteit in het aantal wedstrijden waaraan (junior) atleten deelnemen, vooral op het internationale competitie niveau, vormt echter een complicatie voor het uitvoeren van dit type onderzoek. In **hoofdstukken 6 en 8** is het gebruik van '*multilevel modelling*' geïntroduceerd. Deze methode geeft de mogelijkheid voor het analyseren van data met variatie in zowel het aantal meetmomenten per persoon alsmede de tijd tussen deze meetmomenten. Deze methode maakt het mogelijk om publiekelijk beschikbare wedstrijddata te gebruiken voor longitudinaal onderzoek. Om het effect van de interactie met concurrenten op de ontwikkeling van pacing gedrag beter te begrijpen is deze onderzoeksmethode toegepast bij het bestuderen van zowel zwemmers (weinig interactie tijdens de wedstrijd) als shorttrack schaatsers (veel interactie tijdens de wedstrijd). In **hoofdstuk 6** is de data verzameld van mannelijke shorttrack schaatsers die tussen 2010 en 2018 deelnamen aan de 1500m race in minstens twee wereldkampioenschappen voor junioren (140 schaatsers, 573 observaties). De raceafstand werd in vier secties gesplitst, waarna de absolute en relatieve sectie tijden werden berekend. Het effect van leeftijd (15-20 jaar oud), race type (snel, langzaam) en competitieronde (voorrondes, finales) op deze variabelen werd geanalyseerd met gebruik van multilevel modellen waarin herhaalde metingen waren genest binnen individuele schaatsers. De oudere schaatsers reden een relatief langzamere eerste sectie van de race, om vervolgens een hogere snelheid te behalen in de beslissende laatste sectie. Dit ging gepaard met een afname van de totale tijd die nodig was om de raceafstand af te leggen. Uit de modellen blijkt dat het pacing gedrag van shorttrack schaatsers het meest ontwikkelt rond 15-16 jaar, waarna een meer geleidelijke ontwikkeling volgt tussen 17 en 20 jaar.

Het doel van **hoofdstuk 7** was om meer inzicht te krijgen in de factoren die het pacing gedrag van zwemmers beïnvloeden. Met deze reden werden de databases van PubMed en Web of Science systematisch doorzocht op relevante empirische literatuur (n=16). Uit de verzamelde artikelen is naar voren gekomen dat het pacing gedrag van zwemmers voornamelijk wordt beïnvloed door de raceafstand (100m-1500m) en de zwemslag (vrijeslag, rugslag, schoolslag, vlinderslag). Het indelen van zwemmers in hun eigen baan vermindert de interactie met concurrenten, waardoor het pacing gedrag gelijkenis vertoont met een tijdrit. Het kleine aantal empirische studies dat het pacing gedrag van jongere zwemmers onderzocht (n=3) concludeerde dat jongere zwemmers het lastig vinden om hun pacing gedrag aan te passen aan de kenmerken van de taak en om hun pacing gedrag constant te houden over meerdere races. In **hoofdstuk 8** is de ontwikkeling van pacing gedrag in het zwemmen bestudeerd. De eindtijd en 50m tijden van een grote groep zwemmers die deelnamen aan 100m en 200m vrijeslag races tussen 2000 en 2021 (100m: n=3498, 47%

vrouw; 200m: n=2230, 56% vrouw) werden verzameld. Met deze data werden modellen gemaakt waarin herhaalde metingen werden genest binnen individuele zwemmers. Deze modellen zijn vervolgens gebruikt om het effect van leeftijd (12-24 jaar oud), race ervaring (cumulatieve aantal races) en prestatieniveau als volwassenen (elite, sub-elite, high-competitive) op de relatieve sectietijden per 50m te analyseren. Als zwemmers ouder worden ontwikkelen ze een pacing gedrag dat beter past bij de kenmerken van de taak. Op de 100m betekent dit een relatief snellere start en op de 200m een meer evenredige indeling van de inspanning over de race. De mate van ontwikkeling neemt af naarmate de zwemmers ouder worden. Zwemmers die uiteindelijk het elite niveau bereiken als volwassenen onderscheiden zichzelf al tijdens de adolescentie doordat zij een pacing gedrag hebben dat meer lijkt op het pacing gedrag van volwassenen. Deze differentiatie doet zich op jongere leeftijd voor bij vrouwen (>13 jaar) dan bij mannen (>16 jaar).

