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Pacing Behavior Development in Adolescent Swimmers: A Large-Scale Longitudinal Data Analysis

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[1]Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, the NETHERLANDS; [2]Department Economics, Econometrics and Finance, Faculty of Economics and Business, University of Groningen, the NETHERLANDS; and [3]Department of Sport, Exercise & Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Newcastle, UNITED KINGDOM

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ABSTRACT

MENTING, S. G. P., A. K. POST, S. B. NIJENHUIS, R. H. KONING, C. VISSCHER, F. J. HETTINGA, and M. T. ELFERINK-GEMSER. Pacing Behavior Development in Adolescent Swimmers: A Large-Scale Longitudinal Data Analysis. *Med. Sci. Sports Exerc.*, Vol. 55, No. 4, pp. 700–709, 2023. **Purpose:** This study aimed to use a large-scale longitudinal design to investigate the development of the distribution of effort (e.g., pacing) in adolescent swimmers, specifically disentangling the effects of age and experience and differentiating between performance levels in adulthood. **Methods:** Season best times and 50-m split times of 100- and 200-m freestyle swimmers from five continents were gathered between 2000 and 2021. Included swimmers competed in a minimum of three seasons between 12 and 24 yr old (5.3 ± 1.9 seasons) and were categorized by performance level in adulthood (elite, sub-elite, high-competitive; 100-m: $n = 3498$ (47% female); 200-m: $n = 2230$ (56% female)). Multilevel models in which repeated measures (level 1) were nested within individual swimmers (level 2) were estimated to test the effects of age, race experience, and adult performance level on the percentage of total race time spent in each 50-m section ($P < 0.05$). **Results:** In the 100-m, male swimmers develop a relatively faster first 50-m when becoming older. This behavior also distinguishes elite from high-competitive swimmers. No such effects were found for female swimmers. Conversely, more experienced male and female swimmers exhibit a slower initial 50-m. With age and race experience, swimmers develop a more even velocity distribution in the 200-m. Adolescent swimmers reaching the elite level adopt a more even behavior compared with high-competitive. This differentiation occurs at a younger age in female (>13 yr) compared with male (>16 yr) swimmers. **Conclusions:** Pacing behavior development throughout adolescence is driven by age-related factors besides race experience. Swimmers attaining a higher performance level during adulthood exhibit a pacing behavior that better fits the task demands during adolescence. Monitoring and individually optimizing the pacing behavior of young swimmers is an important step toward elite performance. **Key Words:** SPORT, RACE ANALYSIS, COMPETITIVE SWIMMING, FUTURE PERFORMANCE, TALENT, MULTILEVEL MODELING

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

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into the development of pacing behavior, more rigorous longitudinal studies with large sample sizes are needed.

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

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

METHODS

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

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

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

Inclusion criteria. For the purpose of this study, it was important to outline the development of pacing behavior from

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

Swim performances of multiple generations (i.e., from 2000 to 2021) were included in the data set, which necessitated the correction of evolution in competitive swimming. As such, swim performances were defined as a percentage of the prevailing world record of the corresponding sex, referred to as relative season best time (rSBT) (26,27). World records from 2008 and 2009 were replaced by the prevailing fastest time in a textile swimsuit. According to the event, swimmers were allocated to the elite, sub-elite, or high-competitive performance group by using their event-specific all-time rSBT after 20 (female) or 22 (male) yr of age (Table 1). The elite level was defined as the average rSBT of the 50th swimmer of the event-specific FINA World Ranking List between 2016 and 2021 (11). Sub-elite level and high-competitive level were defined as the average rSBT of the 8th and 50th swimmer of the event-specific National Ranking List of the Netherlands between 2016 and 2021 (11). Swimmers with a best rSBT outside the limits of the high-competitive group were excluded from further analysis. For the 100-m event, this resulted in 3498 swimmers (1659 female) with 15,960 observations (7384 female) with an average of 5.3 ± 1.9 observations per swimmer. For the 200-m event, this resulted in 2230 swimmers (1252 female) with 10,309 observations (5412 female) with an average of 5.3 ± 1.9 observations per swimmer.

