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

Short title: How to develop successful pacing skills.

Stein Gerrit Paul Menting[1,2], Barbara Catharina Huijgen[1,3], Marco Johannes Konings[4], Florentina Johanna. Hettinga[2*], Marije Titia Elferink-Gemser[1].

1. *Center for Human Movement Sciences, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.*
2. *Department of Sport, Exercise & Rehabilitation, Faculty of Health and Life Sciences, Northumbria University, Newcastle, United Kingdom*
3. *Department of Psychology, University of Groningen, Groningen, The Netherlands.*
4. *Faculty of Movement and Rehabilitation Sciences, KU Leuven Campus Brugge, Brugge, Belgium.*

Accepted author manuscript version reprinted, by permission, from Medicine & Science in Sports & Exercise, 2019, DIO: 10.1249/MSS.0000000000002239. Available at: https://t.co/pU6mjT5Ffu?amp=1 .

*Corresponding author:

Department of Sport, Exercise & Rehabilitation

Faculty of Health and Life Sciences

Northumbria University

Room 238, Northumberland Building

Newcastle Upon Tyne

NE1 8ST

United Kingdom

E-mail: florentina.hettinga@northumbria.ac.uk;

Tel: +44 (0)1912273989

Abstract

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

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

Results: Between the ages of 15 and 20, total race time decreased (-6.99s) and skaters reached lower 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 and laps 8-11 (-0.53%) and 12-14 (-1.54%) decreased with age. Fast races were more evenly paced compared to slow races, with slow races having a predominantly slow first half and fast finish. Athletes in finals were faster (2.29s), specifically in laps 4-7 (0.85s) and laps 8-11 (0.84s).

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

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

Introduction

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

Although the first signs of the formation of a pacing template appear during late childhood (~10-11 years old) (12, 13), recent research in both time-trial and head-to-head events established that throughout adolescence, the pacing behaviour of youth athletes further develops to ultimately resemble that of seniors (14, 15). Menting et al (2019) provided a theoretical basis behind this development (11). First, adolescence is characterised by both cognitive and physical changes associated with growth and maturation (16, 17). One key development is that of the pre-frontal cortex (18), which has been associated with self-regulatory learning and executive functioning (19), both of which are imperative for adequate pacing (20). Second, in most athlete development programs the amount and quality of training and competition increases profoundly during adolescence, providing youth athletes with an increase in the quantity and quality of opportunities to gather exercise experience. Lastly, coaches could influence the pacing behaviour development by influencing the athlete's motivation, providing advice in goal setting, and providing high quality learning environments in which the pacing behaviour can be optimally developed (11). Emphasising the importance of pacing development during adolescence, a longitudinal study in long-track speed skaters suggests that the development of pacing behaviour in developing athletes has a decisive influence on the performance level at the senior level (14). In addition, the ability to appropriately distribute energy in the long term also seems vital in safeguarding athlete well-being. If an athlete's ability to adequately distribute their energy is hampered, it could lead to them investing too much energy during an exercise task (for example a training and competition) (21, 22). If this happens repeatedly, it could lead to overtraining, burn-out and drop-out (23). This is especially true for developing athletes who, during adolescence, often endure high training loads for a long period of time in order to reach the elite level (24). In order to optimally guide developing athletes it seems to be essential to have a good understanding of both the general and sport-specific development of pacing behaviour during adolescence (11).

