

# **Pacing behavior 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 ( $5.3 \pm 1.9$  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 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 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 behavior compared to high-competitive. This differentiation occurs at younger age in female ( $>13$  years) compared to male ( $>16$  years) swimmers.

**Conclusion:** 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 which better fits the task demands during adolescence. Monitoring and individually optimizing the pacing behavior of young swimmers is an important step towards elite performance.

**Key words (6/6):** Sport, race analysis, competitive swimming, future performance, talent, multilevel modelling.

## 1 **1. Introduction**

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

21 One sport in which the topic of pacing behavior has gained increasing scientific interest in the  
22 last few years, is competitive swimming (8, 10). Given the highly resistive properties of water  
23 compared to air, and the low mechanical efficiency of the swimming movement, it has been  
24 argued that adequate pacing might be more important in swimming compared to land-based  
25 sports (8, 10). Moreover, competitive swimming is a popular, global sport in which the gap

26 between the gold medalist and the last finisher in international competitions is decreasing (11).  
27 In light of this, optimizing pacing behavior plays an increasingly important role in elite  
28 swimming performance (8, 10). Systematic literature reviews have shown that pacing behavior  
29 of swimmers is primarily determined by the race distance and stroke type (8, 10). In races over  
30 a short distance (50-100m), elite swimmers adopt an all-out pacing behavior, attempting to  
31 achieve a high velocity through rapid acceleration and trying to maintain this velocity  
32 throughout the race (12). During 200m races, elite swimmers adopt a fast start followed by an  
33 even pace (13). Comparing different strokes, it is evident that the butterfly and breaststroke  
34 events are characterized by a gradual decrease in velocity over the duration of the race, which  
35 is mostly attributed to the relative inefficiency of these strokes compared to front crawl or  
36 backstroke. Regarding pacing behavior development in swimming, one study reported that  
37 adolescent swimmers performing a 200m front crawl trial started off too fast and therefore  
38 lacked in speed at the end of the trial (14). A second study reported that adolescent swimmers  
39 have difficulty in selecting the optimal pace, performing better in a 400m front crawl trial when  
40 executing an externally imposed pace compared to a self-selected pace (15). It was proposed  
41 that the difference between adolescent and adult swimmers was due to the disparity in task  
42 experience (13, 17, 18). This, however, seems to be an oversimplification as the shift of pacing  
43 behavior during adolescence is thought to originate not only from increased exercise experience  
44 but also from age-related physical maturation and cognitive development (4, 9). Additionally,  
45 as the chronology of physical maturation and cognitive development processes differ between  
46 boys and girls (19, 20), it logically follows that the timeline of pacing behavior development  
47 differs between sexes (21, 22). A profound understanding of the mechanisms behind the pacing  
48 behavior of adolescent swimmers, including the influence of factors such as age, experience  
49 and sex, could help coaches to guide their athletes in developing a more optimal pacing  
50 behavior.

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

67

## 68 **2. Methods**

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

74

### 75 *2.1. Data collection*

76 All available 100m and 200m freestyle long course performance data (i.e., date of the race, total  
77 race time and available 50m split times) of both male and female swimmers performing between  
78 2000 and 2021, were collected from Swimrankings' database ([www.swimrankings.net](http://www.swimrankings.net)). This  
79 resulted in 2,857,181 (100m freestyle) and 1,897,872 (200m freestyle) observations. The  
80 assumption was made that all swimmers chose the front crawl during the freestyle events.  
81 Performance data were collected from 113 countries across the world. The date of birth of all  
82 included swimmers was collected using the same database.