TABLE 1. Total number of swimmers and observations according to sex, performance level, and event included in the analysis.

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

Statistical analysis. Following the methods introduced by Menting et al. (7), longitudinal multilevel models were created to describe pacing behavior as a function of age, race experience, and performance group. Multilevel modeling allows for the creation of models in which repeated measures (level 1) are nested within individual swimmers (level 2), allowing the use of longitudinal data with varying numbers of measurements between swimmers as well as a variety in temporal spacing between measurements. Analyses were performed using the lmer4 package in R (R version 3.6.0) (28,29). Statistical assumptions (e.g., multicollinearity) were checked, and outliers were screened and removed (100-m, 915; 200-m, 1006). The RST values per 50-m section were included as dependent variables. In contrast to split times, all RST values must add up to 100%. With respect to this constraint, one out of two (100-m freestyle) and three out of four (200-m freestyle) multilevel models were created. The remaining, free section (RST 50–100-m in both events) was calculated from these models. After that the sum of 50-m sections must add up to 100%, the same predictor variables (fixed part) and variance structure (random part) had to be incorporated into each model equation. Predictor variables age and race experience were included as continuous, time-varying factors, whereas performance group was included as a categorical, time-invariant factor. The power law of practice states that the effect of experience on performance decreases as the level of experience increases (30). In addition, the age effect on performance decreases as swimmers are fully matured (26). As such, the effect of a 1-yr increase at age 13 will be larger than a 1-yr increase at age 19. To account for this, the variables age and race experience were log-transformed, of which the latter transformation was needed to meet the assumption of normality. To represent the three performance groups in the statistical models, two dummy variables (sub-elite and high-competitive) were included, and the elite group functioned as reference level. A random intercept model was selected as the most appropriate variance structure, allowing the inclusion of each swimmer's individual trajectory that randomly deviates from the average population trajectory. In sum, the following multilevel model was adopted:

$$\mathrm{RST}_{is} = \alpha + \beta_1 \times \log\left(\mathrm{Age}_{is}\right) + \beta_2 \times \log\left(\mathrm{RaceExperience}_{is}\right) + \beta_3 \times \mathrm{Sub\text{-}Elite}_i + \beta_4 \times \mathrm{HighCompetitive}_i + u_i + \varepsilon_{is}$$

$$u_i \sim N\left(0, \sigma_0^2\right)$$

$$\varepsilon_{is} \sim N\left(0, \sigma^2\right)$$

RST_{is} was the relative split time of a 50-m section for swimming season s of swimmer i; α, the intercept assigned to the elite group; Age_{is}, the corresponding age value; $RaceExperience_{is}$, the corresponding race experience value; $Sub\text{-}Elite_i$, the dummy variable of swimmer i assigned to the sub-elite group; and $HighCompetitive_i$, the dummy variable of swimmer i assigned to the high-competitive group. The unexplained information was the sum of u_i (between-subject variance) and ε_{is} (residual variance). The models were validated by using graphical tools to check violations of homogeneity, normality, and independence. Predictor variables were considered significant if the estimated coefficient is greater than twice the standard error of the estimate ($P < 0.05$). *Post hoc* analyses were performed for models with future performance group as a significant predictor variable. For this analysis, swimmers were classified in age categories based on their age on December 31 of the swimming season. Per age category, an independent sample *t*-test was conducted to examine from which age onward between-group differences in pacing behavior occurred. These follow-up analyses were executed for age categories with at least 30 observations per performance group. For all tests, $P < 0.05$ (two-tailed) was set as significance.