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

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

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

Methods

Participants and events

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

A total of 1487 race performances were collected. The occurrence of a fall or disqualification could affect pacing behaviour. For this reason, races including disqualified skaters were excluded, as were race data of skaters who had fallen or included missing data, consistent with the previous literature (6) (43.5% of total race performances collected). The age of a skater was calculated by taking the date of the competition and subtracting the date of birth. The variable of age was converted to a categorical variable in order to show differences between skaters of specific ages. For example: a 16-year old skater was defined as a skater within the age range 15.50 – 16.49 years. To control for outliers of age, the decision was made to exclude race performances of skaters who were not between 14.5 and 20.5 years old (0.6% of total race performances collected). Previous studies established that the number of competitors and the stage of the competition significantly influenced pacing behaviour and performance of elite short-track speed skaters (28). Hence, data from races with more than seven or less than five skaters were excluded (1.3% of total race performances collected) and data was split in finals (quarter-finals, semi-finals and finals) and non-finals (heats and preliminaries). To account for race type, a race was classified as 'fast' or 'slow' when the winner of a particular race was faster or slower than the average completion time of all race winners. In order to properly study longitudinal development, only data from skaters who performed in at least two different age groups, during Junior World Championships, in various seasons, was included. Therefore, all data from skaters who performed in just one age group (i.e., during one Junior World Championship) was excluded (16.1%). It should be noted that due to the qualifying nature of the Junior World Championships, included skaters can have multiple race performances in one age category. After exclusions, 573 race performances (38.6%) of 140 different skaters were included from the original sample. Of the included skaters, 53.6% performed in two, 30.7% in three, 13.6% in four and 2.1% in five different age groups. Table 1 shows the mean age of included skaters and the number of included race performances, per age category.

Study design

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

Data analyses

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

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

Results

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

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

AST1-3 = (constant) + (17) + (fast) + (non-final)

AST1-3 = 38.486 + 0.590 -5.977 + 0.251

AST1-3 = 33.350

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

RST12-14 = (constant) + (15) + (slow) + (non-final)

RST12-14 = 20.49 + 0 + 0 + -0.16

RST12-14 = 20.33

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

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

<u>Age categories</u>

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

Race type

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

Stage of competition

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

Discussion

The current study was the first to use a longitudinal design in order to investigate the development of pacing behaviour of youth short-track speed skaters on a yearly basis, as well as investigates the influence of race type and stage of competition on the pacing behaviour of youth athletes. As hypothesised, the pacing behaviour of short-track speed skaters developed throughout adolescence. With age, the pacing behaviour became more conservative, characterized by a relatively slower start and faster finish. Furthermore, the total race time decreased with age, parallel with an increase in velocity during the last half of the race. Lastly, both the race type and stage of competition influenced the pacing behaviour of youth short-track speed skaters, indicating that the competitive environment is an aspect of athletic performance to account for, already at a young age.

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

The use of relative section times allows for a comparison of pacing behaviour controlled for differences in total race time. In general, the models in the current study predicted that with age, the skaters develop a more conservative pacing behaviour, characterized by a relatively slower start and faster finish. Remarkably, the development of normalized velocity distribution was most evident when comparing 15 and 16 year old skaters to the other age categories. These findings are conform with a previous study which compared cross-sectional data short-track speed skaters, grouped by age: younger than 17, younger than 19, younger than 21 and adults (older than 21) (15). The group with skaters younger than 17 presented the largest difference in normalized lap times, compared to the other groups, specifically in four initial and four final laps of the race. Combining the development in normalized velocity distribution with the finding that with age, skaters reach a higher velocity in the final half of the race, points to the following idea: short-track speed skaters develop their pacing behaviour throughout adolescence, increasing the preservation of energy in the starting section of the race, in order to achieve a higher velocity in the critical final laps of the race resulting in a decrease in total race time. This development is most evident around the 15-16 year span, becoming more gradual towards adulthood. Interestingly, Wiersma et al. (2017), reported that in the time-trial based sport of long-track speed skating, elite skaters distinguished themselves from sub-elite and non-elite by a distinct development of pacing behaviour in the period from 15 to 18 years old (14). The development in long- and short-track speed skating seems similar: in both disciplines skaters develop a more conservative behaviour in which the conservation of energy during the start of the race results in a higher velocity in another section of the race and an overall decrease in total race time. Furthermore, the 15-16 year old mark constitutes a relatively large shift in behaviour in both disciplines. It could be speculated that this resemblance could entail that, like in long-track speed skating, the development of pacing behaviour of young short-track speed skaters could prove to be a marker for future performance level. However, future research should be done to further explore this hypothesis.