83

## 84 2.2. *Data processing*

85 Swim performances over 180s (100m freestyle) and 360s (200m freestyle) were excluded from  
86 the analysis to ensure a homogeneous dataset. Performance data were classified per swimming  
87 season, starting on the 1<sup>st</sup> of September and ending on the 31<sup>st</sup> of August of the next calendar  
88 year. Data from the 1<sup>st</sup> of January 2008-2010 were excluded from analysis, because of the  
89 impact of full-body polyurethane swimsuits on swimming performance in that period (23-25).  
90 Performance data from season 2019-2020 were excluded as competitions and training  
91 opportunities were disturbed because of the COVID-19 pandemic. A total of 2,773,387  
92 observations (100m freestyle) and 1,842,992 (200m freestyle) observations remained. For each  
93 swimmer, the Season Best Time (SBT) per swimming season was used for further analysis.  
94 Age at SBT was determined using the swimmer's date of birth. Race experience was defined  
95 as the cumulative number of races of a specific event, which the swimmers had completed  
96 before SBT.

97

## 98 2.3. *Inclusion criteria*

99 For the purpose of this study, it was important to outline the development of pacing behavior  
100 from a young age on toward the age of peak performance. Peak performance in competitive

101 swimming is on reached at 24 ( $\pm 2$ ) years for males and at 22 ( $\pm 2$ ) years for females (26).  
102 Therefore, only swimmers who had at least one swim performance in the age category of 22  
103 years or older (male) or 20 years or older (female) were included. To ensure a dataset  
104 representing the developmental pathway of pacing behavior towards peak performance, swim  
105 performances after the swimmer's career-best swim performance were excluded. To  
106 longitudinally study pacing behavior development, included swimmers had to be between 12  
107 and 24 years old and have performance data with 50m split times in at least three swimming  
108 seasons. To study pacing behavior independent of current performance, split times of each 50m  
109 section were converted into relative section times (RST), representing the percentage of the  
110 total race time spent in one section. The inclusion criteria were conducted for the 100m and  
111 200m events separately.

112

113 Swim performances of multiple generations (i.e., from 2000 through 2021) were included in  
114 the dataset, which necessitated the correction of evolution in competitive swimming. As such,  
115 swim performances were defined as a percentage of the prevailing world record (WR) of the  
116 corresponding sex, referred to as relative Season Best Time (rSBT) (27, 28). World records  
117 from 2008 and 2009 were replaced by the prevailing fastest time in a textile swimsuit.  
118 According to the event, swimmers were allocated to the elite, sub-elite or high-competitive  
119 performance group by using their event-specific all-time rSBT after 20 (female) or 22 (male)  
120 years of age (see Table 1). The elite level was defined as the average rSBT of the 50<sup>th</sup> swimmer  
121 of the event-specific FINA World Ranking List between 2016 and 2021 (11). Sub-elite level  
122 and high-competitive level were defined as the average rSBT of the 8<sup>th</sup> and 50<sup>th</sup> swimmer of the  
123 event-specific National Ranking List of the Netherlands between 2016 and 2021 (11).  
124 Swimmers with a best rSBT outside the limits of the high-competitive group were excluded  
125 from further analysis. For the 100m event, this resulted in 3,498 swimmers (1,659 female) with

126 15,960 observations (7,384 female) with an average of  $5.3 \pm 1.9$  observations per swimmer. For  
127 the 200m event, this resulted in 2,230 swimmers (1,252 female) with 10,309 observations  
128 (5,412 female) with an average of  $5.3 \pm 1.9$  observations per swimmer.

129

#### 130 2.4. *Statistical analysis*

131 Following the methods introduced by Menting et al. (7), longitudinal multilevel models were  
132 created to describe pacing behavior as a function of age, race experience and performance  
133 group. Multilevel modelling allows for the creation of models in which repeated measures (level  
134 1) are nested within individual swimmers (level 2), allowing the use of longitudinal data with  
135 varying number of measurements between swimmers as well as a variety in temporal spacing  
136 between measurements. Analyses were performed using the lmer4 package in R (R version  
137 3.6.0)(29, 30). Statistical assumptions (e.g., multicollinearity) were checked and outliers were  
138 screened and removed (100m: 915, 200m: 1,006). The RST per 50m section were included as  
139 dependent variables. In contrast to split times, all RST must add up to 100%. With respect to  
140 this constraint, one out of two (100m freestyle) and three out of four (200m freestyle) multilevel  
141 models were created. The remaining, free section (RST 50-100m in both events) was calculated  
142 from these models. Following that the sum of 50m sections must add up to 100%, the same  
143 predictor variables (fixed part) and variance structure (random part) had to be incorporated into  
144 each model equation. Predictor variables age and race experience were included as continuous,  
145 time-varying factors whereas performance group was included as a categorical, time-invariant  
146 factor. The power law of practice states that the effect of experience on performance decreases  
147 as the level of experience increases (31). In addition, the age effect on performance decreases  
148 as swimmers are fully matured (27). As such, the effect of a 1-year increase at age 13 will be  
149 larger than a 1-year increase at age 19. To account for this, the variables age and race experience  
150 were log-transformed, of which the latter transformation was needed to meet the assumption of