Experimenteel onderzoek: de factoren ten grondslag aan de ontwikkeling

De bevindingen uit de observationele studies, in combinatie met het theoretische rationale van Elferink-Gemser & Hettinga (2017) vormde de basis van de experimentele studies in **hoofdstukken 9 en 10**. Het doel van deze studies was om beter te begrijpen welke factoren ten grondslag liggen aan de ontwikkeling van pacing gedrag tijdens adolescentie. In **hoofdstuk 9** is een groep adolescenten (n=18, F=9; M=9, 15.6 ± 2.5 jaar oud) en een groep volwassenen (n=26, F=13; M=13, 26.8 ± 3.1 jaar oud) gevraagd om twee fysieke taken op een fietsergometer uit te voeren. Tijdens de eerste taak werd aan de proefpersonen gevraagd om 7-minuten lang een doelsnelheid (submaximale inspanning) vast te houden, zowel zonder- (0-5 minuten) als met extra aanwijzingen (5-7 minuten). De tweede taak was een 4-km tijdrit. Voordat de proefpersonen begonnen aan deze tijdrit werd ze gevraagd om een inschatting te maken van hoeveel tijd ze nodig dachten te hebben om de rit te voltooien. Vergeleken met de volwassenen waren de adolescenten aanzienlijk minder accuraat in het maken van deze inschatting. De adolescenten overschatten de tijd die nodig was om de rit te voltooien, wat gepaard ging met een pacing gedrag dat meer past bij een taak van een langere duur (een meer evenredige distributie van vermogen, een lagere mate van ervaren inspanning en een duidelijkere *eindsprint*). Daarnaast hadden de adolescenten relatief meer moeite om in de 7-minuten taak de doelsnelheid te behouden als er geen extra aanwijzingen werden gegeven. Uit een analyse binnen de groep adolescenten bleek dat jongere adolescenten meer moeite hebben met het maken van de tijdsinschatting en het aanhouden van de doelsnelheid, dan oudere adolescenten. Uit dit experiment blijkt dat de (meta-) cognitieve functies die betrokken zijn bij het plannen van de mate van inspanning voor het beginnen van de taak, alsmede het zelf-monitoren en bijsturen van de mate van inspanning tijdens de taak, onderliggend zijn aan de ontwikkeling van pacing gedrag tijdens adolescentie. Dit zorgt er vervolgens voor dat adolescenten meer de noodzaak voelen om hun beslissingen aangaande de mate van inspanning te verifiëren met aanwijzingen vanuit de (sociale) omgeving. Deze bevindingen wijzen erop dat adolescenten hun beslissingen aangaande de indeling van inspanning meer maken vanuit intuïtie ('*intuitive*') dan weloverwogen afweging van de beschikbare opties ('*deliberative*').

In **hoofdstuk 10** is een groep adolescenten (n=9, F=2; M=7, vrouwen, 14.9 ± 2.1 jaar oud) en volwassenen (n=14, F=5; M=9, 24.2 ± 3.2 jaar oud) gevraagd om vier 4-km tijdritten uit te voeren op een fietsergometer. De eerste rit werd gebruikt om de proefpersonen kennis te laten maken met de taak. Vervolgens werden de overige ritten verreden, in willekeurige volgorde, met de volgende condities: a) alleen, met het doel om de taak zo snel mogelijk te voltooien, b) met een concurrent en hetzelfde doel, c) met een concurrent en het doel om de taak te voltooien vóór de concurrent. Gebaseerd op de bevindingen in **hoofdstuk 4**, werd de virtuele concurrent geprogrammeerd om de tijdrit 5% sneller te voltooien dan dat de proefpersonen dit deden tijdens hun eerste poging. Voordat de proefpersonen begonnen aan de tijdrit werd ze gevraagd om een inschatting te maken van hoeveel tijd ze nodig dachten te hebben om de rit te voltooien. In tegenstelling tot de volwassenen was er bij de adolescenten geen verbetering in hun tijdsinschatting, pacing gedrag of prestatie bij de herhaalde taken. Daarnaast pasten de adolescenten hun pacing gedrag aan wanneer er een virtuele concurrent aanwezig was, onafhankelijk of het doel van de taak was gekoppeld aan de concurrent. Anders dan de adolescenten maakten de volwassenen deze aanpassing alleen als ze de instructie hadden gekregen om de taak te voltooien vóór de concurrent. Uit deze bevindingen kan worden geconcludeerd dat het gebruiken van ervaring in het plannen van de mate van inspanning, een vaardigheid is die nog onder ontwikkeling is tijdens de adolescentie. De interactie met de virtuele concurrent wijst erop dat adolescenten op zoek zijn naar externe signalen om hun beslissingen aangaande de mate van inspanning te verifiëren.

