

1 **Pacing behaviour development of youth short-track speed skaters: a longitudinal study**

2

3 Short title: How to develop successful pacing skills.

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30 **Abstract**

31 Purpose: To analyse the development of pacing behaviour of athletes during adolescence, using a
32 longitudinal design.

33

34 Methods: Lap times of male short-track speed skaters (140 skaters, 573 race performances) over two or
35 more 1500-m races during Junior World Championships between 2010 and 2018, were analysed. Races
36 were divided into four sections (laps 1-3, 4-7, 8-11 and 12-14). Using MLwiN ($p < .05$), multilevel
37 prediction models in which repeated measures (level-1) were nested within individual athletes (level-
38 2), were used to analyse the effect of age (15-20), race type (fast, slow) and stage of competition (final,
39 non-final) on absolute section times (AST) and relative section times (RST; percentage of total time
40 spent in a section).

41

42 Results: Between the ages of 15 and 20, total race time decreased (-6.99s) and skaters reached lower
43 AST in laps 8-11 (-2.33s) and 12-14 (-3.28s). The RST's of laps 1-3 (1.42%) and 4-7 (0.66%) increased
44 and laps 8-11 (-0.53%) and 12-14 (-1.54%) decreased with age. Fast races were more evenly paced
45 compared to slow races, with slow races having a predominantly slow first half and fast finish. Athletes
46 in finals were faster (2.29s), specifically in laps 4-7 (0.85s) and laps 8-11 (0.84s).

47

48 Conclusion: Throughout adolescence, short-track speed skaters develop more conservative pacing
49 behaviour, reserving energy during the start of the race in order to achieve a higher velocity in the final
50 section of the race and a decrease in total race time. Coaches should take into consideration that the
51 pacing behaviour of young athletes develops during adolescence, prepare athletes for the differences in
52 velocity distribution between race types and inform them on how to best distribute their efforts over the
53 different stages of competition.

54

55 Keywords: pacing, development, head-to-head competition, performance analysis, adolescence,
56 multilevel modelling.

57 **Introduction**

58 The goal-directed distribution of energy over a predetermined exercise task (1), a process of
59 decision-making regarding how and when to spend energy (2), has been defined as pacing.
60 Pacing has proven to be an essential aspect of athletic performance, both in time-trial (3, 4) and
61 head-to-head competition (5-7). The final outcome of an individuals' goal-directed distribution
62 of energy over the race is termed pacing behaviour (2). A range of factors which influence
63 pacing during an exercise task have been identified, including amongst others: the duration of
64 the event (8), the perceived level of exertion (9), and sport specific demands (10). In addition,
65 recent literature emphasizes the importance of the competitive environment in regards to
66 pacing behaviour (2). Yet, little is known on how athletes acquire the skills to successfully pace
67 in races, and there is little information on the development of pacing behaviour in youth athletes
68 (11).

69
70 Although the first signs of the formation of a pacing template appear during late childhood
71 (~10-11 years old) (12, 13), recent research in both time-trial and head-to-head events
72 established that throughout adolescence, the pacing behaviour of youth athletes further
73 develops to ultimately resemble that of seniors (14, 15). Menting et al (2019) provided a
74 theoretical basis behind this development (11). First, adolescence is characterised by both
75 cognitive and physical changes associated with growth and maturation (16, 17). One key
76 development is that of the pre-frontal cortex (18), which has been associated with self-
77 regulatory learning and executive functioning (19), both of which are imperative for adequate
78 pacing (20). Second, in most athlete development programs the amount and quality of training
79 and competition increases profoundly during adolescence, providing youth athletes with an
80 increase in the quantity and quality of opportunities to gather exercise experience. Lastly,
81 coaches could influence the pacing behaviour development by influencing the athlete's

82 motivation, providing advice in goal setting, and providing high quality learning environments
83 in which the pacing behaviour can be optimally developed (11). Emphasising the importance
84 of pacing development during adolescence, a longitudinal study in long-track speed skaters
85 suggests that the development of pacing behaviour in developing athletes has a decisive
86 influence on the performance level at the senior level (14). In addition, the ability to
87 appropriately distribute energy in the long term also seems vital in safeguarding athlete well-
88 being. If an athlete's ability to adequately distribute their energy is hampered, it could lead to
89 them investing too much energy during an exercise task (for example a training and
90 competition) (21, 22). If this happens repeatedly, it could lead to overtraining, burn-out and
91 drop-out (23). This is especially true for developing athletes who, during adolescence, often
92 endure high training loads for a long period of time in order to reach the elite level (24). In
93 order to optimally guide developing athletes it seems to be essential to have a good
94 understanding of both the general and sport-specific development of pacing behaviour during
95 adolescence (11).

96

97 Much of the previous literature studying the effect of age and experience on pacing behaviour
98 has been cross-sectional in design, comparing athletes from different age groups, experience
99 or performance levels (13, 15, 25). A cross-sectional design can provide a good general image
100 of skill development, given that the sample size is large enough. However, in order to properly
101 study development of a particular skill over a period of time, a longitudinal design is desirable.
102 In longitudinal studies, the same variable(s) are observed repeatedly over a period of time,
103 therefore allowing for an exclusion of time-invariant unobserved individual differences (26)..
104 The only study to longitudinally analyse the development of pacing behaviour throughout
105 adolescence was a study on long-track speed skaters performing 1500-m races (14). That study
106 concluded that the absolute velocity of junior skaters increased in all sections of the race.