151 normality. To represent the three performance groups in the statistical models, two dummy  
152 variables (sub-elite and high-competitive) were included and the elite group functioned as  
153 reference level. A random intercept model was selected as the most appropriate variance  
154 structure, allowing the inclusion of each swimmer's individual trajectory that randomly  
155 deviates from the average population trajectory. In sum, the following multilevel model was  
156 adopted:

157

$$158 \quad RST_{is} = \alpha + \beta_1 \times \log(Age_{is}) + \beta_2 \times \log(RaceExperience_{is}) + \beta_3 \times SubElite_i \\ 159 \quad \quad \quad + \beta_4 \times HighCompetitive_i + u_i + \varepsilon_{is}$$

$$160 \quad \quad \quad u_i \sim N(0, \sigma_0^2)$$

$$161 \quad \quad \quad \varepsilon_{is} \sim N(0, \sigma^2)$$

162

163  $RST_{is}$  was the relative split time of a 50m section for swimming season  $s$  of swimmer  $i$ ,  $\alpha$  the  
164 intercept assigned to the elite group,  $Age_{is}$  the corresponding age value,  $RaceExperience_{is}$ ,  
165 the corresponding race experience value,  $SubElite_i$  the dummy variable of swimmer  $i$  assigned  
166 to the sub-elite group and  $HighCompetitive_i$  the dummy variable of swimmer  $i$  assigned to  
167 the high-competitive group. The unexplained information was the sum of  $u_i$  (between-subject  
168 variance) and  $\varepsilon_{is}$  (residual variance). The models were validated by using graphical tools to  
169 check violations of homogeneity, normality and independence. Predictor variables were  
170 considered significant if the estimated coefficient is greater than twice the standard error of the  
171 estimate ( $p < 0.05$ ). Post-hoc analyses were performed for models with future performance group  
172 as significant predictor variable. For this analysis, swimmers were classified in age categories  
173 based on their age on the 31st of December of the swimming season. Per age category, an  
174 independent sample t-test was conducted to examine from which age onward between-group  
175 differences in pacing behavior occurred. These follow-up analyses were executed for age

176 categories with at least 30 observations per performance group. For all tests,  $p < 0.05$  (two-  
177 tailed) was set as significance.

178

### 179 **3. Results**

180 The models created can be found in Table 2. Using the fixed part of the models, predictions for  
181 the dependent variables can be made. For example, for the RST in the 100-150m segment of a  
182 200m event performed by an 18-year-old male swimmer, with 20 previous races and an adult  
183 performance level as high-competitive, the following value will be predicted as:

184

$$\begin{aligned} 185 \quad RST \ 150m &= 27.42 + (-0.55 \times \log 18) + (-0.03 \times \log 20) + (-0.00 \times 0) + (0.09 \times 1) \\ 186 \quad &= 25.83\% \end{aligned}$$

187

#### 188 3.1. Age

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

194

#### 195 3.2. Race experience

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

200 section, but faster in the 150m section. More experienced female swimmers were relatively  
201 slower in the first 50m section and relatively faster in the 150m and 200m sections.

