Picking up the pace

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Chapter 8

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

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Abstract

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

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

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

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

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

1. Introduction

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

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

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

2. Methods

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

2.1. Data collection

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

2.2. Data processing

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

2.3. Inclusion criteria

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

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

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

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

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

rSBT: relative Season Best Time

2.4. Statistical analysis

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

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$$RST_{is} = \alpha_i + \beta_1 \times \log(Age_{is}) + \beta_2 \times \log(RaceExperience_{is}) + \beta_3 \times SubElite_i + \beta_4 \times HighCompetitive_i + u_i + \varepsilon_{is}$$

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

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

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

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

3. Results

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

$$RST\ 150m = 27.42 + (-0.55 \times \log 18) + (-0.03 \times \log 20) + (-0.00 \times 0) + (0.09 \times 1) \\ = 25.83\%$$

3.1. Age

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

3.2. Race experience

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

3.3. Performance level

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

4. Discussion

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

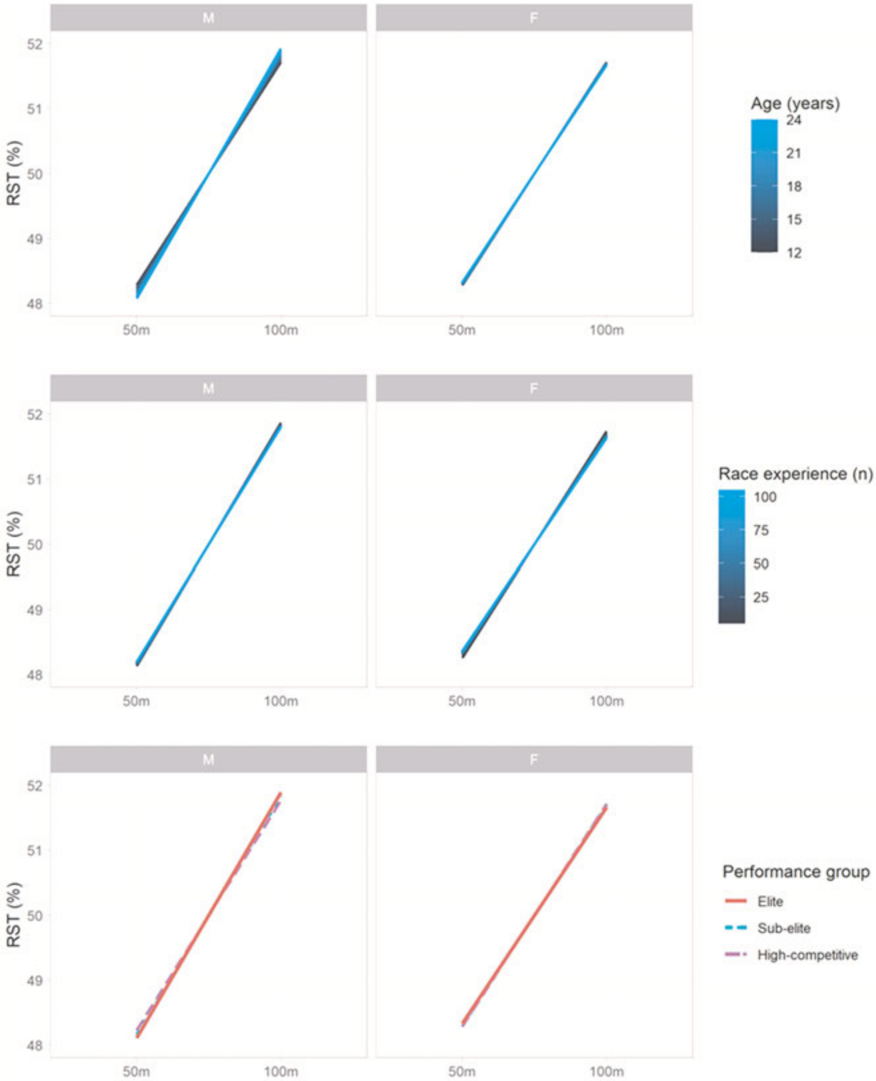

Figure 1. Predicted pacing behaviour for males and females in the 100m freestyle event according to age, race experience and performance level.