107 However, when normalising the velocity distribution it became apparent that with age, skaters
108 developed a more conservative velocity profile. Accompanying the results in long-track speed
109 skaters, a cross-sectional study analysing short-track speed skaters concluded that the pacing
110 behaviour and positioning behaviour of skaters changes throughout different stages of
111 adolescence (15). With each older age group (under 17, under 19 and under 21), the normalised
112 velocity distribution and the positioning resembled that of senior skaters to a greater extent,
113 with skaters adapting a more conservative pacing behaviour. Although there are small
114 physiological differences between long- and short-track speed skating, there seems to be a
115 consensus that the sport disciplines are rather comparable in physiological perspective (27).
116 However, where long-track speed skating is a classic time trial sport, short-track speed skating
117 features head-to-head competition, involving highly interactive races with up to nine skaters
118 (6). Therefore, athletes incorporate factors such as drafting and avoiding collisions in their
119 pacing behaviour (6). Previous research showed that the importance of the competition, the
120 number of competitors and the stage of the competition, all influence the performance and
121 pacing behaviour of short-track speed skaters (28). Furthermore, due to the head-to-head nature
122 of short-track speed skating, the winner is the athlete who crosses the finish line first, regardless
123 of the time it takes the skater to complete the race. Consequently, there is a large variation in
124 total race time compared to long-track speed skating, as short-track speed skaters are not
125 concerned with setting a fast finishing time, but with crossing the finish line first. To account
126 for this phenomenon, previous literature categorised races as either 'slow' or 'fast' (e.g. race
127 type) and found a significant difference in pacing behaviour in adult athletes between the race
128 types (6). Following the notion that the competitive environment has a critical role in pacing
129 behaviour (29), a longitudinal study involving a highly interactive head-to-head sport, such as
130 short-track speed skating, would enrich the current literature.

131

132 In order to gain a thorough understanding of the development of pacing behaviour in athletes
133 during adolescence, an increase in longitudinal studies seems indispensable. Therefore, the
134 current study investigated the development of pacing behaviour of short-track speed skaters,
135 on a year by year basis, applying a longitudinally study design. It was hypothesised that the
136 pacing behaviour of these athletes would develop throughout adolescence to show a more
137 conservative profile, characterised by a relatively slower start and a faster finish. Additionally,
138 the current study investigated the influence of the competitive environment (race type and stage
139 of competition) on the pacing behaviour of youth athletes. Following the findings in adults
140 (30), it is hypothesized that the pacing behaviour of youth skaters will be impacted by the
141 behaviour of other competitors, facilitating either a slow or fast race. Additionally, based on
142 findings in adults (6, 28), it is hypothesized that the young skaters will exhibit a more
143 conservative pacing behaviour as athletes progress through the stages of competition.

144

145 **Methods**

146 *Participants and events*

147 The finishing times, lap times and date of birth of all male competitors competing in the 1500-
148 m (13.5 laps) at the yearly Junior World Championships between 2010 and 2018 were gathered.
149 The lap times were recorded electronically with an accuracy of at least one hundredths of a
150 second, as is demanded by the International Skating Union. All competitive events followed a
151 qualification structure in which skaters qualify directly for the next round by finishing first or
152 second. Additionally, participants could qualify indirectly by setting the fastest finishing time
153 of a specific qualification round or through advance by jury decision. All data were publically
154 available through the International Skating Union website
155 (<http://www.sportresult.com/federations/ISU/ShortTrack/>) therefore no written consent was

156 asked from the participants. The study was approved by the local ethical committee and is in
157 accordance with the Declaration of Helsinki.

158

159 A total of 1487 race performances were collected. The occurrence of a fall or disqualification
160 could affect pacing behaviour. For this reason, races including disqualified skaters were
161 excluded, as were race data of skaters who had fallen or included missing data, consistent with
162 the previous literature (6) (43.5% of total race performances collected). The age of a skater was
163 calculated by taking the date of the competition and subtracting the date of birth. The variable
164 of age was converted to a categorical variable in order to show differences between skaters of
165 specific ages. For example: a 16-year old skater was defined as a skater within the age range
166 15.50 – 16.49 years. To control for outliers of age, the decision was made to exclude race
167 performances of skaters who were not between 14.5 and 20.5 years old (0.6% of total race
168 performances collected). Previous studies established that the number of competitors and the
169 stage of the competition significantly influenced pacing behaviour and performance of elite
170 short-track speed skaters (28). Hence, data from races with more than seven or less than five
171 skaters were excluded (1.3% of total race performances collected) and data was split in finals
172 (quarter-finals, semi-finals and finals) and non-finals (heats and preliminaries). To account for
173 race type, a race was classified as ‘fast’ or ‘slow’ when the winner of a particular race was
174 faster or slower than the average completion time of all race winners. In order to properly study
175 longitudinal development, only data from skaters who performed in at least two different age
176 groups, during Junior World Championships, in various seasons, was included. Therefore, all
177 data from skaters who performed in just one age group (i.e., during one Junior World
178 Championship) was excluded (16.1%). It should be noted that due to the qualifying nature of
179 the Junior World Championships, included skaters can have multiple race performances in one
180 age category. After exclusions, 573 race performances (38.6%) of 140 different skaters were

181 included from the original sample. Of the included skaters, 53.6% performed in two, 30.7% in
182 three, 13.6% in four and 2.1% in five different age groups. Table 1 shows the mean age of
183 included skaters and the number of included race performances, per age category.

184

185 *Study design*

186 The 1500-m race was split into four sections: laps one to three, four to seven, eight to eleven
187 and laps twelve to fourteen. With lap one effectively being a half lap this adds up to a total of
188 13.5 laps. In order to analyse how skaters distribute their velocity over a race, total race time
189 and absolute section time (AST) (i.e. time to complete a section) over the four sections of the
190 race were taken as outcome measures. Furthermore, in order to analyse pacing behaviour
191 independent of possible differences in total race time between skaters, each AST was converted
192 into relative section time (RST), which presents the percentage of total race time spent in one
193 section. A comparative approach has been taken in other longitudinal and cross-sectional
194 studies investigating pacing behaviour throughout adolescence (14, 15).