202

### 203 3.3. Performance level

204 Elite male swimmers were faster in the first 50m of the 100m, compared to the high-competitive  
205 group. Post hoc analysis revealed that the male swimmers of the elite group started  
206 differentiating themselves at 17 years old ( $t_{(99.6)} = -2.21, p < 0.05$ ). No difference was found  
207 between female swimmers of differing performance groups. In the 200m, elite male swimmers  
208 were predicted to be relatively slower in the first 50m, but faster in the 150m section, compared  
209 to swimmers from the high-competitive group. Swimmers from the elite group differentiated  
210 themselves as early as 16 years old (RST50:  $t_{(51.728)} = 3.10, p < 0.01$ ; RST150:  $t_{(57.699)} = 3.11, p$   
211  $< 0.01$ ). Elite female swimmers were relatively slower in the first 50m section, but faster in the  
212 150m and 200m sections, compared to the high-competitive group. The difference started at 13  
213 years of age (RST50:  $t_{(51.07)} = 2.36, p < 0.05$ , RST150:  $t_{(77.62)} = 4.62, p < 0.001$ ; RST200:  $t_{(97.66)}$   
214  $= -3.065, p < 0.01$ ). In both the 100m and 200m, the model predicted no significant difference  
215 in RST between the elite and sub-elite groups (Figure 1C and Figure 2C).

216

## 217 **4. Discussion**

218 The present study aimed to investigate the pacing behavior development of swimmers  
219 throughout adolescence, explicitly differentiating between the effects of age and experience as  
220 well as investigating its relationship to performance level in adulthood. As hypothesized, older  
221 male swimmers adopted a more all-out distribution of effort in the 100m event, although this  
222 development was not exhibited by female swimmers. In the 200m, male and female swimmers  
223 exhibited a more even distribution of effort as they became older. Both race experience and age  
224 independently impacted the pacing behavior of adolescent swimmers, providing evidence that

225 experience is not the sole driver of pacing behavior development. Furthermore, adolescent  
226 swimmers who in adulthood reached the elite level (100m: male, 200m: male & female)  
227 exhibited a pacing behavior more resembling adult swimmers compared to swimmers in the  
228 high-competitive group. As hypothesized, the distinction in pacing behavior between swimmers  
229 of differing future performance level occurred earlier in female compared to male swimmers.

230

#### 231 4.1. *Pacing behavior development in swimming*

232 In previous literature, the effect of experience and age has often been used synonymously (13,  
233 17, 18). However, this seems to be an oversimplification. In the 100m, the behavior of older  
234 male swimmers moves towards a fast first 50m, hereby paralleling the behavior of the elite  
235 swimmers in adulthood. This resemblance, however, was not observed when comparing male  
236 swimmers based on race experience. It supports the notion that pacing behavior development  
237 is driven by other age-related factors (e.g., physical maturation and cognitive development)  
238 alongside the increase in experience. Additionally, these findings suggest that race experience  
239 in itself may not be sufficient to explain the development of future elite performers. Further  
240 evidence for this view is provided by the finding that in the 200m event, age still impacts on  
241 pacing behavior in both male and female swimmers, even with a separate variable for race  
242 experience included in the model. Moreover, the results show that in line with the hypothesis,  
243 the separation between future performance levels occurs at a younger age in females (13 years  
244 old) compared to males (16 years old). The earlier onset of pacing behavior development in  
245 females which has previously been described in a cross-sectional study (21) is thereby  
246 confirmed by the current longitudinal study and is thought to be caused by the earlier onset of  
247 physical maturation and cognitive development (21, 22).

248 Based on previous literature, it was proposed that with experience and age, adolescent athletes  
249 adapt their pacing behavior to better fit the task demands (6, 7). Indeed, within the present study,

