University of Groningen

Unraveling the Role of (Meta-) Cognitive Functions in Pacing Behavior Development during Adolescence

Menting, Stein Gerrit Paul; Khudair, Mohammed; Elferink-Gemser, Marije Titia; Hettinga, Florentina Johanna

Published in:
Medicine and Science in Sports and Exercise

DOI:
10.1249/MSS.0000000000003225

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2023

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Menting, S. G. P., Khudair, M., Elferink-Gemser, M. T., & Hettinga, F. J. (2023). Unraveling the Role of (Meta-) Cognitive Functions in Pacing Behavior Development during Adolescence: Planning, Monitoring, and Adaptation. *Medicine and Science in Sports and Exercise*, *55*(10), 1894-1904. https://doi.org/10.1249/MSS.0000000000003225

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Unraveling the Role of (Meta-) Cognitive Functions in Pacing Behavior Development during Adolescence: Planning, Monitoring, and Adaptation

STEIN GERRIT PAUL MENTING[1], MOHAMMED KHUDAIR[2], MARIJE TITIA ELFERINK-GEMSER[1], and FLORENTINA JOHANNA HETTINGA[2]

[1]*Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, THE NETHERLANDS; and* [2]*Department of Sport, Exercise & Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Newcastle, UNITED KINGDOM*

ABSTRACT

MENTING, S. G. P., M. KHUDAIR, M. T. ELFERINK-GEMSER, and F. J. HETTINGA.Unraveling the Role of (Meta-) Cognitive Functions in Pacing Behavior Development during Adolescence: Planning, Monitoring, and Adaptation. *Med. Sci. Sports Exerc.*, Vol. 55, No. 10, pp. 1894–1904, 2023. **Purpose:** This study aimed 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 girls, 15.6 ± 2.5 yr old) and 26 adults (13 women, 26.8 ± 3.1 yr old), all recreationally active but unfamiliar with time trial cycling. The (meta-) cognitive functions involved in preexercise 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 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, estimation of task duration accuracy ($r = 0.48$) and adherence to goal velocity ($r = 0.59$) correlated with age. **Conclusions:** The (meta-) cognitive functions involved in the preexercise 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. **Key Words:** EXERCISE, CYCLING, PERFORMANCE, TIME TRIAL, ADOLESCENCE, COGNITION

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 with 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 behavior, 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 behavior (1,5,7–9). Following Newell's constraints-led approach (10), an individual's pacing behavior is determined by a multitude of interacting factors (5), broadly falling into three

---

Address for correspondence: Florentina Johanna Hettinga, Ph.D., Department of Sport, Exercise & Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Room 238, Northumberland Building, Newcastle Upon Tyne, NE1 8ST, United Kingdom; E-mail: florentina.hettinga@northumbria.ac.uk.

Submitted for publication December 2022.
Accepted for publication May 2023.

0195-9131/23/5510-1894/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000003225

main categories (8): the task (e.g., task duration or sport-specific characteristics (2,11)), the environment (e.g., terrain or presence/behavior of competitors (12,13)), and the individual (e.g., muscle fiber distribution or level of experience (8,14)). With regard to the individual, a recent series of robust longitudinal studies evidenced that the pacing behavior 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 behavior development, it was noted that a long-term misdistribution of effort could not only lead to suboptimal performance, which could decrease the individuals' feeling of competence and enjoyment during exercise, but could also result in overexertion, injury, and dropout of sports and exercise (8,18). Aiding the pacing behavior 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 behavior 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 behavior 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 behavior of younger individuals by helping them to set realistic task goals, plan an appropriate pacing strategy, and reflect upon the pacing behavior after exercise (21). However, pacing is a complex process, involving a multitude of psychophysiological interactions (22). Unraveling 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 behavior development (8,23,24). Focusing on cognitive development, Micklewright et al. (23) reported that the pacing behavior of schoolchildren was related to their scoring on tests for Piaget's stages of cognitive development. 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 behavior development, in which repeated task exposure and the development of the prefrontal 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 that were proposed to facilitate the development of pacing behavior included preexercise planning as well as the monitoring and adaptation of effort distribution during the task. An essential part of the preexercise 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 suboptimal pacing behavior (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 yr (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 with 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 preplanned submaximal pace, compared with 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). However, 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 behavior. However, 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 behavior, as well as offer practitioners a basis to support children and adolescents in their pacing behavior development (3,8,20).