RESULTS

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

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

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

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

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

DISCUSSION

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

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

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

	50-m				100-m			
Male (100-m Freestyle)	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***
Fixed effects								
Intercept	48.90	0.15	48.61 to 49.19	**<0.001**	51.10	—	—	—
Age[a]	−0.30	0.05	−0.40 to −0.20	**<0.001**	0.30	—	—	—
Race experience[a]	0.02	0.01	0.01 to 0.04	**<0.01**	−0.02	—	—	—
Elite vs sub-elite	0.05	0.04	−0.02 to 0.12	0.190	−0.05	—	—	—
Elite vs high-competitive	0.12	0.03	0.06 to 0.19	**<0.001**	−0.12	—	—	—
Random effects								
σ^2	0.22					—	—	—
τ_{00}	0.11					—	—	—
ICC	0.33					—	—	—
Marginal R^2/conditional R^2	0.011/0.334					—	—	—

	50-m				100-m				150-m				200-m			
Male (200-m Freestyle)	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***
Fixed effects																
Intercept	22.20	0.14	21.94 to 22.47	**<0.001**	26.14	—	—	—	27.42	0.10	27.23 to 27.61	**<0.001**	24.24	0.16	23.92 to 24.55	**<0.001**
Age[a]	0.38	0.05	0.28 to 0.47	**<0.001**	−0.26	—	—	—	−0.55	0.03	−0.62 to −0.48	**<0.001**	0.43	0.06	0.32 to 0.54	**<0.001**
Race experience[a]	0.05	0.01	0.03 to 0.06	**<0.001**	−0.01	—	—	—	−0.03	0.01	−0.04 to −0.02	**<0.001**	−0.01	0.01	−0.03 to 0.01	0.240
Elite vs sub-elite	0.03	0.03	−0.03 to 0.09	0.412	−0.00	—	—	—	−0.00	0.02	−0.04 to 0.04	0.858	−0.02	0.03	−0.09 to 0.04	0.495
Elite vs high-competitive	−0.11	0.03	−0.16 to −0.05	**<0.001**	−0.03	—	—	—	0.09	0.02	0.06 to 0.13	**<0.001**	0.04	0.03	−0.02 to 0.10	0.150
Random effects																
σ^2	0.10					—	—	—	0.06				0.17			
τ_{00}	0.05					—	—	—	0.02				0.05			
ICC	0.34					—	—	—	0.23				0.22			
Marginal R^2/conditional R^2	0.011/0.334								0.152/0.345				0.020/0.233			

	50-m				100-m			
Female (100-m Freestyle)	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***
Fixed effects								
Intercept	48.06	0.13	47.80 to 48.31	**<0.001**	51.94	—	—	—
Age[a]	0.06	0.05	−0.03 to 0.15	0.215	−0.06	—	—	—
Race experience[a]	0.04	0.01	0.02 to 0.05	**<0.001**	−0.04	—	—	—
Elite vs sub-elite	−0.03	0.03	−0.10 to 0.03	0.331	0.03	—	—	—
Elite vs high-competitive	−0.05	0.03	−0.10 to 0.01	0.095	0.05	—	—	—
Random effects								
σ^2	0.17					—	—	—
τ_{00}	0.08					—	—	—
ICC	0.33					—	—	—
Marginal R^2/conditional R^2	0.010/0.335							

	50-m				100-m				150-m				200-m			
Female (200-m Freestyle)	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***	**Estimates**	**SE**	**CI**	***P***
Fixed effects																
Intercept	22.24	0.12	22.01 to 22.46	**<0.001**	26.02	—	—	—	27.15	0.08	26.99 to 27.31	**<0.001**	24.60	0.12	24.36 to 24.84	**<0.001**
Age[a]	0.40	0.04	0.32 to 0.49	**<0.001**	−0.24	—	—	—	−0.47	0.03	−0.52 to −0.41	**<0.001**	0.30	0.05	0.22 to 0.39	**<0.001**
Race experience[a]	0.06	0.01	0.05 to 0.07	**<0.001**	−0.00	—	—	—	−0.04	0.00	−0.04 to −0.03	**<0.001**	−0.02	0.01	−0.04 to −0.01	**<0.001**
Elite vs sub-elite	−0.01	0.03	−0.07 to 0.04	0.616	−0.02	—	—	—	0.01	0.02	−0.03 to 0.04	0.719	0.03	0.03	−0.02 to 0.08	0.203
Elite vs high-competitive	−0.18	0.02	−0.23 to −0.14	**<0.001**	0.00	—	—	—	0.11	0.02	0.08 to 0.14	**<0.001**	0.07	0.02	0.03 to 0.12	**0.001**
Random effects																
σ^2	0.09					—	—	—	0.05				0.12			
τ_{00}	0.05					—	—	—	0.02				0.03			
ICC	0.37					—	—	—	0.26				0.21			
Marginal R^2/conditional R^2	0.142/0.463								0.166/0.380				0.015/0.225			