250 there is a difference in the development of pacing behavior in the 100m and the 200m events.  
251 In the 100m event, older male swimmers adopt a more all-out pacing behavior, characterized  
252 by a relatively faster first lap. The relatively faster initial 50m could be the result of an improved  
253 race start, including the dive and underwater phase. Alternatively, it has been established that  
254 in tasks of similar duration to the 100m freestyle event, better-performing athletes differentiated  
255 themselves by a relatively more all-out pacing behavior (32, 33). De Koning et al proposed that  
256 for shorter events (<2min), the advantage of a higher velocity in the first part of an exercise task  
257 and the lower amount of kinetic energy left at the end of the race, outweighed the disadvantage  
258 of higher frictional losses associated with the higher average velocity (33), which was further  
259 evidenced through modelling studies in speed skating and track cycling (34, 35), though  
260 differences between sports were visible (36). Indeed, elite swimmers competing in the 100m  
261 freestyle finals of international events exhibited an all-out pacing behavior, comparable to the  
262 one found in the current study (12). Moreover, it was reported that elite male swimmers adopted  
263 a more all-out pacing behavior (RST50m: 47.91%, RST100m: 52.09%) compared to female  
264 swimmers (RST 0m: 48.29%, RST100m: 51.77%) (12). These findings are supported by the  
265 results of the present study, as adolescent male swimmers not only presented a more all-out  
266 pacing behavior, but also continued to develop this behavior with age. The reason behind the  
267 apparent difference in pacing behavior between male and female swimmers could potentially  
268 be found in the physical and physiological differences between male and female swimmers  
269 (37). Alternatively, it has been reported that males engage more in risk-taking behavior and  
270 therefore are expected to generally adopt a more all-out pacing behavior (38).

271 Contrary to the 100m event, older male and female swimmers adopt a relatively more even  
272 distribution of velocity in the 200m event. This is achieved by a relatively slower first and last  
273 50m section and a relatively faster middle section. Swimming is a head-to-head type event, as  
274 the winner of a race is the swimmer who covers the given distance before the other swimmers,

275 independent of the time set by swimmers in previous races (8). Remarkably, the development  
276 of pacing behavior in swimming does not resemble that of other middle-distance head-to-head  
277 events, such as short-track speed skating. Studies in these events have reported that the athletes'  
278 pacing behavior develops towards a more conservative start and middle section of the race to  
279 facilitate the athlete to position themselves well and be relatively faster in the key final stages  
280 of the race (7, 21, 22). The development of pacing behavior in the 200m more resembles the  
281 one found in time-trials of a similar duration (6, 39, 40). This development is characterized by  
282 a shift towards a more even distribution of effort, which allows for a minimization of energy  
283 loss due to acceleration and deceleration, resulting in better performance in middle- and long-  
284 distance time-trial based events (41). This resemblance to time-trials likely originates from the  
285 lane-based nature of competitive swimming (8). The lanes inhibit the interaction with other  
286 competitors, resulting in a less interactive competitive environment as is also found in time-  
287 trial events. Taken together, coaches could expect to encounter sex- and age-related differences  
288 in pacing behavior in adolescent swimmers of the same level of race experience. Additionally,  
289 as adolescent athletes get older, they adapt their pacing behavior to fit the characteristics of the  
290 task, with male swimmers adopting a more all-out behavior on the 100m and both male and  
291 female swimmers adopting a more even distribution of effort in the 200m event.

292

#### 293 4.2. *Future performance*

294 The findings of the present study provide evidence that the swimmers who perform within  
295 104% of the prevailing world record as adults (i.e., the elite group), exhibit pacing behavior that  
296 differentiates them from other adolescent swimmers (i.e., the high-competitive group). It  
297 therefore establishes that adequate pacing behavior development is an essential part of the  
298 developmental pathway towards elite swimming performance. In the 200m event, the effect of  
299 future performance level parallels the effects of age and race experience in both males and

300 females. In other words, swimmers that achieve a higher level of performance in adulthood,  
301 exhibited a pacing behavior resembling that of older and more experienced swimmers during  
302 adolescence. This is different for the 100m event. Adolescent male swimmers who reach the  
303 elite level as an adult, exhibit a pacing behavior that is more resembling the pacing behavior of  
304 the older swimmers (all-out pacing behavior) compared to that of their peers who reach the  
305 high-competitive level. However, the current findings suggest that more race experience results  
306 in a more conservative first 50m in the 100m instead of going more all-out. The underlying  
307 mechanism for this converse effect of race experience on pacing behavior in 100m event  
308 remains unclear and warrants further research. In females no effect of either performance level  
309 or age was found, however the effect of race experience was equal to males.