195

196 *Data analyses*

197 Due to the qualifying nature of the short-track speed skating competition, there is considerable
198 variability in the number of measurements among skaters. Hence, traditional repeated
199 measurements analyses were not possible. Longitudinal changes in pacing behaviour were
200 investigated using multilevel modelling program MlwiN (31). Multilevel modelling was
201 developed to analyse nested data, allowing for longitudinal analyses of datasets which include
202 a varying number of measurements between participants as well as a variety in temporal
203 spacing between measurements. In the current study, hierarchy was defined as repeated
204 measures (level 1) nested within the individual skaters (level 2). Dependent variables in these
205 models were total race time, absolute section times (AST1-3, AST4-7, AST8-11, and AST12-

206 14) and relative section times (RST1-3, RST4-7, RST8-11, and RST12-14) for the four race
207 sections. The predictive variables included were: age category (15, 16, 17, 18, 19 and 20), race
208 type (fast, slow) and stage of competition (final, non-final). Goodness of fit for each model was
209 evaluated using the $-2 * \text{Log Likelihood}$. Differences in outcome measures between age
210 categories were evaluated by comparing the mean of the coefficient and its standard error (SE)
211 (coefficient/SE >1.96 = significant).

212

213 **Results**

214 The models created for the outcome measures can be found in Table 2 (AST and total race
215 time) and Table 3 (RST). Each model consists of a constant value and a coefficient for the
216 appropriate predictive variable. As all predictive variables (e.g. age, race type and stage of
217 competition) in the model are categorical of nature, the coefficient will represent the difference
218 between one chosen sample category and the other possible categories. The age category 15
219 was used as a sample category for age. In the case of race type, races categorised as 'slow' are
220 the sample category. For stage of competition, 'finals' are the sample category. This effectively
221 means that if a race is categorised as 'slow', 'final' or '15', the coefficient for race type, stage
222 of competition and age, will be multiplied by 0. Conversely, if a race is categorised as 'fast',
223 'non-final' and age category 16 through 20, the various coefficients will be included into the
224 models prediction. This way, the models are used to make predictions for outcome measures
225 for the different combinations of predictive variables: age, race type and stage of competition.

226 For example:

227

228 The AST1-3 for a 17 year old, in a fast non-finale was predicted as:

229 $AST1-3 = (\text{constant}) + (17) + (\text{fast}) + (\text{non-final})$

230 $AST1-3 = 38.486 + 0.590 - 5.977 + 0.251$

231 AST1-3 = 33.350

232

233 The RST12-14 for a 15 year old, in a slow non-final was predicted as:

234 $RST_{12-14} = (\text{constant}) + (15) + (\text{slow}) + (\text{non-final})$

235 $RST_{12-14} = 20.49 + 0 + 0 + -0.16$

236 $RST_{12-14} = 20.33$

237

238 Following the principles of the models, the coefficients also indicated the effect that a variable
239 (age, race type, stage of competition) has on the outcome measure (AST, RST and total race
240 time). For example, in the model for total race time, the coefficient for race type is -10.44. This
241 meaning that the model predicts that fast races have a total race time which is 10.44s less
242 compared to slow races.

243

244 As AST and total race time are indicated in seconds, a lower outcome of these variables
245 represents a higher velocity. The models created for AST's and total race time can be found in
246 Table 2. Visual representations of the predictions of these models can be found in figure 1. The
247 RST is reported in percentages of the total race spend in a specific section. Therefore, a lower
248 RST indicates that a skater was relatively faster, and therefore distributed more effort, in that
249 section of the race. The predictions made by the models for the RST's can be found in Table
250 3, as well as visually presented in Figure 2. In order to visualize the pacing behaviour of skaters
251 over a full race, the predictions of the four models for the AST's, and the four models for the
252 RST's, are presented alongside each other in Figure 3.

253

254 Age categories

255 Comparing total race time between the age categories, the following age categories reported a
256 higher total race time: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20, 18 vs 20. No difference between
257 age categories was found for AST1-3 and AST4-7. AST8-11 was higher in the following age
258 categories: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20. Subsequently, AST12-14 was higher in age
259 categories: 15 vs 16-20, 16 vs 18-20, 17 vs 18-20 and 18 vs 19-20. There was a difference in
260 RST between the age categories throughout the race. The RST1-3 was lower in the following
261 age categories: 15 vs 17-20 and 16 vs 19-20. The RST4-7 was reported to only be significantly
262 lower in age category 15 compared to all other age categories. Conversely, the RST8-11 was
263 modelled to only be higher in age category 15 compared to all other age categories. The RST12-
264 14 was higher in age categories: 15 vs 16-20, 16 vs 18-20, 17 vs 19-20 and 18 vs 19-20.
265 Summarized, skaters in an older age group set a faster total race time by reaching a higher
266 velocity in the second part of the race. Furthermore, older skaters were relatively slower during
267 the first half of the race and relatively faster during the second half of the race. The differences
268 in normalized velocity in the first three sections of the races significantly contrasted the 15 and
269 16 year old skaters against the skaters in the older age categories. In the last section, with every
270 step to an older age category, skaters were relatively faster compared to all younger skaters.

271

272 Race type

273 The total race time, AST1-3 and AST4-7 were higher in races classified as slow compared to
274 those classified as fast. AST12-14 was lower in fast races compared to slow races. There was
275 no effect for race type on AST8-11. These findings point out that skaters in slow races had a
276 lower velocity during the first half of the race, but were faster during the final three laps of the
277 race, compared to skaters in races classified as fast. The RST1-3 and RST4-7 were lower in
278 races classified as fast, compared those classified as slow. Vice versa, the RST8-11 and RST12-
279 14 were higher in fast races, compared to slow. Therefore, skaters in fast races are relatively

280 faster in the first half of the race and slower in the second half of the race. Contrariwise, skaters
281 in a slow race are relatively slow in the first half of the race and have a high relative velocity
282 in the second part of the race.

283

284 Stage of competition

285 The total race time, AST4-7 and AST8-11 were higher in non-finals compared to finals. There
286 was no difference between the stages of competition for AST1-3 and AST12-14. Altogether,
287 the finals were in total faster compared to the non-finals, with the skaters in the finals reaching
288 a higher velocity in the middle part of the race. There was only significant difference in RST8-
289 11 between the stages of competition. Skaters in finals were found to have a lower RST8-11.
290 It should however be acknowledged that there is a trend suggesting RST1-3 is higher in finals
291 compared to non-finals ($p = 0.07$). Therefore it can be suggested that skaters in the finals are
292 relatively slower in the first section and faster during the third section of the race, compared to
293 the non-finals.