The overall aim of the current study was to investigate the differences in pacing behavior between adolescents and adults. Initially, age-related differences were investigated by comparing the pacing behavior of both groups during a 4-km cycling time trial. In addition, to investigate the hypothesized underlying mechanisms of pacing behavior development as described by Elferink-Gemser and Hettinga (3), specific (meta-) cognitive functions related to pacing were tested. The preexercise 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 behavior 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.

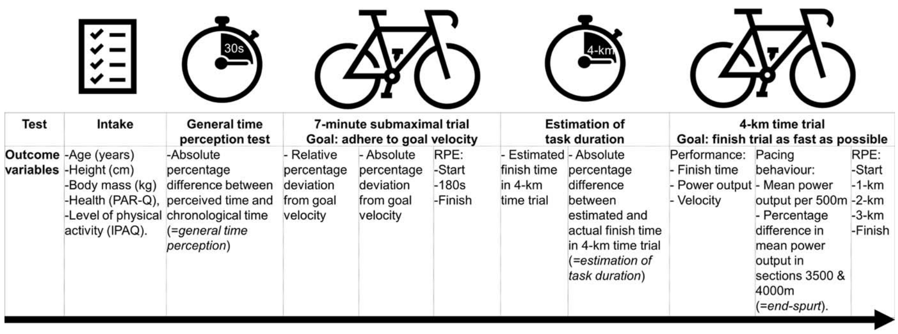
METHODS

Participants. Two groups of adolescents (12–18 yr old) and adults (20–35 yr 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 Physical Activity Readiness Questionnaire) (39), did not have moderate to high activity levels (International Physical Activity Questionnaire) (40), or had any prior experience with cycling time trials. A total of 18 adolescents (9 girls; 15.6 ± 2.5 yr old; height, 168.5 ± 15.8 cm; body mass, 60.2 ± 19.9 kg) and 26 adults (13 women; 26.8 ± 3.1 yr 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, their parents or legal guardians provided written consent. Participants were asked to refrain from any strenuous exercise and alcohol consumption in the preceding 24 h, and from caffeine and food consumption, respectively, 4 and 2 h 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).

Experiment proceedings. An integrated design of several measurements was used to test the hypotheses (Fig. 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, IL). Using the Velotron 3D software, a straight 4-km track was created, which was used in both trials. The track, including an avatar that 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 25 Hz and monitored by the experimenter during both cycling trials. Trials were conducted at ambient temperatures between 19°C and 21°C.

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 s 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 s 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



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 procedure and outcome variables (chronological from left to right).

cycling at a set goal velocity for a duration of 7 min. 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 75 m) 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^{-1}, there would be a beep every 11.0 s). 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 the following: 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 5 min 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 75-m sign. During the last 2 min 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^{-1}, female: 21.0 km·h^{-1}; adult male: 26.0 km·h^{-1}, female: 23.5 km·h^{-1}) (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 s 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 min 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." In addition, 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 250 m before the end of the trial. To increase the impact of the estimation of task duration on pacing behavior 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.

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. In addition, 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 analyzed 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 ρ 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 behavior between the two age groups were analyzed using a two-way repeated-measures ANOVA, using mean power output during each 500-m 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 500-m 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 3000–3500 m to the 3500–4000 m sections. 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 ρ correlation. In addition, 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 ρ correlation). Because of 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, 2m, and 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 min) and without additional feedback (5–7 min), were analyzed using the Brown–Forsythe test. In addition, 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 ρ 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 s, and at the 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, respectively (46). Effect size and correlations were compared with 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).

RESULTS

Time perception and estimation of task duration. Mean (±SD) 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 (Fig. 2A), as well as between age and estimation of task duration (Fig. 2B). No such correlations were found in the adult group.

Four-kilometer 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 (±SD) values of the velocity and normalized power output per 500 m, for both adolescents and adults, are presented in Figure 3. Adolescents exhibited a lower normalized power output during section 0–500 m and a higher normalized power output during sections 1500–2000 m and 3500–4000 m ($F_{1.80,\ 76.05} = 7.09$, $P < 0.01$, $f = 0.40$). Adolescents exhibited a 9.2% larger increase in power output during the last 500 m of the trial (i.e., the end-spurt) compared with the adults. Both in the adolescent and adult groups, there was no significant correlation between age and end-spurt (Fig. 2C). However, it should be mentioned that the regression equations in both groups indicate a trend toward 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 (Fig. 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, 2, and 3 km, and at the finish of the trial (Fig. 4).