[a]The variables age and race experience were log-transformed. The *P* value of significant predictor variables (α-<-0.05) indicated in bold.

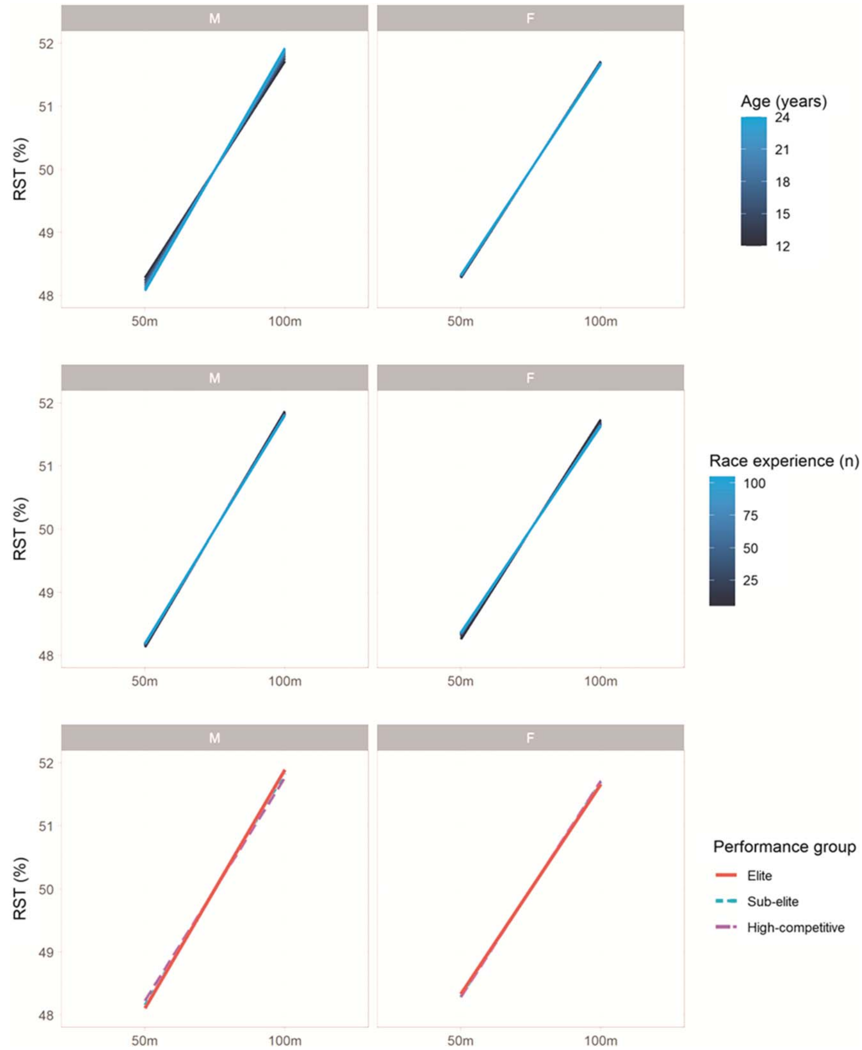

FIGURE 1—Predicted pacing behavior for male and female swimmers in the 100-m freestyle event according to age, race experience, and performance level.

thereby confirmed by the current longitudinal study and is thought to be caused by the earlier onset of physical maturation and cognitive development (20,21).