294

295 **Discussion**

296 The current study was the first to use a longitudinal design in order to investigate the
297 development of pacing behaviour of youth short-track speed skaters on a yearly basis, as well
298 as investigates the influence of race type and stage of competition on the pacing behaviour of
299 youth athletes. As hypothesised, the pacing behaviour of short-track speed skaters developed
300 throughout adolescence. With age, the pacing behaviour became more conservative,
301 characterized by a relatively slower start and faster finish. Furthermore, the total race time
302 decreased with age, parallel with an increase in velocity during the last half of the race. Lastly,
303 both the race type and stage of competition influenced the pacing behaviour of youth short-

304 track speed skaters, indicating that the competitive environment is an aspect of athletic
305 performance to account for, already at a young age.

306

307 The model for total race time predicted the largest development between the 15 and 16 years
308 old: a drop of -3.704s, equal to a 2.310% decrease in total race time. Between the ages of 16
309 and 20 there was a -3.285s (2.142%) decrease in total race time, averaging 0.821s (0.524%) a
310 year. In addition, there was a notable difference in the distribution of velocity between the age
311 categories. In the first half of the race, there was no predicted difference in velocity between
312 age categories. In the final two sections of the race, however, the predicted absolute velocity
313 was higher with each age category. These findings indicate that older skaters can set a better
314 finish time because they are able to reach a higher velocity in laps 8-11 and laps 12-14. Notable
315 here are the large differences between age categories 15 and 16 (1.373s for laps 8-11 and 1.624s
316 for laps 12-14, respectively), compared to the difference between age categories 16 and 20
317 (0.956s for laps 8-11 and 1.660s for laps 12-14, respectively). Previous research showed that
318 the final phase of the race is most crucial to winning the race (6). The current findings suggest
319 that older adolescent skaters also achieve a higher velocity in this critical final part of the race.
320 One explanation for this could be that older skaters possess more developed physical attributes
321 and a better skating technique, therefore being able to achieve a higher velocity in general.
322 However, the models for relative sections times reveal an additional explanation.

323

324 The use of relative section times allows for a comparison of pacing behaviour controlled for
325 differences in total race time. In general, the models in the current study predicted that with
326 age, the skaters develop a more conservative pacing behaviour, characterized by a relatively
327 slower start and faster finish. Remarkably, the development of normalized velocity distribution
328 was most evident when comparing 15 and 16 year old skaters to the other age categories. These

329 findings are conform with a previous study which compared cross-sectional data short-track
330 speed skaters, grouped by age: younger than 17, younger than 19, younger than 21 and adults
331 (older than 21) (15). The group with skaters younger than 17 presented the largest difference
332 in normalized lap times, compared to the other groups, specifically in four initial and four final
333 laps of the race. Combining the development in normalized velocity distribution with the
334 finding that with age, skaters reach a higher velocity in the final half of the race, points to the
335 following idea: short-track speed skaters develop their pacing behaviour throughout
336 adolescence, increasing the preservation of energy in the starting section of the race, in order
337 to achieve a higher velocity in the critical final laps of the race resulting in a decrease in total
338 race time. This development is most evident around the 15-16 year span, becoming more
339 gradual towards adulthood. Interestingly, Wiersma et al. (2017), reported that in the time-trial
340 based sport of long-track speed skating, elite skaters distinguished themselves from sub-elite
341 and non-elite by a distinct development of pacing behaviour in the period from 15 to 18 years
342 old (14). The development in long- and short-track speed skating seems similar: in both
343 disciplines skaters develop a more conservative behaviour in which the conservation of energy
344 during the start of the race results in a higher velocity in another section of the race and an
345 overall decrease in total race time. Furthermore, the 15-16 year old mark constitutes a relatively
346 large shift in behaviour in both disciplines. It could be speculated that this resemblance could
347 entail that, like in long-track speed skating, the development of pacing behaviour of young
348 short-track speed skaters could prove to be a marker for future performance level. However,
349 future research should be done to further explore this hypothesis.

350

351 A possible underlying mechanism for the rapid development at the 15-16 year old mark could
352 be found in the occurrence of multitude of physical and cognitive changes in athletes of this
353 age (11). Studies have shown that males on average attain their peak height velocity at 14 years

354 old. Muscle-mass (32), aerobic capacity (33) and morphological characteristics of the heart
355 (34), all develop during this age period. These physiological changes have a direct impact on
356 the physical capacities of young athletes, and consequently impact their pacing behaviour.
357 Another likely underlying mechanism is the development of the self-regulatory skillset and
358 core executive functions (11). The self-regulatory skillset comprises aspects of motivation,
359 self-efficacy as well as (meta-) cognitive functions such as the ability to reflect, plan, monitor
360 and evaluate a goal-directed process such as pacing (35). Complementary, literature generally
361 includes under the core executive functions; the ability to maintain information within the
362 working memory for quick retrieval, the ability to deliberately inhibit or override dominant,
363 automatic, or pre-potent responses and the ability to shift between multiple tasks, operations,
364 or mental sets (20). Both skillsets are suggested to be vital for adequate pacing behaviour and
365 performance (20, 35). A variety of self-regulatory skills and core executive functions are shown
366 to develop between 12 to 21 years old (35, 36). However, there is evidence to suggest that the
367 pre-frontal cortex related (meta-) cognitive skills develop at different rates (36). It could be
368 hypothesised that the cognitive functions that play an important role in the development of
369 pacing behaviour in short-track speed skating, develop specifically during the 15-16 year
370 period. To confirm this hypothesis, further exploration of the relation between pre-frontal
371 cortical related (meta-) cognitive skills, pacing behaviour and athletic performance
372 development is needed.