Seven-minute submaximal trial. The mean (±SD) 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 300–360 s. No difference between age groups in the absolute deviation from goal velocity was found in the section with additional feedback (0–5 min). In the section without additional feedback (5–7 min), the adolescents' absolute deviation from goal velocity was higher compared with the adults ($\Delta 0.87\%$, $U = 2.46$, $P < 0.05$). Within the adolescent group, the absolute deviation from goal velocity was higher in the section without additional feedback, compared with additional feedback ($\Delta 0.87\%$, $U = 2.59$, $P < 0.01$). 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 (Fig. 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 (Fig. 2F). No such correlations were found in the adult group. No differences in RPE were found between the age groups during the submaximal trial ($F_{1.42,\ 59.80} = 0.65$, $P = 0.47$, $f = 0.12$; Fig. 4).

DISCUSSION

The current study revealed a difference in pacing behavior during the 4-km cycling time trial between adolescents and adults, providing further support for the view that pacing

TABLE 1. Means (±SD) for performance variables, estimation of task duration, and start and end-spurt measures for adolescent and adult groups.

	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 (W)	136.7 (±52.2)	174.0 (±51.6)	37.3 (±15.9)	$t = 2.34$, $P < 0.05$. $d = 0.72$
Velocity ($\text{km}\cdot\text{h}^{-1}$)	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)	$t = 2.67$, $P < 0.05$, $d = 0.82$

Including mean difference (±SE) between age groups and outcomes of the statistical between-group tests.