310 In the present study, no distinction could be made between elite and sub-elite swimmers. A  
311 possible reason for this could be the high performance level of all included swimmers in the  
312 present study. To place it into context, for a male 200m swimmer competing in 2022, the  
313 performance levels equal a time of <106.18s (elite), 106.18-109.75s (sub-elite) and 109.75-  
314 118.93 (high-competitive). The Olympic Qualifying Time for Tokyo 2021 was set at 107.02s  
315 (42). In comparison to the current study, a previous study did report a difference in pacing  
316 behavior between three performance levels (6). However, Wiersma et al determined adult  
317 performance using the season best performance at 18-19 years of age, whereas the present study  
318 used a more appropriate measure to indicate adult performance level: all-time peak performance  
319 after 20 (female) or 22 (male) years of age expressed as a percentage of the prevailing world  
320 record. Recalculating the performance level of the athletes in the previous study, using these  
321 methods results in a much wider spectrum of performance (elite: 113.8%, sub-elite: 120.6%,  
322 non-elite: 129.7%), could explain why the previous study did find a difference in pacing  
323 behavior development between the performance levels.

324

### 325 4.3. *Limitations and future directions*

326 Although the models created in the present study provide novel insights into the relationship  
327 between age, experience and pacing behavior, the models do not account for all the variance in  
328 a swimmers' pacing behavior. Pacing is a complex, psychophysiological process and even when  
329 the task characteristics are set, it is influenced by a multitude of factors relating to the individual  
330 (i.e., physical maturity, cognitive development, muscle fiber type distribution) and environment  
331 (i.e., coaching culture, training opportunities) (1, 9, 43, 44). The absence of these factors has  
332 potentially led to the lower explained variance of the models. For example, there was no effect  
333 for age or performance level on pacing behavior in female swimmers competing in the 100m  
334 event. In males, the effect of age and performance group was also more pronounced in the 200m  
335 event compared to the 100m event. It could be that 100m freestyle performance is  
336 predominantly driven by the development of physical characteristics, such as muscle fiber type  
337 distribution, whereas in the 200m event the distribution of effort is a larger determination factor  
338 in the outcome of the race. However, another reason might be that the 100m freestyle is often  
339 contested by both 50m and 200m specialists. The energetic system requirements between the  
340 50m and 200m freestyle events differ significantly and therefore swimmers who compete in  
341 these events are adapted to physiologically very different tasks (37), therefore exhibiting a  
342 different pacing behavior. The coming together of these two types of specialized swimmers  
343 might have impacted the results of the present study. It should be pointed out that previous  
344 studies have evidenced that swimming performance is impacted by velocity in free swimming  
345 sections, but also by turns and underwater phases (45). Quantification using 25m or even 5m  
346 and 10m sections has previously been demonstrated to reveal more detailed definitions of  
347 impact of these factors on a swimmers' performance (18, 45). However, these data have to be  
348 gathered using camera set-ups and specialized software, which drastically decreases practicality  
349 and would have reduced the sample size greatly. In the end, the present study aimed to create



350 models which could provide insight into the relation between age, experience and future  
351 performance level, not precisely predict each individual swimmers' pacing behavior. The large  
352 sample size, consisting of swimmers from five continents, and the strong longitudinal nature of  
353 the data are of key importance to the rigidity of the present study's design, not in the first place  
354 because more large scale longitudinal studies on pacing behavior development are needed (4,  
355 22). Consequently, the decision was made to use publicly available 50m split times. The choice  
356 for this approach does allow for future studies, using more detailed quantifications of pacing  
357 behavior and the inclusion of more individual and environmental factors, to provide additional  
358 insights into the development of pacing behavior in the 100m and 200m freestyle events.

