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Picking up the pace

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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.

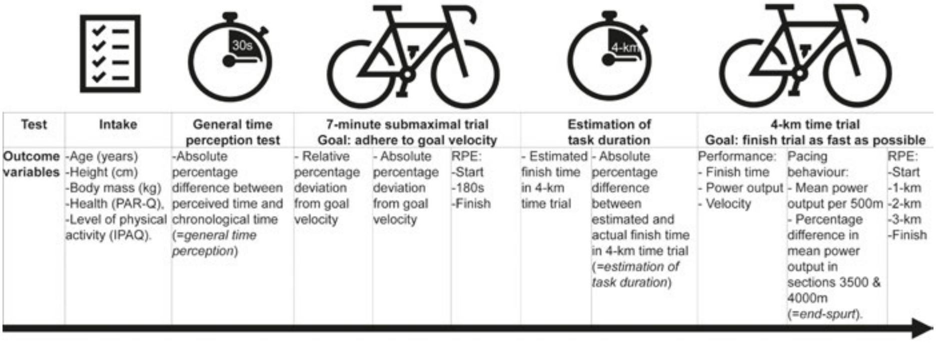
2. Methods

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).

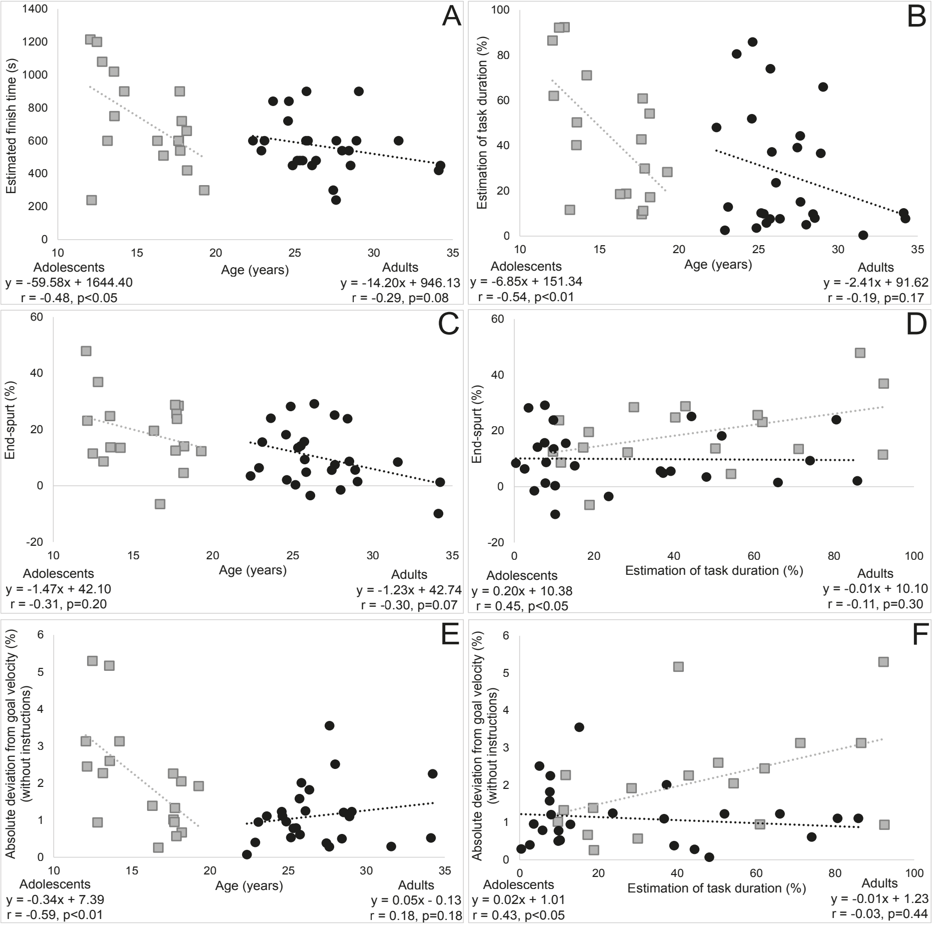


Figure 2. Scatterplots displaying data points of adolescents (grey squares) and adults (black circles), including linear trendlines and regression equations as well as outcomes of the statistical tests (correlations) of the following relations: A) age and estimated finish time, B) age and estimation 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).