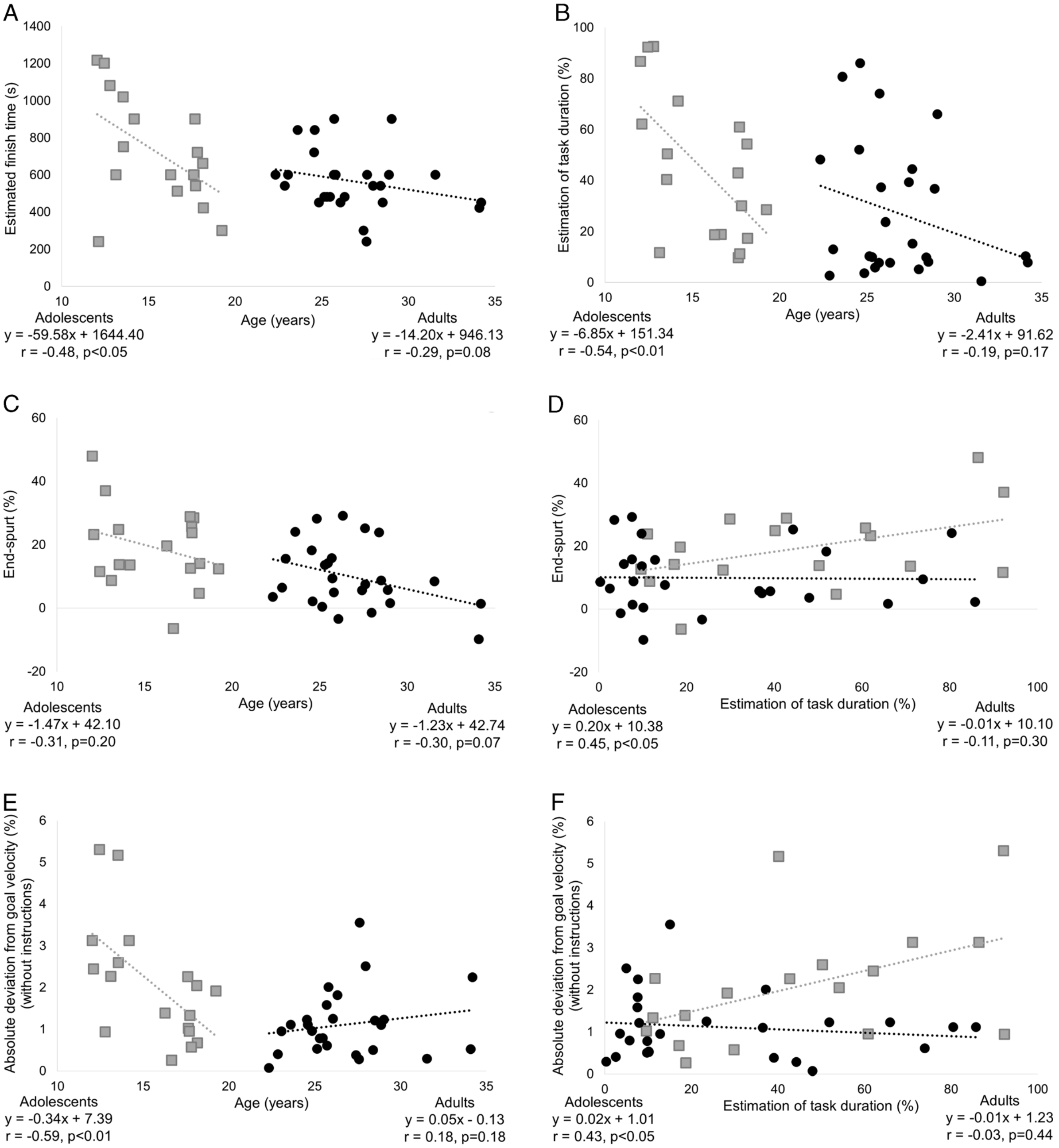


FIGURE 2—Scatterplots displaying data points of adolescents (*gray squares*) and adults (*black circles*), including linear trendlines and regression equations as well as outcomes of the statistical tests (correlations) of the following relations: age and estimated finish time (A), age and estimation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

behavior 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 behavior.

Pacing behavior: adolescents and adults. Previous observational cross-sectional and longitudinal studies in the (elite) athlete population reported that pacing behavior differs between adolescent and adult athletes (8). The current study, using a well-controlled laboratory design, corroborates these findings, as the pacing behavior during the 4-km time trial differed between the age groups. Furthermore, the demonstrated difference in pacing behavior between adolescents and adults who are recreationally active suggests that pacing behavior 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 attribute to the risk of injury, overexertion, and dropout (8,18,19). Suitable support of the development of pacing