359

#### 360 4.4. *Practical application*

361 The effect of age and race experience on pacing behavior as reported in the present study are  
362 relatively small compared to that of task defining characteristics such as race duration or stroke  
363 type (8). However, in a 200m freestyle, an average 0.16% difference in velocity distribution per  
364 50m section (the difference between a 12 and 18-year-old male swimmer as calculated using  
365 the models in the present study) constitutes 0.20s. In a sport where 0.01 of a second can be the  
366 difference between winning and losing, a 0.20s difference in velocity distribution in every 50m  
367 section can indeed have a very real impact on competition performance. Using the formula  
368 provided in the present study, coaches could determine whether their swimmers are on track of  
369 developing the pacing behavior necessary to achieve the elite performance level. One point of  
370 notice should be made to this approach: the road to elite performance is not always linear and  
371 pacing is only a part of the skillset necessary to reach the top (46). In addition, it has been  
372 established that to pace adequately, athletes need to match their personal performance capacities  
373 to the task demands. Seeing as there is variation in each swimmer's performance capacities, a  
374 slightly different pacing behavior could be optimal for each swimmer. It is therefore important

375 to take the outcomes of the formula from the present study as a starting point and take an  
376 individualized approach to the development of each swimmer. Within this approach, coaches  
377 are advised to provide the swimmers with opportunities to experiment with variants of their  
378 established pacing behavior (4). Introducing variability would provide swimmers with the  
379 opportunity to discover a more optimal match between their personal performance capacities  
380 and the task demands (47). Coaches could induce this variation by providing augmented  
381 feedback via tools such as a stopwatch, pacer clock, wearable metronome, underwater lights or  
382 smart goggles (48). Demonstrating this method, a recent study reported that a three week  
383 training program in which adolescent swimmers were provided with feedback on their own  
384 pacing behavior was effective in increasing 400m freestyle performance (49). Subsequently,  
385 practice of the new variation of pacing behavior could be further increased by gradually taking  
386 away sources of feedback and adding environmental factors such as opponents, therefore  
387 training the swimmers to maintain their capability of decision-making regarding effort  
388 distribution in a more realistic competitive environment (22, 48).

389

## 390 **5. Conclusion**

391 The current large-scale study is the first in its kind in that it investigates the pacing behavior of  
392 swimmers from five continents over a period spanning the last twenty years. The rigorous  
393 multilevel modelling approach with corrections for prevailing world records revealed insights  
394 on developmental patterns based on thousands of swimmers with on average five competitive  
395 seasons in adolescence. The pacing behavior of swimmers develops during adolescence, as  
396 older swimmers adopt a pacing behavior that better suits the task demands (100m: more all-out  
397 [males only], 200m: more even). Although swimming is a head-to-head type of competition,  
398 the development of pacing behavior resembles that of time-trial events, most likely due to the  
399 lane-based nature of the sport. The persistence of the effect of age on pacing behavior when

400 race experience was also included as predicting variable, supports the hypothesis that pacing  
401 behavior development during adolescence is driven by other factors in addition to increased  
402 experience, such as physical maturation and cognitive development. Swimmers who reach the  
403 elite performance level in adulthood, exhibit a pacing behavior better suits the task demands  
404 and that resembles that of adults (100m: more all-out [only males], 200m: more even) during  
405 adolescence. In the 200m, this differentiation occurs earlier in females compared to males, most  
406 likely due to the earlier onset of age-related physical maturation and cognitive development in  
407 females. Coaches are advised to take notice of the complex development of pacing behavior  
408 which occurs throughout adolescence. Furthermore, coaches could use the data presented in the  
409 present study as a starting point for an individualized approach to optimize the pacing behavior  
410 development in their swimmers and better guide them on the road towards elite performance.

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412 *6.1. Authors' contributions*

413 The study conception and design were done in full collaboration with all authors. SGPM and  
414 AKP contributed equally to this manuscript. All authors critically revised the work. All authors  
415 read and approved the final manuscript.

416

417 *6.2. Conflict of interest*

418 The authors do not have any conflict of interest. The authors declare that the results of the study  
419 are presented clearly, honestly, and without fabrication, falsification, or inappropriate data  
420 manipulation. The results of the present study do not constitute endorsement by the American  
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422

423 **7. Tables and figures**

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

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

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

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

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