Afsluitende verklaringen

Als een collectief laten de studies in dit proefschrift zien dat de ontwikkeling van pacing gedrag 1) start in de laatste fase van de kindertijd, het meest prominent is tijdens de adolescentie en daarna geleidelijk afneemt, 2) op een jongere leeftijd aanvangt bij vrouwen dan bij mannen, en 3) resulteert in een indeling van de mate van inspanning die beter aansluit bij de kenmerken van de taak (zoals de duur van de activiteit) en de omgevingsfactoren (zoals concurrenten). Verder tonen de studies de belangrijke rol van de (meta-) cognitieve functies die betrokken zijn bij: a) het beoordelen van de eisen van de taak in relatie tot de prestatiemogelijkheden van de persoon, b) het zelf-monitoren en bijstellen van de mate van inspanning tijdens de taak, en c) de vaardigheid om ervaringen uit het verleden te gebruiken in het maken van een plan van aanpak. Aangezien deze (meta-) cognitieve functies zich ontwikkelen tijdens adolescentie, zullen kinderen en jongere adolescenten meer geneigd zijn om intuïtieve beslissingen te maken aangaande de mate van inspanning. Daarnaast zullen ze meer de neiging hebben om deze beslissingen te verifiëren aan de hand van stimuli uit de (sociale) omgeving. De bevindingen uit dit proefschrift bieden een theoretische basis voor het ontwikkelen van interventies en praktische hulpmiddelen die gericht zijn op het ondersteunen van de mate van inspanning. Deze hulpmiddelen kunnen niet alleen waardevol zijn voor het verbeteren van sportprestatie, maar ook in meer algemene zin voor het bevorderen van plezier tijdens sport en beweging, wat kan bijdragen aan een gezonde levensstijl.

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In parallel with my personal journey during the writing of this thesis, this section is written in a mix of Dutch and English.

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Dear friends and family, please accept this doctoral thesis as a letter of apology for the general confusion about my whereabouts in the past couple of years.

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Dear Christina, sorry for working until late at night, being tired, grumpy, stressed out and generally horrible. Thank you for making me laugh, allowing me to cry and for your unwavering support. Thank you for all the small moments of happiness. I love you very much.

About the author

Stein Gerrit Paul Menting was born June 22th 1994 in Veldhoven. At school he demonstrated his natural curiosity, often to the annoyance of his teachers. Outside school, Stein was often found in the swimming pool and he had great admiration for the way coach and athlete duo Pieter van den Hoogenband and Jacco Verhaeren used science to achieve sports success. In 2012, Stein moved to Maastricht to study Biomedical Sciences, with a major in Human Movement Sciences. During his time in Maastricht, he joined rowing club M.S.R.V. Saurus and H.G. Sunergos. Here, he found a community of likeminded people who encouraged his ambition and passion for sports. Following his graduation in 2016, Stein moved to Groningen to enrol in the master Sport Science. In Groningen, his academic interests fit well with that of his lecturers, in particular Dr. Marije Elferink-Gemser. An internship at Innosportlab 'De Tongelreep' afforded him the chance to work in the same swimming laboratory that once sparked his interest in sport science. During his masters, there was also the initial contact with Prof. Florentina Hettinga, who invited him to come and study the topic of pacing at the University of Essex. Under supervision of Marije and Floor, Stein performed a series of academic assignments and a literature review on the topic of pacing behaviour development. His master graduation thesis on the same topic earned him the runner-up position in the Boymansfonds Encouragement-award competition for best masters' dissertations. After finishing his masters in 2018, Stein pitched a continuation of this line of research and was awarded a fully funded 3-year PhD position via the Master-PhD grant from the University Medical Centre Groningen. Stein moved to Newcastle-upon-Tyne to perform the first part of his studies at Northumbria University. During his time as a PhD researcher, Stein was eager to connect with various international collaborators, either at conferences or through shared research projects. Stein was asked to give an oral presentation at the Annual meeting of the European College of Sport Science every year between 2018 and 2023. In 2021, he was invited as a speaker during a highlighted symposium of the American College of Sport Medicine 68th Annual Meeting. Stein won the Top Publication Awards from the research institute SHARE in 2019, 2020 and 2022 for his journal publications studying the development of pacing behaviour using publicly available athlete data. During his PhD project, Stein supervised multiple bachelor and master projects, both as internal supervisor at the Center for Human Movement Sciences and as external supervisor. Stein was co-initiator and co-organiser of the monthly Sport PhD Meetings. These meetings provided