Based on previous literature, it was proposed that with experience and age, adolescent athletes adapt their pacing behavior to better fit the task demands (6,7). Indeed, within the present study, there is a difference in the development of pacing behavior in the 100- and 200-m events. In the 100-m event, older male swimmers adopt a more all-out pacing behavior, characterized by a relatively faster first lap. The relatively faster initial 50-m could be the result of an improved race start, including the dive and underwater phase. Alternatively, it has been established that in tasks of similar duration to the 100-m freestyle event, better-performing athletes differentiated themselves by a relatively more all-out pacing behavior (31,32). De Koning et al. (32) proposed that for shorter events (<2 min), the advantage of a higher velocity in the first part of an exercise task and the lower amount of kinetic energy left at the end of the race outweighed the disadvantage of higher frictional losses associated with the higher average velocity, which was further evidenced through modeling studies in speed skating and track cycling (33,34), although differences between sports were visible (35). Indeed, elite swimmers competing in the 100-m freestyle finals of international events exhibited an all-out pacing behavior, comparable to the one found in the current study (12). Moreover, it was reported that elite male swimmers adopted a more all-out pacing behavior (RST50 m, 47.91%; RST100 m, 52.09%) compared with female swimmers (RST50 m, 48.29%; RST100 m, 51.77%) (12). These findings are supported by the results of the present study, as adolescent male swimmers not only presented a more all-out pacing behavior but also continued to develop this behavior with age. The reason behind the apparent difference in pacing behavior between male and female swimmers could potentially be found in the physical and physiological differences between male and female swimmers (36). Alternatively, it has been reported that male individuals engage more in risk-taking behavior and therefore are expected to generally adopt a more all-out pacing behavior (37).

Contrary to the 100-m event, older male and female swimmers adopt a relatively more even distribution of velocity in the 200-m event. This is achieved by a relatively slower first