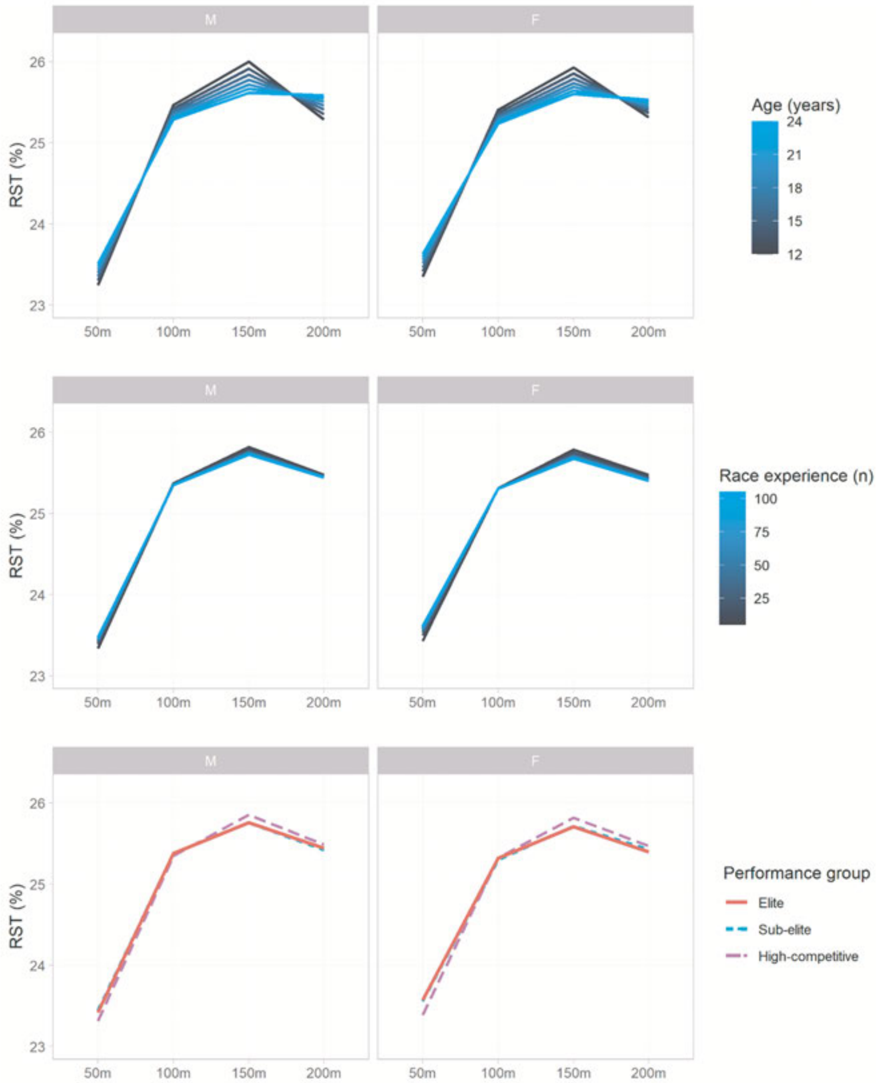

Figure 2. Predicted pacing behaviour for males and females in the 200m freestyle event according to age, race experience and performance level.

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

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

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

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

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

Table 2. (Continued)

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

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

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

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

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4.1. Pacing behaviour development in swimming

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

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

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

4.2. Future performance

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

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

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

4.3. Limitations and future directions

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

4.4. Practical application

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

5. Conclusion

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

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8. Appendix

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

Table 3. Measure of fit with dataset for each model

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

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