Picking up the pace

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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.

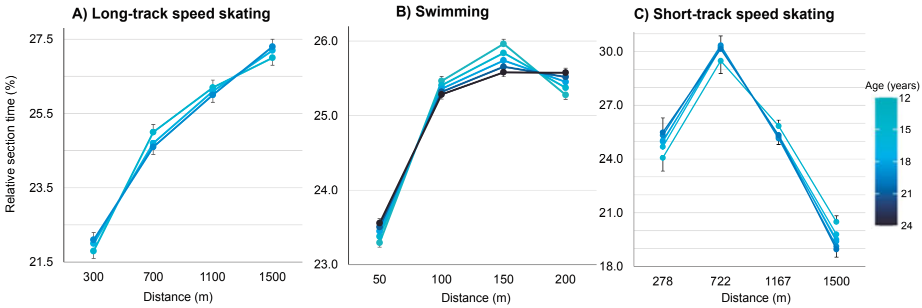

Figure 1. Mean relative section times (±SD/SE) for adolescent athletes performing A) 1500-m long-track speed skating (adopted from Wiersma *et al*), B) 200-m freestyle swimming (Chapter 8), and C) 1500-m short-track speed skating (Chapter 6). Gridlines equal 1.0%.

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.

7. References

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