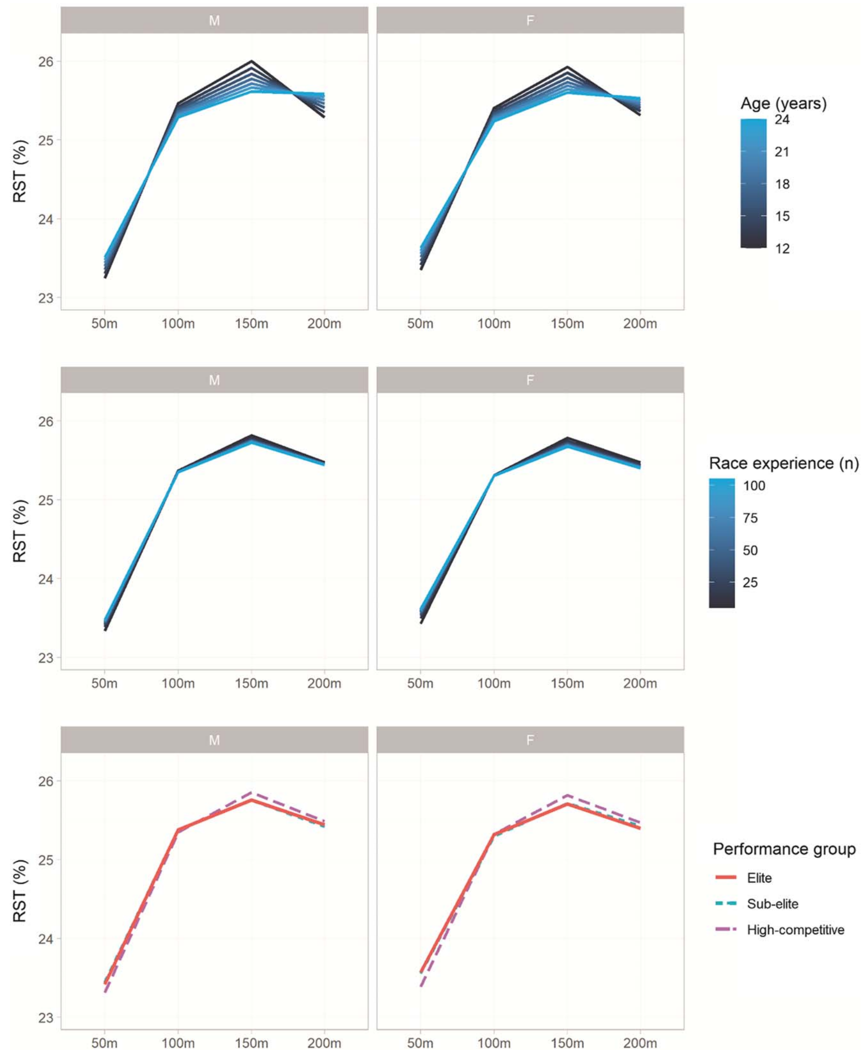

FIGURE 2—Predicted pacing behavior for male and female swimmers in the 200-m freestyle event according to age, race experience, and performance level.

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

Future performance. The findings of the present study provide evidence that the swimmers who perform within 104% of the prevailing world record as adults (i.e., the elite group) exhibit pacing behavior that differentiates them from other adolescent swimmers (i.e., the high-competitive group). It therefore establishes that adequate pacing behavior development is an essential part of the developmental pathway toward elite swimming performance. In the 200-m event, the effect of future performance level parallels the effects of age and race experience in both male and female swimmers. In other words, swimmers that achieve a higher level of performance in adulthood exhibited a pacing behavior resembling that of older and more experienced swimmers during adolescence. This is different for the 100-m event. Adolescent male swimmers who reach the elite level as an adult exhibit a pacing behavior that is more resembling the pacing behavior of the older swimmers (all-out pacing behavior) compared with that of their peers who reach the high-competitive level. However, the current findings suggest that more race experience results in a more conservative first 50-m in the 100-m instead of going more all-out. The underlying mechanism for this converse effect of race experience on pacing behavior in 100-m event remains unclear and warrants further research. In female athletes, no effect of either performance level or age was found; however, the effect of race experience was equal to male athletes.

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

Limitations and future directions. Although the models created in the present study provide novel insights into the relationship between age, experience, and pacing behavior, the models do not account for all the variance in a swimmers' pacing behavior. Pacing is a complex, psychophysiological process, and even when the task characteristics are set, it is influenced by a multitude of factors relating to the individual (i.e., physical maturity, cognitive development, muscle fiber type distribution) and environment (i.e., coaching culture, training opportunities) (1,9,42,43). The absence of these factors has potentially led to the lower explained variance of the models. For example, there was no effect for age or performance level on pacing behavior in female swimmers competing in the 100-m event. In male swimmers, the effect of age and performance group was also more pronounced in the 200-m event compared with the 100-m event. It could be that 100-m freestyle performance is predominantly driven by the development of physical characteristics, such as muscle fiber type distribution, whereas in the 200-m event, the distribution of effort is a larger determination factor in the outcome of the race. However, another reason might be that the 100-m freestyle is often contested by both 50- and 200-m specialists. The energetic system requirements between the 50- and 200-m freestyle events differ significantly, and therefore, swimmers who compete in these events are adapted to physiologically very different tasks (36), therefore exhibiting a different pacing behavior. The coming together of these two types of specialized swimmers might have impacted the results of the present study.