373

374 Considering the difference in pacing behaviour between race types, it is evident that the pacing
375 behaviour in youth short-track speed skating is influenced by the velocity in the first section of
376 the race. A fast start of the race will lead to a rather evenly paced race, whereas in a race with
377 a slow start the velocity increases considerably in the second half of the race. These findings
378 are not fully unexpected. Previous research, in adult elite short-track speed skaters, found that

379 skaters adjust their pacing behaviour in response to the behaviour of other competitors in the
380 early stages of 1500-m competitions (30). A possible reason for the variability in behaviour
381 could be tactical. It has previously been brought forward that following the pace of an opponent
382 can be more physiologically demanding compared to self-pacing a race (37). Consequently,
383 some skaters will opt to take the lead in the race in order to control the pace. On the other hand,
384 positioning oneself closely behind an opponent could reduce air frictional losses by 23%, due
385 to drafting (38). Additionally, positioning in another position than the leading position allows
386 the athlete to directly observe their opponents (30). The planning of race tactics and the
387 anticipation the behaviour of opponents seems to have a substantial impact on the course and
388 outcome of a short-track speed skating race. This further emphasizes the important role of the
389 development of the self-regulatory skillset and core executive functions in short-track speed
390 skating.

391

392 Compared to the age of the skaters and the type of race, the stage of competition had a less
393 pronounced influence on the skaters' pacing behaviour. The finals were predicted to be faster
394 compared to the non-finals (2.292s). The difference in performance was present in all sections
395 of the race, but was most notable in the middle section. The normalized velocity distribution
396 data paralleled these findings, as skaters in the finals were relatively faster in the first and last
397 sections, but slower in the middle sections. Interestingly, previous research in elite adult short-
398 track speed skaters, pointed to a pronounced change in pacing behaviour throughout a
399 tournament (6, 28). The pacing behaviour of adult skaters was observed to become more
400 conservative, featuring a slower start and fast finish, towards the finals. It would seem
401 therefore, that adult skaters adapt their pacing behaviour throughout the stages of competition,
402 and adapt the most conservative pacing behaviour in the finals (28). It has previously been put
403 forward that athletes not only pace individual races, but also regulate their effort over longer

404 periods of time (e.g. stages of competition, seasons, Olympic cycles) (39). There is some
405 evidence to suggest that young athletes have difficulties with planning an effective regulation
406 of effort (40). It could therefore be suggested that the planning of energy distribution over a
407 longer period than a single race is a skill which is still being developed in young athletes. If
408 this is the case, it should be recognized as a potential concern, as it has previously put forwards
409 that inadequate regulation of effort over long-term could lead to overtraining, burn-out and
410 drop-out among young athletes (23).

411

412 The current study is the first to use multilevel modelling to longitudinally analyse pacing
413 behaviour development. Using a repeated measurement of variance approach (as done in the
414 majority of the literature on pacing), the analyses would have only included data of three skaters
415 (in comparison to the 140 included skaters in the current study), as only three skaters performed
416 in all five different age groups. It has been put forward that more (longitudinal) research on
417 pacing behaviour development in young athletes is needed (11). Following the example set in
418 the current study, multilevel modelling could be used in future studies to provide the much
419 needed longitudinal analysis of pacing behaviour development in other sports in which there
420 are varying number of measurements between participants as well as a variety in temporal
421 spacing between measurements.

422

423 **Conclusion**

424 The current study is the first to study the development of pacing behaviour in a head-to-head
425 sport, throughout adolescence, using a rigorous longitudinal approach. Between 15 and 20
426 years of age, short-track speed skaters become faster by developing the ability to reserve energy
427 in the starting section of the race in order to reach a higher absolute velocity in the second half
428 of the race. The most notably shift in this development seems to occur when skaters are 15-16

429 year of age. In young, as in adult skaters, the pace set in the initial laps dictates the velocity
430 changes in the rest of the race. This phenomenon is suggested to stem from the various tactical
431 choices made by athletes, balancing between the advantages afforded by either drafting or pace
432 control. Lastly, the impact of the competitive environment (e.g. the stage of competition) on
433 the pacing behaviour of young short-track speed skaters is less pronounced compared to adult
434 skaters. Coaches are advised to monitor the pacing behaviour development of athletes, make
435 athletes aware of the tactical advantages of setting a slow or fast initial pace and instruct them
436 on how to pace themselves throughout the different stages of competition, in order to optimise
437 their pacing behaviour and in turn their athletic performance.

438

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444

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545

546 Table 1. Number of included performances per age category.

Age category	Age (mean \pm SD)	Number of race performances				Total
		2	3	4	5	
15	15.19 \pm 0.26	11	9	9	3	32
16	16.11 \pm 0.29	24	29	16	3	72
17	17.05 \pm 0.29	35	48	28	5	116
18	18.03 \pm 0.31	77	48	26	3	154
19	18.97 \pm 0.31	69	58	23	4	154
20	19.56 \pm 0.03	20	14	11	0	45
Total included race performances		236	206	113	18	573

547

548 Table 2. Multilevel model for the absolute section times (AST) presented for each race section
 549 and total race time. * = significant difference from sample category (p <0.05).
 550