PhD students with an informal environment in which to present and discuss their work with fellow PhD students and staff. In 2021, Stein took up the role as Embedded Scientist at the Dutch Royal Speed Skating Association (KNSB). In this role, he manages the collection, storage and analysis of data in a multi-year research project into the identification and development of talented junior speed skaters. From 2023, Stein works as Research Associate in the Administrative Data Research Centre at Ulster University in Northern Ireland. Here he performs epidemiological research using population-scale datasets, while also continuing to be engaged in various research projects in the field of sports science.

Scientific output

Peer-reviewed journals

Edwards A.M., **Menting S.G.P.,** Elferink-Gemser M.T., Hettinga F.J. Time is perceived to slow down during exercise, an effect not compounded by the presence of opponents. *Medicine & Science in Sports & Exercise (in peer-review process).*

Menting S.G.P., Khudair M., Elferink-Gemser M.T., Hettinga F.J. Pacing behavior development: the role of task experience and the presence of competitors. *Medicine & Science in Sports & Exercise (in peer-review process).*

Sakalidis K.E., **Menting S.G.P.,** Hettinga F.J. The role of cognition and the social environment in exercise regulation. *BMJ Open Sport & Exercise Medicine (in peer-review process).*

Menting S.G.P., Khudair M., Elferink-Gemser M.T., Hettinga F.J. Unraveling the role of (meta-) cognitive functions in pacing behavior development: planning, monitoring and adaptation. *Medicine & Science in Sports & Exercise (in press).*

Van den Brandt F.A.P., **Menting S.G.P.,** Hettinga F.J., Elferink-Gemser M.T. Drafting in long-track speed skating team pursuit on the ice rink. *Journal of Sports Sciences. 2023;41(5):456-462.*

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Dutch journals

Menting S.G.P., Elferink-Gemser M.T., Hettinga F.J. Optimaal pacing gedrag: jong geleerd, oud gedaan. *SPORTgericht. 2020;74(1):41-45.*

Conference proceedings

Invited speaker at seminar

Menting, S.G.P. The Development of Pacing Behavior During Adolescence: The Influence of Self-regulatory, Meta-cognitive Skills and Executive Functioning. 68th annual meeting of the American College of Sport Medicine, Virtual Congress.

Oral presentations

Menting S.G.P., Khudair M., Elferink-Gemser M.T. Hettinga F.J. How do we learn to pace the race? Exploring the role of age and cognition in effort regulation. 28th Annual Congress of the European College of Sport Science, Paris, France.

Menting S.G.P., Post A.K., Nijenhuis B.S., Koning R., Visscher C., Hettinga F.J., Elferink-Gemser M.T. Pacing behaviour development of swimmers: a longitudinal analysis of the 200m freestyle. 27th Annual Congress of the European College of Sport Science, Sevilla, Spain.

Van Son B.L., Verhoef T., **Menting S.G.P.** The flying rabbit: the use of a drone to impact pacing behaviour in 1500m running. 27th Annual Congress of the European College of Sport Science, Sevilla, Spain.

Menting S.G.P., Stoter I.K., Hettinga F.J., Elferink-Gemser M.T. The development of pacing behaviour during adolescence differs between men and women: a longitudinal study in long-track speed skating. 26th Annual Congress of the European College of Sport Science, Virtual Congress.

Menting S.G.P., Edwards A.M., Hettinga, F.J. Time for action: the impact of fatigue and the presence of opponents on the perception of time during a 4-km cycling trial. 25th Annual Congress of the European College of Sport Science, Virtual Congress.

Matta G., **Menting S.G.P.**, Edwards A.M., Hettinga F.J., Roelands B., Hurst P. Pacing and performance during the World 24-Hour Mountain Bike Championships. 25th Annual Congress of the European College of Sport Science, Virtual Congress.

Elferink-Gemser M.T., Hettinga F.J., **Menting S.G.P.** Pacing and self-regulation in youth athletes: how to coach youth endurance athletes towards excellence? 25th Annual Congress of the European College of Sport Science, Virtual Congress.

Menting S.G.P., Konings M.J., Huijgen B.H.G., Elferink-Gemser M.T., Hettinga F.J. Development of 1500-m pacing behaviour in elite youth short-track speed skaters: a longitudinal study. 24th Annual Congress of the European College of Sport Science, Prague, Czech Republic.