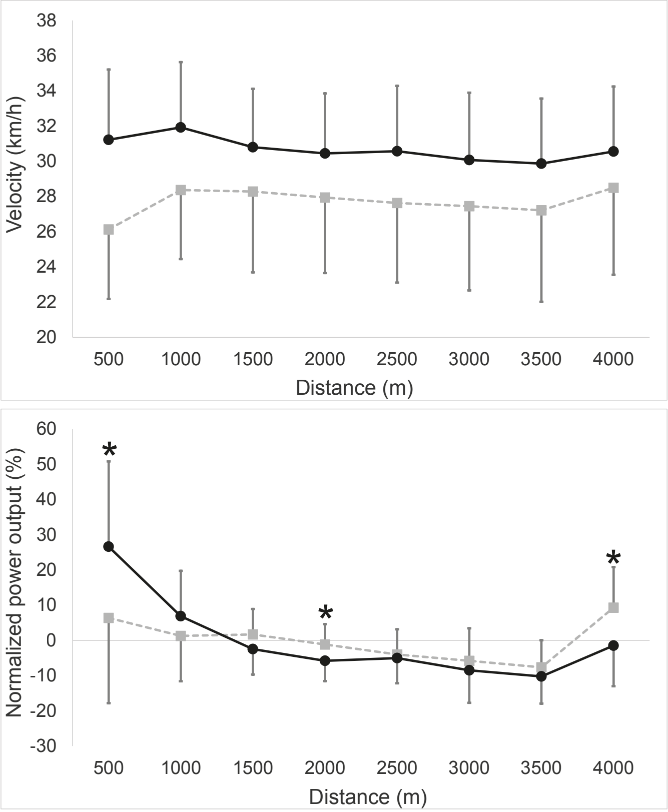


Figure 3. Pacing behaviour of adolescents (grey, squares) and adults (black circles) during the 4-km time trial, expressed as velocity and normalized power output over 500m sections. * = $p<0.01$, $d>0.80$.

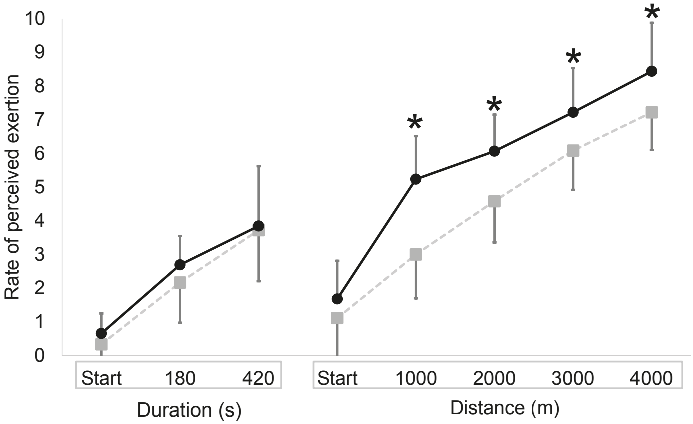


Figure 4. Rate of perceived exertion of adolescents (grey squares) and adults (black circles) per section during the 7-min submaximal trial and 4-km time trial. * = $p<0.05$, $d>0.90$.

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).

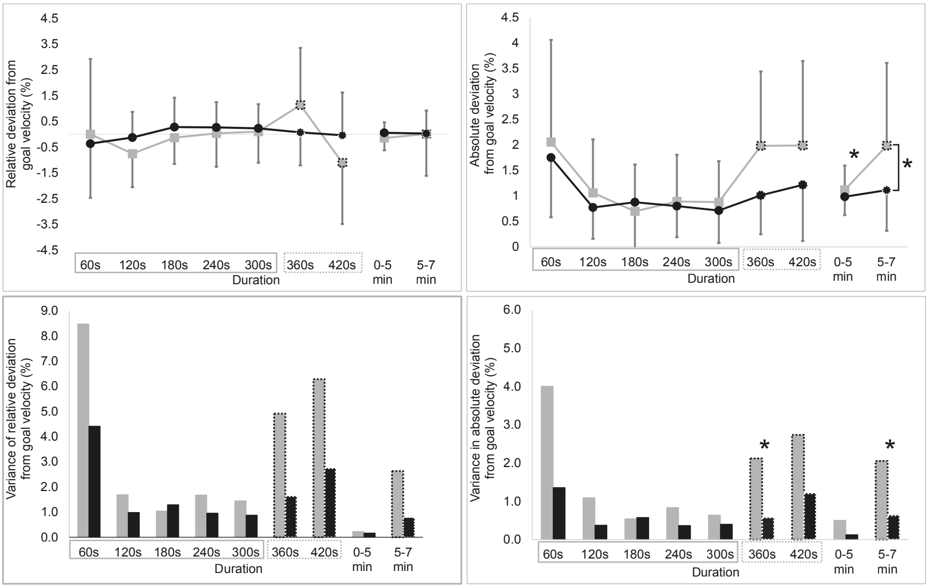


Figure 5. Mean (±standard deviation) and variance of the relative and absolute deviation from goal velocity for adolescents (grey squares) and adults (black circles) during each minute of the 7-min submaximal trial, as well as the full sections with additional feedback (solid border) and without additional 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.

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