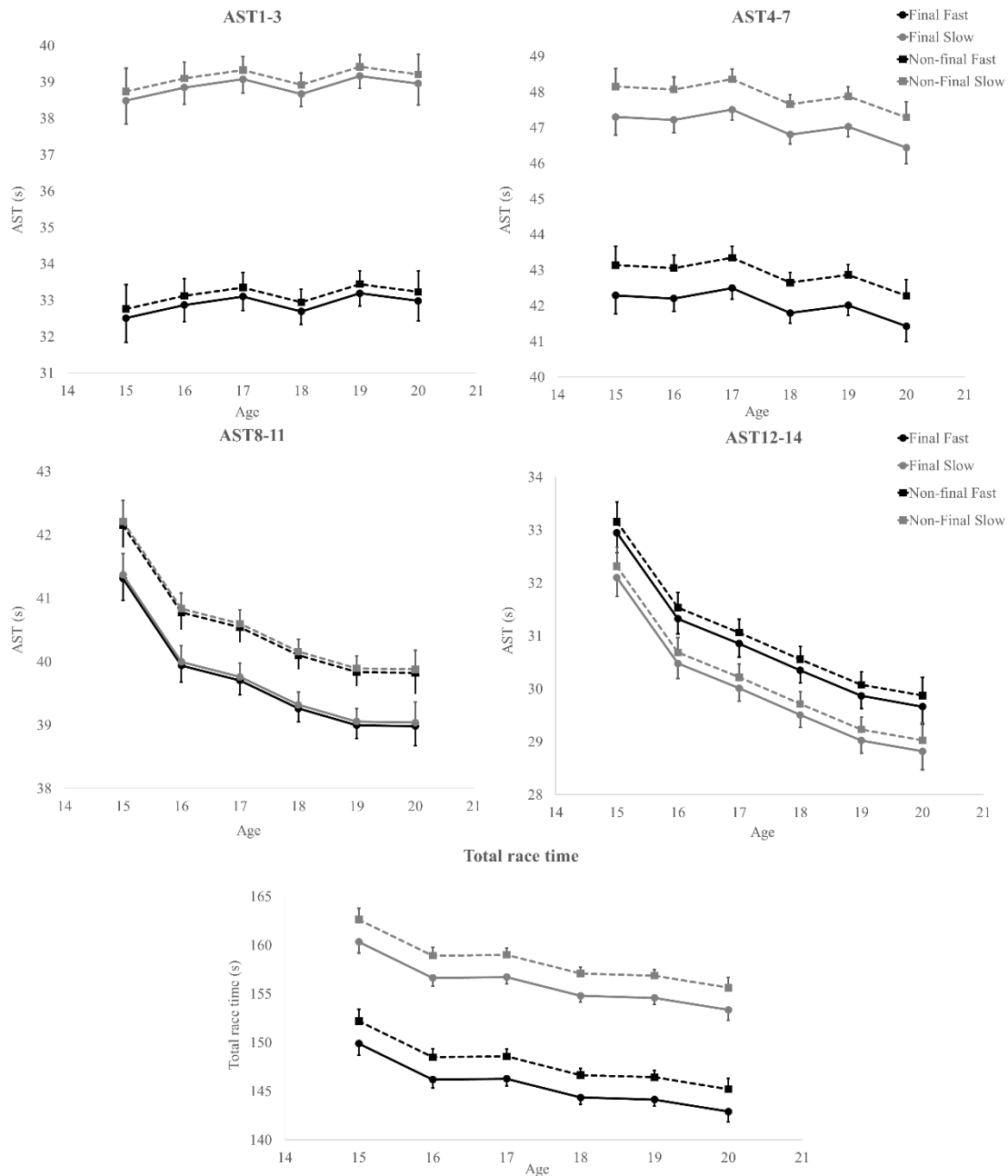
Race phase			Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
Laps 1-3	Fixed effects	Constant	38.486	0.664	<0.001	37.158	39.814
		Fast*	-5.977	0.293	<0.001	-6.563	-5.391
		Non-final	0.251	0.294	0.393	-0.337	0.839
		16	0.361	0.739	0.625	-1.117	1.839
		17	0.590	0.695	0.396	-0.800	1.980
		18	0.182	0.677	0.788	-1.172	1.536
	19	0.680	0.678	0.316	-0.676	2.036	
	20	0.470	0.813	0.563	-1.156	2.096	
	Random effects	level 1: season	11.802	0.787			
		level 2: individual	0.261	0.396			
		Deviance	3052.499				
Deviance empty model		3397.162					
Laps 4-7	Fixed effects	Constant	47.300	0.521	<0.001	46.258	48.342
		Fast*	-5.012	0.230	<0.001	-5.472	-4.552
		Non-final*	0.853	0.231	<0.001	0.391	1.315
		16	-0.084	0.581	0.885	-1.246	1.078
		17	0.206	0.546	0.706	-0.886	1.298
		18	-0.493	0.532	0.354	-1.557	0.571
	19	-0.274	0.532	0.607	-1.338	0.790	
	20	-0.864	0.639	0.176	-2.142	0.414	
	Random effects	level 1: season	7.292	0.486			
		level 2: individual	0.150	0.243			
		Deviance	2775.802				
Deviance empty model		3134.143					
Laps 8-11	Fixed effects	Constant	41.368	0.340	<0.001	40.688	42.048
		Fast	0.057	0.134	0.671	-0.211	0.325
		Non-final*	0.840	0.130	<0.001	0.580	1.100
		16*	-1.373	0.342	<0.001	-2.057	-0.689
		17*	-1.609	0.325	<0.001	-2.259	-0.959
		18*	-2.050	0.329	<0.001	-2.708	-1.392
	19*	-2.315	0.331	<0.001	-2.977	-1.653	
	20*	-2.329	0.414	<0.001	-3.157	-1.501	
	Random effects	level 1: season	2.030	0.138			
		level 2: individual	2.430	0.359			
		Deviance	2272.711				
Deviance empty model		2366.554					
Laps 12-14	Fixed effects	Constant	32.103	0.367	<0.001	31.369	32.837
		Fast*	0.844	0.137	<0.001	0.570	1.118
		Non-final	0.208	0.132	0.115	-0.056	0.472
		16*	-1.624	0.349	<0.001	-2.322	-0.926
		17*	-2.093	0.334	<0.001	-2.761	-1.425
		18*	-2.598	0.340	<0.001	-3.278	-1.918
	19*	-3.080	0.342	<0.001	-3.764	-2.396	
	20*	-3.284	0.429	<0.001	-4.142	-2.426	
	Random effects	level 1: season	2.073	0.141			
		level 2: individual	4.404	0.596			
		Deviance	2352.867				
Deviance empty model		2470.692					
Total race time	Fixed effects	Constant	160.327	1.204	<0.001	157.919	162.735
		Fast*	-10.438	0.510	<0.001	-11.458	-9.418
		Non-final*	2.292	0.500	<0.001	1.292	3.292
		16*	-3.704	1.295	0.004	-6.294	-1.114
		17*	-3.621	1.222	0.003	-6.065	-1.177
		18*	-5.544	1.217	<0.001	-7.978	-3.110
	19*	-5.758	1.221	<0.001	-8.200	-3.316	
	20*	-6.989	1.507	<0.001	-10.003	-3.975	
	Random effects	level 1: season	31.491	2.133			
		level 2: individual	10.857	2.321			
		Deviance	3722.275				
Deviance empty model		4072.143					