A possible underlying mechanism for the rapid development at the 15-16 year old mark could be found in the occurrence of multitude of physical and cognitive changes in athletes of this age (11). Studies have shown that males on average attain their peak height velocity at 14 years old. Muscle-mass (32), aerobic capacity (33) and morphological characteristics of the heart (34), all develop during this age period. These physiological changes have a direct impact on the physical capacities of young athletes, and consequently impact their pacing behaviour. Another likely underlying mechanism is the development of the self-regulatory skillset and core executive functions (11). The self-regulatory skillset comprises aspects of motivation, self-efficacy as well as (meta-) cognitive functions such as the ability to reflect, plan, monitor and evaluate a goal-directed process such as pacing (35). Complementary, literature generally includes under the core executive functions; the ability to maintain information within the working memory for quick retrieval, the ability to deliberately inhibit or override dominant, automatic, or pre-potent responses and the ability to shift between multiple tasks, operations, or mental sets (20). Both skillsets are suggested to be vital for adequate pacing behaviour and performance (20, 35). A variety of self-regulatory skills and core executive functions are shown to develop between 12 to 21 years old (35, 36). However, there is evidence to suggest that the pre-frontal cortex related (meta-) cognitive skills develop at different rates (36). It could be hypothesised that the cognitive functions that play an important role in the development of pacing behaviour in short-track speed skating, develop specifically during the 15-16 year period. To confirm this hypothesis, further exploration of the relation between pre-frontal cortical related (meta-) cognitive skills, pacing behaviour and athletic performance development is needed.

Considering the difference in pacing behaviour between race types, it is evident that the pacing behaviour in youth short-track speed skating is influenced by the velocity in the first section of the race. A fast start of the race will lead to a rather evenly paced race, whereas in a race with a slow start the velocity increases considerably in the second half of the race. These findings are not fully unexpected. Previous research, in adult elite short-track speed skaters, found that skaters adjust their pacing behaviour in response to the behaviour of other competitors in the early stages of 1500-m competitions (30). A possible reason for the variability in behaviour could be tactical. It has previously been brought forward that following the pace of an opponent can be more physiologically demanding compared to self-pacing a race (37). Consequently, some skaters will opt to take the lead in the race in order to control the pace. On the other hand, positioning oneself closely behind an opponent could reduce air frictional losses by 23%, due to drafting (38). Additionally, positioning in another position than the leading position allows the athlete to directly observe their opponents (30). The planning of race tactics and the anticipation the behaviour of opponents seems to have a substantial impact on the course and outcome of a short-track speed skating race. This further emphasizes the important role of the development of the self-regulatory skillset and core executive functions in short-track speed skating.

Compared to the age of the skaters and the type of race, the stage of competition had a less pronounced influence on the skaters' pacing behaviour. The finals were predicted to be faster compared to the non-finals (2.292s). The difference in performance was present in all sections of the race, but was most notable in the middle section. The normalized velocity distribution data paralleled these findings, as skaters in the finals were relatively faster in the first and last sections, but slower in the middle sections. Interestingly, previous research in elite adult short-track speed skaters, pointed to a pronounced change in pacing behaviour throughout a tournament (6, 28). The pacing behaviour of adult skaters was observed to become more conservative, featuring a slower start and fast finish, towards the finals. It would seem therefore, that adult skaters adapt their pacing behaviour throughout the stages of competition, and adapt the most conservative pacing behaviour in the finals (28). It has previously been put forward that athletes not only pace individual races, but also regulate their effort over longer periods of time (e.g. stages of competition, seasons, Olympic cycles) (39). There is some evidence to suggest that young athletes have difficulties with planning an effective regulation of effort (40). It could therefore be suggested that the planning of energy distribution over a longer period than a single race is a skill which is still being developed in young athletes. If this is the case, it should be recognized as a potential concern, as it has previously put forwards that inadequate regulation of effort over long-term could lead to overtraining, burn-out and drop-out among young athletes (23).

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

Conclusion

The current study is the first to study the development of pacing behaviour in a head-to-head sport, throughout adolescence, using a rigorous longitudinal approach. Between 15 and 20 years of age, short-track speed skaters become faster by developing the ability to reserve energy in the starting section of the race in order to reach a higher absolute velocity in the second half of the race. The most notably shift in this development seems to occur when skaters are 15-16 year of age. In young, as in adult skaters, the pace set in the initial laps dictates the velocity changes in the rest of the race. This phenomenon is suggested to stem from the various tactical choices made by athletes, balancing between the advantages afforded by either drafting or pace control. Lastly, the impact of the competitive environment (e.g. the stage of competition) on the pacing behaviour of young short-track speed skaters is less pronounced compared to adult skaters. Coaches are advised to monitor the pacing behaviour development of athletes, make athletes aware of the tactical advantages of setting a slow or fast initial pace and instruct them on how to pace themselves throughout the different stages of competition, in order to optimise their pacing behaviour and in turn their athletic performance.