It should be pointed out that previous studies have evidenced that swimming performance is impacted by velocity in free swimming sections, but also by turns and underwater phases (44). Quantification using 25-m or even 5- and 10-m sections has previously been demonstrated to reveal more detailed definitions of impact of these factors on a swimmers' performance (17,44). However, these data have to be gathered using camera setups and specialized software, which drastically decreases practicality and would have reduced the sample size greatly. In the end, the present study aimed to create models that could provide insight into the relation between age, experience, and future performance level, not precisely predict each individual swimmers' pacing behavior. The large sample size, consisting of swimmers from five continents, and the strong longitudinal nature of the data are of key importance to the rigidity of the present study's design, not in the first place because more large-scale longitudinal studies on pacing behavior development are needed (4,21). Consequently, the decision was made to use publicly available 50-m split times. The choice for this approach does allow for future studies, using more detailed quantifications of pacing behavior and the inclusion of more individual and environmental factors, to provide additional insights into the development of pacing behavior in the 100- and 200-m freestyle events.

Practical application. The effect of age and race experience on pacing behavior as reported in the present study are relatively small compared with that of task defining characteristics such as race duration or stroke type (8). However, in a 200-m freestyle, an average 0.16% difference in velocity distribution per 50-m section (the difference between a 12- and 18-yr-old male swimmer as calculated using the models in the present study) constitutes 0.20 s. In a sport where 0.01 of a second can be the difference between winning and losing, a 0.20-s difference in velocity distribution in every 50-m section can indeed have a very real impact on competition performance. Using the formula provided in the present study, coaches could determine whether their swimmers are on track of developing the pacing behavior necessary to achieve the elite performance level. One point of notice should be made to this approach: the road to elite performance is not always linear, and pacing is only a part of the skillset necessary to reach the top (45). In addition, it has been established that to pace adequately, athletes need to match their personal performance capacities to the task demands. Seeing as there is variation in each swimmer's performance capacities, a slightly different pacing behavior could be optimal for each swimmer. It is therefore important to take the outcomes of the formula from the present study as a starting point and take an individualized approach to the development of each swimmer. Within this approach, coaches are advised to provide the swimmers with opportunities to experiment with variants of their established pacing behavior (4). Introducing variability would provide swimmers with the opportunity to discover a more optimal match between their personal performance capacities and the task demands (46). Coaches could induce this variation by providing augmented feedback via tools such as a stopwatch, pacer clock, wearable metronome, underwater lights, or smart goggles (47). Demonstrating this method, a recent study reported that a 3-wk training program in which adolescent swimmers were provided with feedback on their own pacing behavior was effective in increasing 400-m freestyle performance (48). Subsequently, practice of the new variation of pacing behavior could be further increased by gradually taking away sources of feedback and adding environmental factors such as opponents, therefore training the swimmers to maintain their capability of decision making regarding effort distribution in a more realistic competitive environment (9,47).

CONCLUSIONS

The current large-scale study is the first in its kind in that it investigates the pacing behavior of swimmers from five continents over a period spanning the last 20 yr. The rigorous multilevel modeling approach with corrections for prevailing world records revealed insights into developmental patterns based on thousands of swimmers with, on average, five competitive seasons in adolescence. The pacing behavior of swimmers develops during adolescence, as older swimmers adopt a pacing behavior that better suits the task demands (100-m, more all-out (male only); 200-m, more even). Although swimming is a head-to-head type of competition, the development of pacing behavior resembles that of time-trial events, most likely because of the lane-based nature of the sport. The persistence of the effect of age on pacing behavior when race experience was also included as predicting variable supports the hypothesis that pacing behavior development during adolescence is driven by other factors in addition to increased experience, such as physical maturation and cognitive development. Swimmers who reach the elite performance level in adulthood exhibit a pacing behavior better suits the task demands and that resembles that of adults (100-m, more all-out (only male); 200-m, more even) during adolescence. In the 200-m, this differentiation occurs earlier in female compared with male swimmers, most likely because of the earlier onset of age-related physical maturation and cognitive development in female swimmers. Coaches are advised to take notice of the complex development of pacing behavior that occurs throughout adolescence. Furthermore, coaches could use the data presented in the present study as a starting point for an individualized approach to optimize the pacing behavior development in their swimmers and better guide them on the road toward elite performance.

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