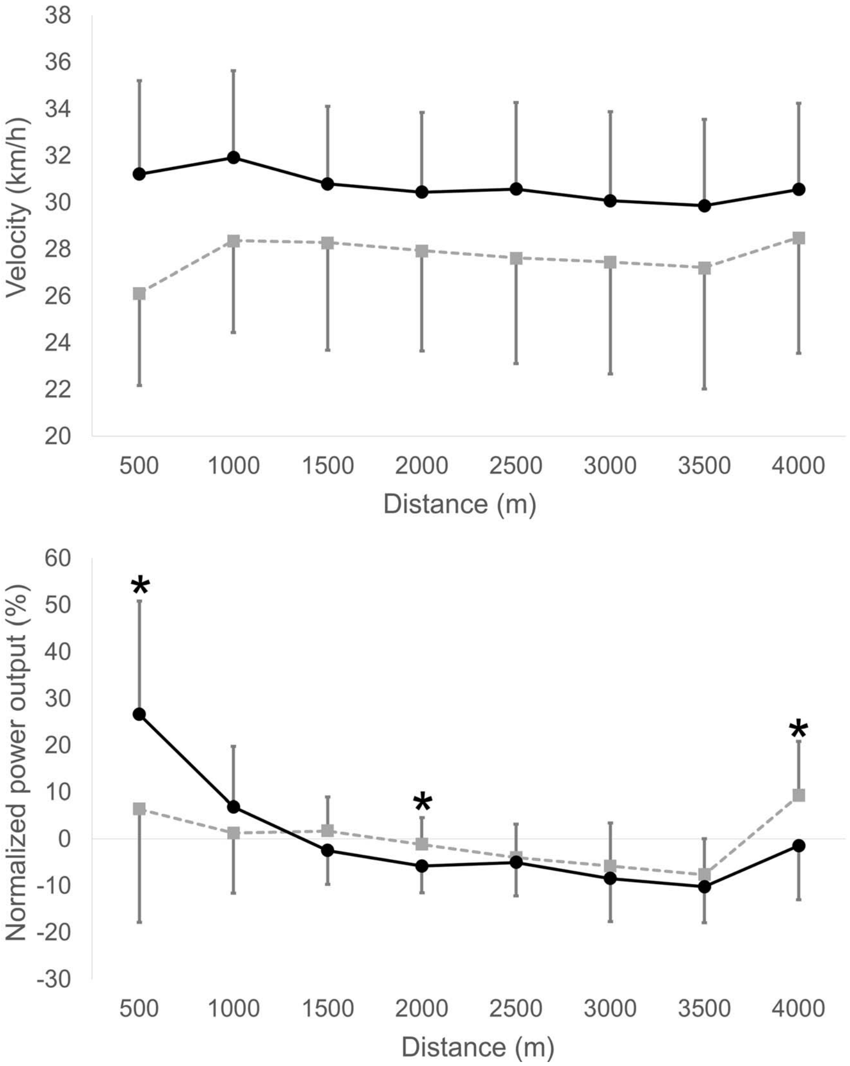


FIGURE 3—Pacing behavior of adolescents (*gray*, *squares*) and adults (*black circles*) during the 4-km time trial, expressed as velocity and normalized power output over 500-m sections. $^*P < 0.01$, $d > 0.80$.

behavior 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.

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 behavior (23,26). These (meta-) cognitive functions are proposed to develop during late childhood and adolescence, and are theorized to underpin the development of pacing behavior (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 with adults. In addition, within the adolescent group, younger adolescents were less accurate in their estimation of task duration, compared with 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 behavior 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 behavior 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. However, this overestimation of the trial's duration was

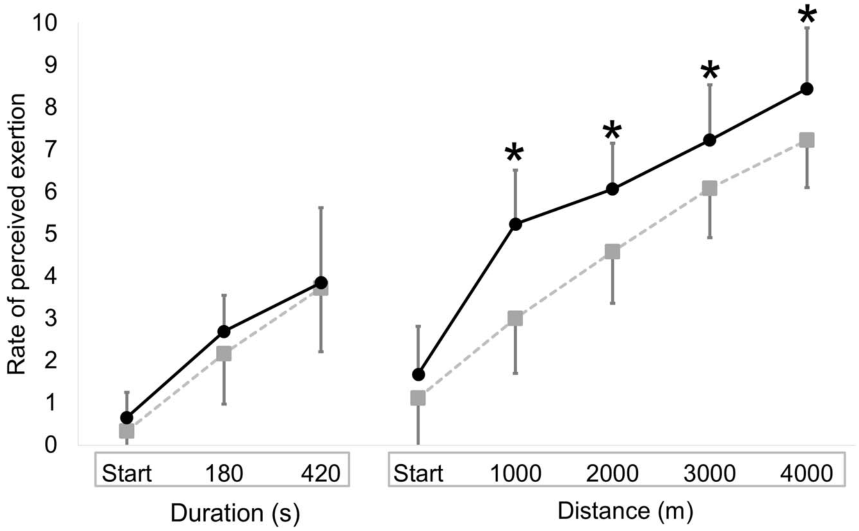


FIGURE 4—RPE of adolescents (*gray squares*) and adults (*black circles*) per section during the 7-min submaximal trial and 4-km time trial. *$P < 0.05$, $d > 0.90$.

significantly larger in the adolescent group, compared with 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 behavior results from the notion that power output and velocity scale nonlinearly 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 behavior 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 500 m of the trial, compared with the adults. Furthermore, in both groups, the regression equations indicated a trend toward a decrease in the end-spurt with age. Within the adolescent group, a larger estimated task duration