Acknowledgements

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

References

1. Edwards AM, Polman RCJ. Pacing and awareness: brain regulation of physical activity. Sports Medicine. 2013;43:1057-64.
2. Smits BLM, Pepping G-J, Hettinga FJ. Pacing and decision making in sport and exercise: the roles of perception and action in the regulation of exercise intensity. Sports Medicine. 2014;44:763-75.
3. Foster C, De Koning JJ, Hettinga F, Lampen J, La Clair KL, Dodge C, et al. Pattern of energy expenditure during simulated competition. Medicine and science in sports and exercise. 2003;35:826-31.
4. van Ingen Schenau GJ, De Koning JJ, De Groot G. The distribution of anaerobic energy in 1000 and 4000 metre cycling bouts. International journal of sports medicine. 1992;13:447-51.
5. Edwards AM, Guy JH, Hettinga FJ. Oxford and Cambridge boat race: performance, pacing and tactics between 1890 and 2014. Sports Medicine. 2016;46:1553-62.
6. Konings MJ, Noorbergen OS, Parry D, Hettinga FJ. Pacing Behavior and Tactical Positioning in 1500-m Short-Track Speed Skating. International journal of sports physiology and performance. 2016;11:122-9.

7. Mauger AR, Neuloh J, Castle PC. Analysis of pacing strategy selection in elite 400-m freestyle swimming. Med Sci Sports Exerc. 2012;44:2205-12. Epub 2012/06/01. doi: 10.1249/MSS.0b013e3182604b84.
8. Hettinga FJ, De Koning JJ, Foster C. VO2 response in supramaximal cycling time trial exercise of 750 to 4000 m. Med Sci Sports Exerc. 2009;41:230-6.
9. De Koning JJ, Foster C, Bakkum A, Kloppenburg S, Thiel C, Joseph T, et al. Regulation of pacing strategy during athletic competition. PloS one. 2011;6:e15863.
10. Stoter IK, MacIntosh BR, Fletcher JR, Pootz S, Zijdewind I, Hettinga FJ. Pacing Strategy, Muscle Fatigue, and Technique in 1500-m Speed-Skating and Cycling Time Trials. International journal of sports physiology and performance. 2016;11:337-43.
11. Menting SGP, Hendry DT, Schiphof-Godart L, Elferink-Gemser MT, Hettinga FJ. Optimal Development of Youth Athletes Toward Elite Athletic Performance: How to Coach Their Motivation, Plan Exercise Training, and Pace the Race. Frontiers in Sports and Active Living. 2019;1(14). doi: 10.3389/fspor.2019.00014.
12. Lambrick D, Rowlands A, Rowland T, Eston R. Pacing strategies of inexperienced children during repeated 800 m individual time-trials and simulated competition. Pediatric exercise science. 2013;25:198-211.
13. Micklewright D, Angus C, Suddaby J, St Clair GA, Sandercock G, Chinnasamy C. Pacing strategy in schoolchildren differs with age and cognitive development. Medicine and science in sports and exercise. 2012;44:362-9.
14. Wiersma R, Stoter IK, Visscher C, Hettinga FJ, Elferink-Gemser MT. Development of 1500-m Pacing Behavior in Junior Speed Skaters: A Longitudinal Study. International Journal of Sports Physiology and Performance. 2017;12:1-20. doi: 10.1123/ijspp.2016-0517.
15. Menting SGP, Konings MJ, Elferink-Gemser MT, Hettinga FJ. Pacing Behavior of Elite Youth Athletes: Analyzing 1500-m Short-Track Speed Skating. International Journal of Sports Physiology and Performance. 2019;14:222-31. doi: 10.1123/ijspp.2018-0285.
16. Beunen GP, Malina RM, Renson R, Simons J, Ostyn M, Lefevre J. Physical activity and growth, maturation and performance: a longitudinal study. Medicine and science in sports and exercise. 1992;24:576-85.
17. Blakemore SJ, Burnett S, Dahl RE. The role of puberty in the developing adolescent brain. Human brain mapping. 2010;31:926-33.
18. Casey B, Jones RM, Hare TA. The adolescent brain. Annals of the New York Academy of Sciences. 2008;1124(1):111-26.
19. Hofmann W, Schmeichel BJ, Baddeley AD. Executive functions and self-regulation. Trends in cognitive sciences. 2012;16(3):174-80.
20. Hyland-Monks R, Cronin L, McNaughton L, Marchant D. The role of executive function in the self-regulation of endurance performance: A critical review. Progress in brain research. 2018;240:353-70.
21. Baron B, Moullan F, Deruelle F, Noakes TD. The role of emotions on pacing strategies and performance in middle and long duration sport events. British Journal of Sports Medicine. 2011;45(6):511-7.
22. Foster C, Snyder A, Thompson NN, Green MA, Foley M, Schrager M. Effect of pacing strategy on cycle time trial performance. Medicine and Science in Sports and Exercise. 1993;25(3):383-8.
23. Schiphof-Godart L, Hettinga FJ. Passion and Pacing in Endurance Performance Frontiers in Physiology 2017;8 83.
24. Raglin JS, Wilson GS. Overtraining in athletes. Emotions in sport. 2000;191207.
25. Carlsson M, Assarsson H, Carlsson T. The influence of sex, age, and race experience on pacing profiles during the 90 km Vasaloppet ski race. OPEN ACCESS JOURNAL OF SPORTS MEDICINE. 2016;7:11-9. doi: 10.2147/OAJSM.S101995.