552 Table 3. Multilevel model for the relative section times (RST) presented for each race section.
 553 * = significant difference from sample category (p < 0.05).
 554

Race segment			Coefficient	standard error	p-value	95% CI (-)	95% CI (+)
Laps 1-3	Fixed effects	Constant	24.068	0.339	<0.001	23.390	24.746
		Fast*	-2.294	0.146	<0.001	-2.586	-2.002
		Non-final	-0.258	0.144	0.073	-0.546	0.030
		16*	0.615	0.370	0.096	-0.125	1.355
		17*	0.892	0.349	0.011	0.194	1.590
		18*	0.959	0.345	0.005	0.269	1.649
	19*	1.252	0.346	<0.001	0.560	1.944	
	20*	1.420	0.424	0.001	0.572	2.268	
	Random effects	level 1: season	2.673	0.180			
		level 2: individual	0.543	0.151			
		Deviance	2271.992				
		Deviance empty model	2485.771				
Laps 4-7	Fixed effects	Constant	29.484	0.242	<0.001	29.010	29.958
		Fast*	-1.200	0.104	<0.001	-1.404	-0.996
		Non-final	0.111	0.103	0.281	-0.091	0.313
		16*	0.732	0.264	0.006	0.215	1.249
		17*	0.817	0.249	0.001	0.329	1.305
		18*	0.741	0.246	0.003	0.259	1.223
	19*	0.866	0.247	<0.001	0.382	1.350	
	20*	0.664	0.302	0.028	0.072	1.256	
	Random effects	level 1: season	1.363	0.092			
		level 2: individual	0.276	0.077			
		Deviance	1885.939				
		Deviance empty model	2014.313				
Laps 8-11	Fixed effects	Constant	25.947	0.221	<0.001	25.505	26.389
		Fast*	1.685	0.096	<0.001	1.493	1.877
		Non-final*	0.222	0.096	0.021	0.030	0.414
		16*	-0.514	0.244	0.035	-1.002	-0.026
		17*	-0.632	0.229	0.006	-1.090	-0.174
		18*	-0.576	0.225	0.010	-1.026	-0.126
	19*	-0.701	0.225	0.002	-1.151	-0.251	
	20	-0.525	0.273	0.054	-1.071	0.021	
	Random effects	level 1: season	1.232	0.083			
		level 2: individual	0.097	0.050			
		Deviance	1784.004				
		Deviance empty model	2039.665				
Laps 12-14	Fixed effects	Constant	20.487	0.243	<0.001	20.001	20.973
		Fast*	1.887	0.100	<0.001	1.687	2.087
		Non-final	-0.159	0.097	0.101	-0.353	0.035
		16*	-0.706	0.253	0.005	-1.212	-0.200
		17*	-0.988	0.240	<0.001	-1.468	-0.508
		18*	-1.086	0.242	<0.001	-1.570	-0.602
	19*	-1.371	0.243	<0.001	-1.857	-0.885	
	20*	-1.539	0.302	<0.001	-2.143	-0.935	
	Random effects	level 1: season	1.147	0.078			
		level 2: individual	0.818	0.135			
		Deviance	1889.767				
		Deviance empty model	2169.998				