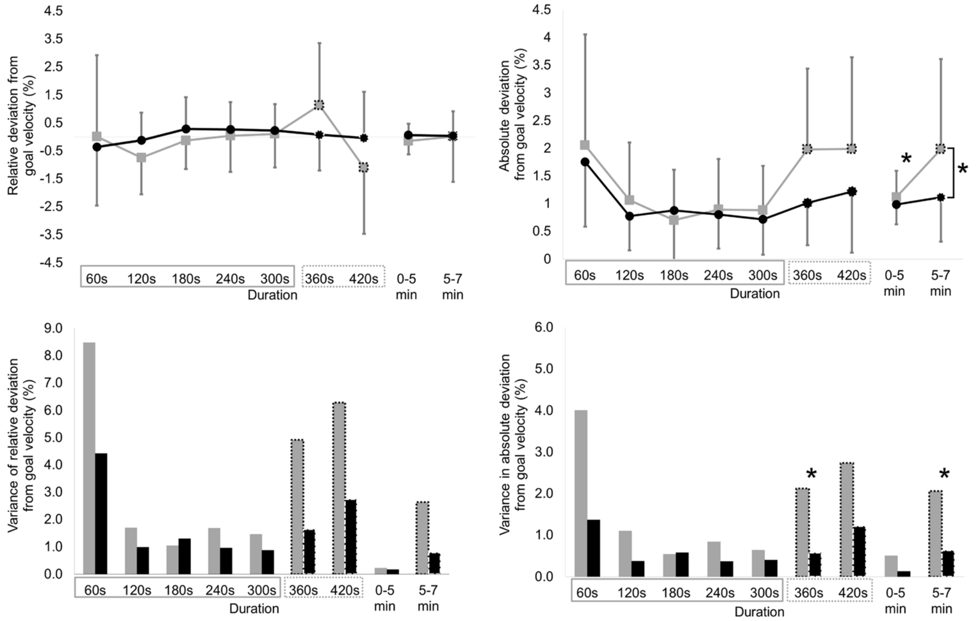


FIGURE 5—Mean (±SD) and variance of the relative and absolute deviation from goal velocity for adolescents (*gray squares*) and adults (*black circles*) during each minute of the 7-min submaximal trial, as well as the full sections with additional feedback (*solid border*) and without additional feedback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

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). Taken together, 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 behavior during exercise. Furthermore, based on our current findings, it could be argued that it is the (meta-) cognitive process of accurately establishing a preexercise pacing plan that 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 preexercise 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 behavior which fits these demands (3,8).

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 behavior during adolescence and would therefore differ between adolescents and adults. In addition, 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 analyzing 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 with 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 preset 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 prefrontal 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 preexercise but also in the monitoring and adaptation of effort expenditure during exercise (3,4). However, additional experiments would be needed to confer the nature of the relationship between these (meta-) cognitive functions and the development of pacing behavior.

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 preexercise planning by asking questions such as follows: "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?" In addition, 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 suboptimal distribution of effort and the associated risks of injury, burnout, and dropout 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 behavior.

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 behavior, as well as match their pacing behavior to their task performance (4). Repeated task exposure leads individuals to adapt their pacing behavior 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 behavior and integrate this in anticipation of a future task could be another (meta-) cognitive function, which is associated with the development of pacing behavior during adolescence. Future studies are warranted to enlighten whether younger individuals might need additional aid in these reflective and adaptive aspects of pacing behavior.

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 preexercise 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. However, 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.

CONCLUSIONS

The current study investigated the development of pacing behavior 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 behavior 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. However, 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 behavior developing during adolescence but also differentiates specific (meta-) cognitive functions involved in the complex pacing process, which underpins 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 behavior.

Author contributions: The study conception and design were done in full collaboration with all authors. All authors critically revised the work. All authors read and approved the final manuscript.

The authors received no specific funding for this work. The authors do not have any conflict of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

REFERENCES

1. Edwards A, Polman R. An introduction to pacing in sport and exercise. In: *Pacing in Sport and Exercise: A Psychophysiological Perspective*. New York: Nova Science Publishers; 2012. p. 23–48.
2. Foster C, DeKoning J, Hettinga FJ, et al. Effect of competitive distance on energy expenditure during simulated competition. *Int J Sports Med*. 2004;25(3):198–204.
3. Elferink-Gemser MT, Hettinga FJ. Pacing and self-regulation: important skills for talent development in endurance sports. *Int J Sports Physiol Perform*. 2017;12(6):831–5.
4. Brick NE, MacIntyre TE, Campbell MJ. Thinking and action: a cognitive perspective on self-regulation during endurance performance. *Front Physiol*. 2016;7:159.
5. Smits BL, Pepping GJ, Hettinga FJ. Pacing and decision making in sport and exercise: the roles of perception and action in the regulation of exercise intensity. *Sports Med*. 2014;44(6):763–75.
6. Konings MJ, Hettinga FJ. Pacing decision making in sport and the effects of interpersonal competition: a critical review. *Sports Med*. 2018;48(8):1829–43.
7. Renfree A, Martin L, Micklewright D, St Clair Gibson A. Application of decision-making theory to the regulation of muscular work rate during self-paced competitive endurance activity. *Sports Med*. 2014;44(2):147–58.
8. Menting SGP, Edwards AM, Hettinga FJ, Elferink-Gemser MT. Pacing behaviour development and acquisition: a systematic review. *Sports Med Open*. 2022;8(1):143.