Menting S.G.P., Konings M.J., Elferink-Gemser M.T., Hettinga F.J. Pacing behaviour of elite youth short track speed skaters in 1500m head-to-head competition. 23th Annual Congress of the European College of Sport Science, Dublin, Republic of Ireland.

Poster presentations

Menting S.G.P., Konings M.J., Huijgen B.H.G., Elferink-Gemser M.T., Hettinga F.J. A longitudinal study of the development of 1500-m performance and pacing behaviour in world-class youth short-track speed skaters. British Association of Sport and Exercise Sciences Conference, Leicester, United Kingdom.

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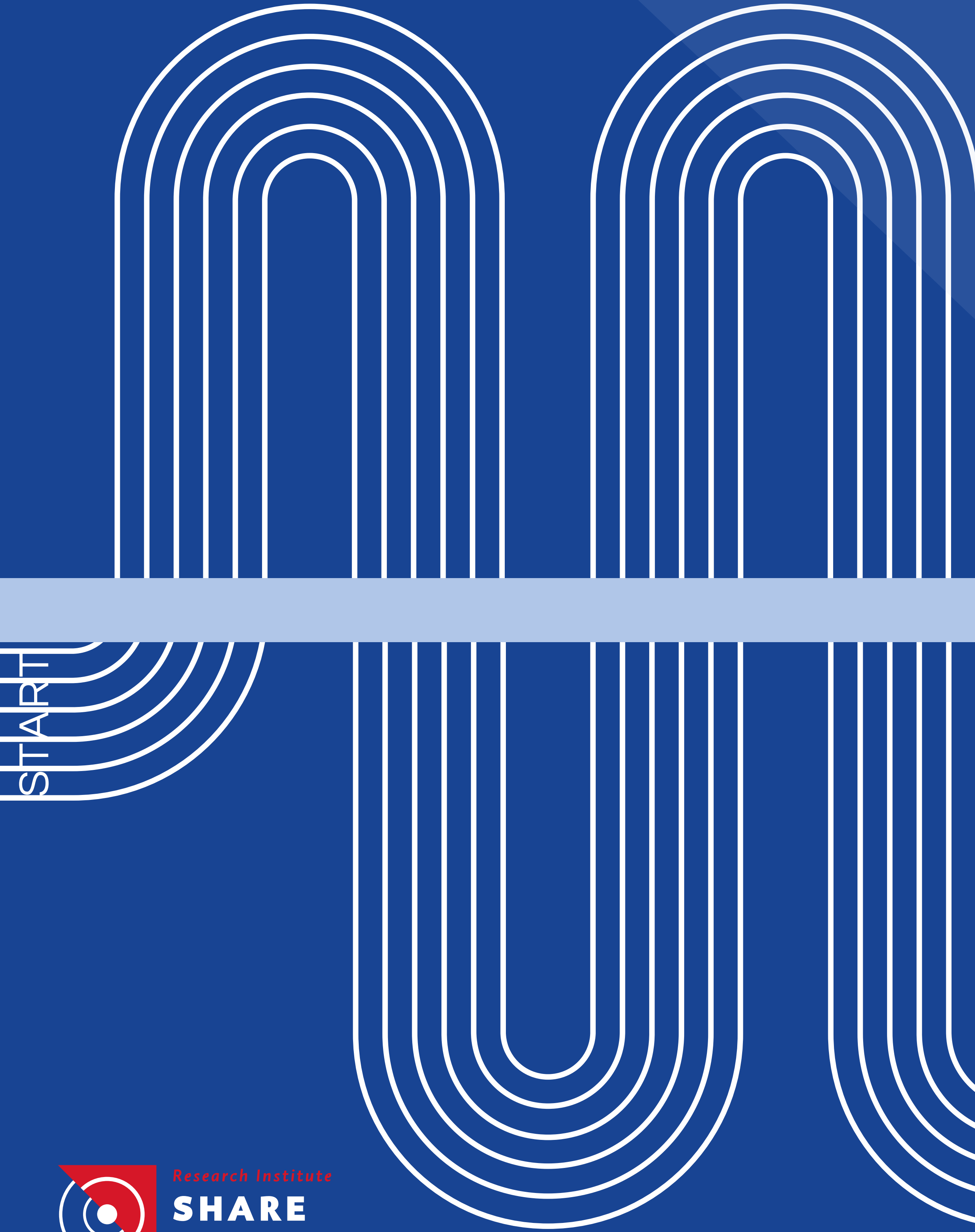

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