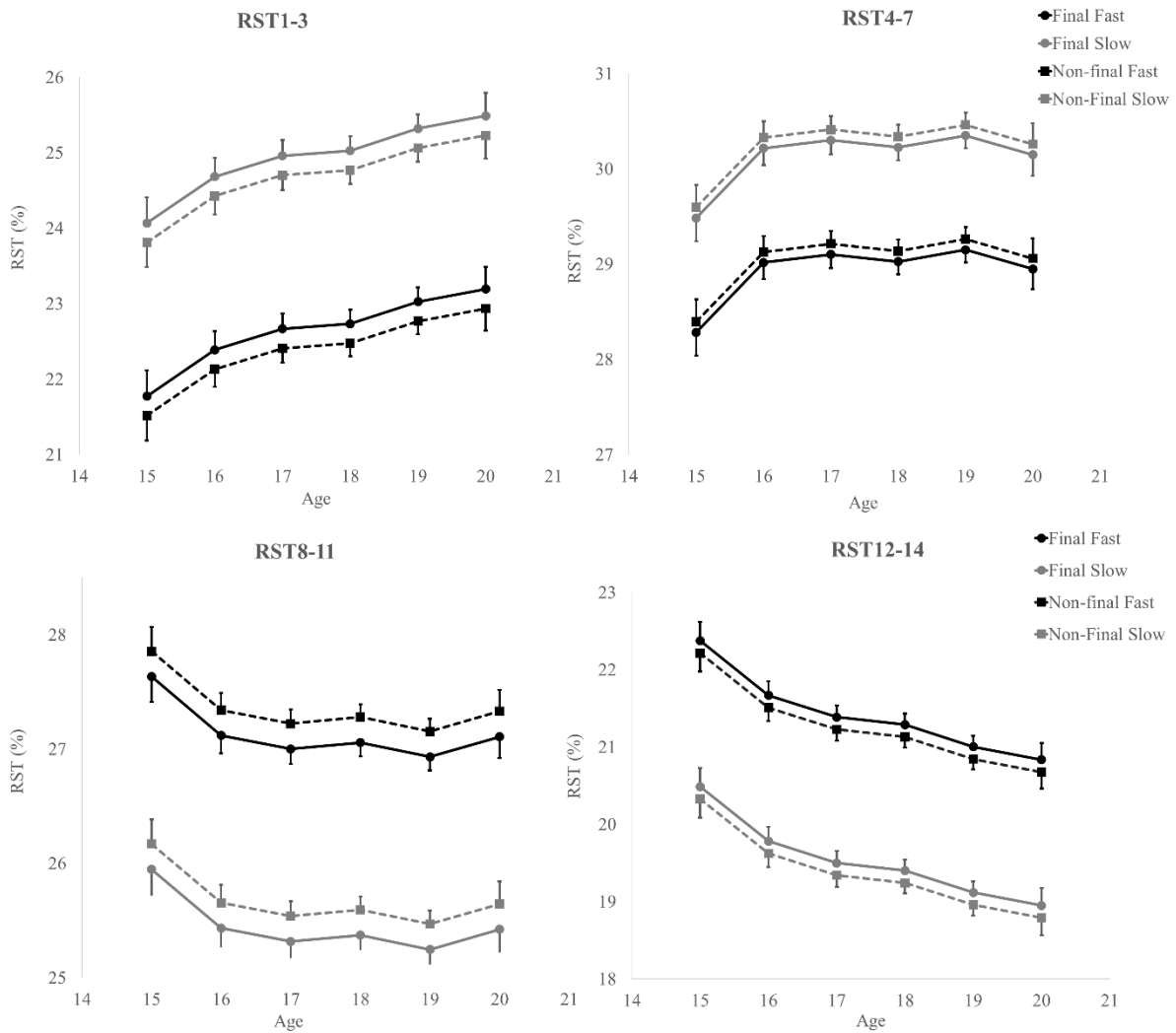
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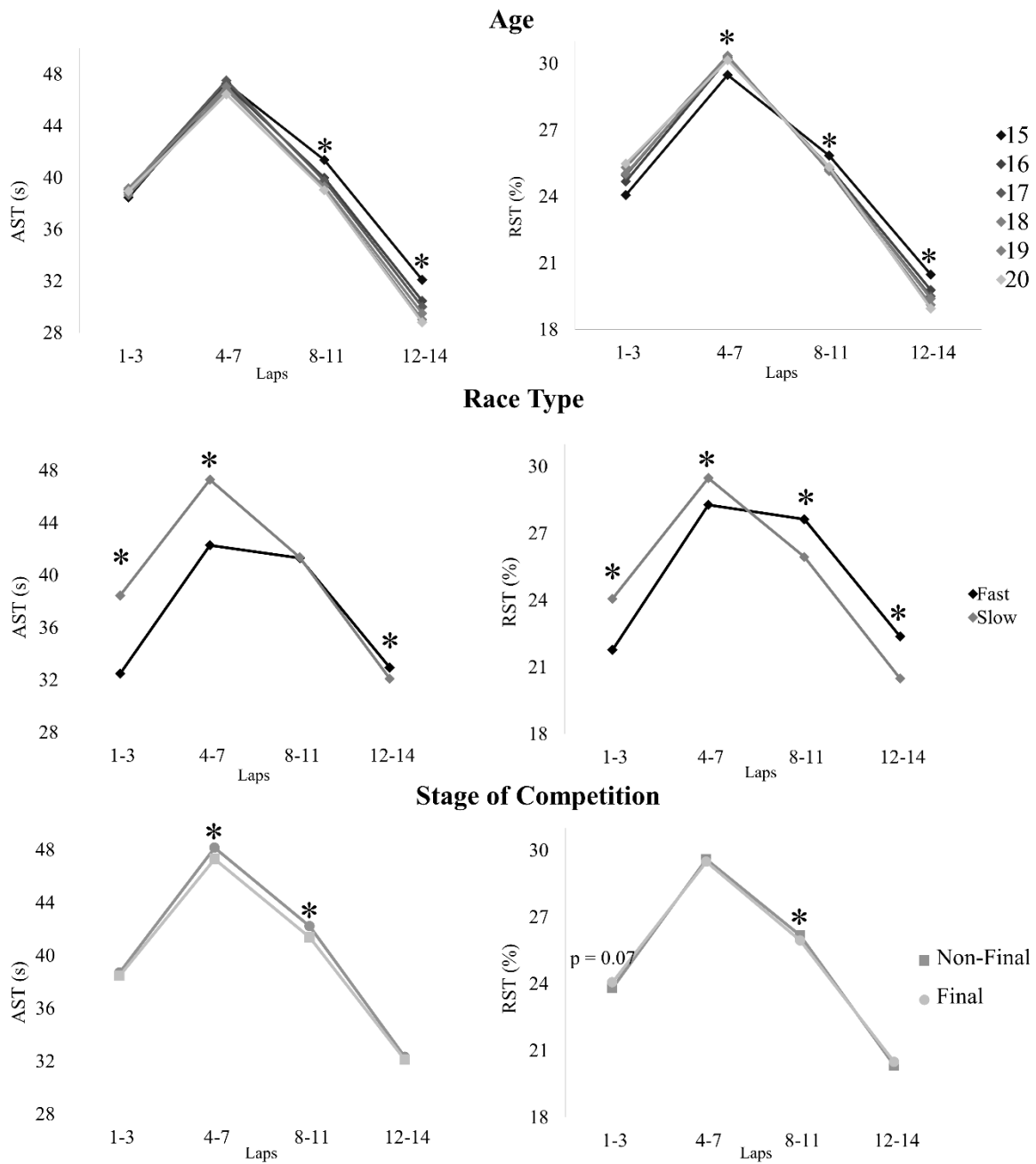
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558 Figure 1. Predicted absolute section times (± 1 SE) per race section and total race time,
 559 presented for each age category. Symbols indicate; grey = slow races, black = fast races,
 560 circles = finals, squares = non-finals.



562

563 Figure 2. Predicted relative section times (± 1 SE) per race section, presented for each age
 564 category. Symbols indicate; grey = slow races, black = fast races, circles = finals, squares =
 565 non-finals.



566

567 Figure 3. Absolute and normalized velocity distribution of skaters: the predicted values for the
 568 absolute and relative section times per race section for each age category, race type and stage
 569 of competition. *p<0.05