9. Foster C, De Koning JJ, Hettinga F, et al. Pattern of energy expenditure during simulated competition. *Med Sci Sports Exerc*. 2003;35(5):826–31.
10. Newell K. Constraints on the development of coordination. In: Wade MG, Whiting HTA, editors. *Motor Development in Children: Aspects of Coordination and Control*. Dordrecht (The Netherlands): Martinus Nijhoff; 1986. p. 341–60.
11. Stoter IK, MacIntosh BR, Fletcher JR, Pootz S, Zijdewind I, Hettinga FJ. Pacing strategy, muscle fatigue, and technique in 1500-m speed-skating and cycling time trials. *Int J Sports Physiol Perform*. 2016;11(3):337–43.
12. Welde B, Stöggl TL, Mathisen GE, et al. The pacing strategy and technique of male cross-country skiers with different levels of performance during a 15-km classical race. *PLoS One*. 2017;12(11):e0187111.
13. Hettinga FJ, Konings MJ, Pepping GJ. The science of racing against opponents: affordance competition and the regulation of exercise intensity in head-to-head competition. *Front Physiol*. 2017;8:118.
14. Bellinger P, Derave W, Lievens E, et al. Determinants of performance in paced and maximal 800-m running time trials. *Med Sci Sports Exerc*. 2021;53(12):2635–44.
15. Wiersma R, Stoter IK, Visscher C, Hettinga FJ, Elferink-Gemser MT. Development of 1500-m pacing behavior in junior speed skaters: a longitudinal study. *Int J Sports Physiol Perform*. 2017;12(9):1224–31.
16. Menting SGP, Huijgen BC, Konings MJ, Hettinga F, Elferink-Gemser MT. Pacing behavior development of youth short-track speed skaters: a longitudinal study. *Med Sci Sports Exerc*. 2020;52(5):1099–108.
17. Menting SGP, Post AK, Nijenhuis SB, et al. Pacing behavior development in adolescent swimmers: a large-scale longitudinal data analysis. *Med Sci Sports Exerc*. 2023;55(4):700–9.
18. Schiphof-Godart L, Hettinga FJ. Passion and pacing in endurance performance. *Front Physiol*. 2017;8:83.
19. Edwards AM, Abonie US, Hettinga FJ, Pyne DB, Oh TM, Polman RC. Practical and clinical approaches using pacing to improve selfregulation in special populations such as children and people with mental health or learning disabilities. *J Rehabil Med Clin Commun*. 2021;4:1000058.
20. Menting SGP, Hendry DT, Schiphof-Godart L, Elferink-Gemser MT, Hettinga FJ. Optimal development of youth athletes toward elite athletic performance: how to coach their motivation, plan exercise training, and pace the race. *Front Sports Act Living*. 2019;1:14.
21. Sakalidis KE, Menting SGP, Elferink-Gemser MT, Hettinga FJ. The role of the social environment in pacing and sports performance: a narrative review from a self-regulatory perspective. *Int J Environ Res Public Health*. 2022;19(23):16131.
22. Renfree A, Casado A. Athletic races represent complex systems, and pacing behavior should be viewed as an emergent phenomenon. *Front Physiol*. 2018;9:1432.
23. Micklewright D, Angus C, Suddaby J, St Clair Gibson A, Sandercock G, Chinnasamy C. Pacing strategy in schoolchildren differs with age and cognitive development. *Med Sci Sports Exerc*. 2012;44(2):362–9.
24. Foster C, Hendrickson KJ, Peyer K, et al. Pattern of developing the performance template. *Br J Sports Med*. 2009;43(10):765–9.
25. Micklewright D, Kegerreis S, Raglin J, Hettinga F. Will the conscious–subconscious pacing quagmire help elucidate the mechanisms of self-paced exercise? New opportunities in dual process theory and process tracing methods. *Sports Med*. 2017;47(7):1231–9.
26. Micklewright D. Decision-making, pacing, and performance in endurance sport. In: Meijen C, editor. *Endurance Performance in Sport*. London (UK): Routledge; 2019. p. 47–69.
27. Hyland-Monks R, Cronin L, McNaughton L, Marchant D. The role of executive function in the self-regulation of endurance performance: a critical review. *Prog Brain Res*. 2018;240:353–70.
28. Swart J, Lamberts RP, Lambert MI, et al. Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. *Br J Sports Med*. 2009;43(10):775–81.
29. Micklewright D, Papadopoulou E, Swart J, Noakes T. Previous experience influences pacing during 20 km time trial cycling. *Br J Sports Med*. 2010;44(13):952–60.
30. Smits BL, Polman RC, Otten B, Pepping GJ, Hettinga FJ. Cycling in the absence of task-related feedback: effects on pacing and performance. *Front Physiol*. 2016;7:348.
31. Payne VG, Isaacs LD. Cognitive and motor development. In: *Human Motor Development: A Lifespan Approach*. London (UK): Routledge; 2017. p. 23–44.
32. Lyons KE, Zelazo PD. Monitoring, metacognition, and executive function: elucidating the role of self-reflection in the development of self-regulation. *Adv Child Dev Behav*. 2011;40:379–412.
33. Menting SGP, Elferink-Gemser MT, Edwards AM, Hettinga FJ. Effects of experience and opponents on pacing behavior and 2-km cycling performance of novice youths. *Res Q Exerc Sport*. 2019;90(4):609–18.
34. Chinnasamy C, St Clair Gibson A, Micklewright D. Effect of spatial and temporal cues on athletic pacing in schoolchildren. *Med Sci Sports Exerc*. 2013;45(2):395–402.
35. Green JM, Sapp AL, Pritchett RC, Bishop PA. Pacing accuracy in collegiate and recreational runners. *Eur J Appl Physiol*. 2010;108(3):567–72.
36. Van Biesen D, Hettinga F, McCulloch K, Vanlandewijck YC. Pacing ability in elite runners with intellectual impairment. *Med Sci Sports Exerc*. 2017;49(3):588–94.
37. Scruton A, Baker J, Roberts J, Basevitch I, Merzbach V, Gordon D. Pacing accuracy during an incremental step test in adolescent swimmers. *Open Access J Sports Med*. 2015;6:249–57.
38. Turner AP, Smith T, Coleman SG. Use of an audio-paced incremental swimming test in young national-level swimmers. *Int J Sports Physiol Perform*. 2008;3(1):68–79.
39. Thomas S, Reading J, Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci*. 1992;17(4):338–45.
40. Dinger MK, Behrens TK, Han JL. Validity and reliability of the International Physical Activity Questionnaire in college students. *Am J Health Educ*. 2006;37(6):337–43.
41. Burke ER, Pruitt AL. Body positioning for cycling. In: Burke ER, editor. *High-Tech Cycling*. 2nd ed. vol. 2. Champaign, IL: Human Kinetics; 2003. pp. 69–92.
42. Lim AC, Peterman JE, Turner BM, Livingston LR, Byrnes WC. Comparison of male and female road cyclists under identical stage race conditions. *Med Sci Sports Exerc*. 2011;43(5):846–52.
43. Konings MJ, Schoenmakers PP, Walker AJ, Hettinga FJ. The behavior of an opponent alters pacing decisions in 4-km cycling time trials. *Physiol Behav*. 2016;158:1–5.
44. Robertson RJ, Goss FL, Aaron DJ, et al. Observation of perceived exertion in children using the OMNI pictorial scale. *Med Sci Sports Exerc*. 2006;38(1):158–66.
45. Robertson RJ, Goss FL, Dube J, et al. Validation of the adult OMNI scale of perceived exertion for cycle ergometer exercise. *Med Sci Sports Exerc*. 2004;36(1):102–8.
46. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. New York: Routledge; 1988.
47. Field A. Chapter 4: Correlation. In: Wright DB, editor. *Discovering Statistics Using SPSS*. London: Sage Publications Ltd; 2005. pp. 107–42.
48. Hettinga FJ, De Koning JJ, Schmidt LJ, Wind NA, MacIntosh BR, Foster C. Optimal pacing strategy: from theoretical modelling to reality in 1500-m speed skating. *Br J Sports Med*. 2011;45(1):30–5.
49. Coughlan EK, Williams AM, Ford PR. Lessons from the experts: the effect of a cognitive processing intervention during deliberate practice of a complex task. *J Sport Exerc Psychol*. 2019;41(5):298–308.
50. Toering T, Elferink-Gemser MT, Jonker L, et al. Measuring self-regulation in a learning context: reliability and validity of the Self-Regulation of Learning Self-Report Scale (SRL-SRS). *Int J Sport Exerc Psychol*. 2012;10(1):24–38.