26. Elferink-Gemser MT, te Wierike SC, Visscher C. 16 Multidisciplinary Longitudinal Studies: A Perspective from the Field of Sports. The Cambridge Handbook of Expertise and Expert Performance. 2018:271.

27. Hettinga FJ, Konings MJ, Cooper CE. Differences in Muscle Oxygenation, Perceived Fatigue and Recovery between Long-Track and Short-Track Speed Skating. Frontiers in physiology. 2016;7.

28. Konings MJ, Hettinga FJ. The Impact of Different Competitive Environments on Pacing and Performance. Int J Sports Physiol Perform. 2018;13(6):701-8. doi: 10.1123/ijspp.2017-0407.

29. Konings MJ, Hettinga FJ. Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review. Sports Medicine. 2018;48(8):1829-43.

30. Konings MJ, Hettinga FJ. Objectifying Tactics: Athlete and Race Variability in Elite Short-Track Speed Skating. International Journal of Sports Physiology and Performance. 2018;13(2):170-5. doi: 10.1123/ijspp.2016-0779.

31. Charlton C, Rasbash J, Browne WJ, Healy M, Cameron B. MLwiN Version 3.04. Centre for Multilevel Modelling, University of Bristol.; 2019.

32. McCarthy H, Samani-Radia D, Jebb S, Prentice A. Skeletal muscle mass reference curves for children and adolescents. Pediatric obesity. 2014;9(4):249-59.

33. Armstrong N, Welsman JR. Development of aerobic fitness during childhood and adolescence. Pediatric Exercise Science. 2000;12(2):128-49.

34. de Simone G, Devereux RB, Kimball TR, Mureddu GF, Roman MJ, Contaldo F, et al. Interaction between body size and cardiac workload: influence on left ventricular mass during body growth and adulthood. Hypertension. 1998;31(5):1077-82.

35. Elferink-Gemser MT, Hettinga FJ. Pacing and Self-Regulation: Important Skills for Talent Development in Endurance Sports. International Journal of Sports Physiology and Performance. 2017:1-17.

36. Huizinga M, Dolan CV, van der Molen MW. Age-related change in executive function: Developmental trends and a latent variable analysis. Neuropsychologia. 2006;44(11):2017-36.

37. Lander PJ, Butterly RJ, Edwards AM. Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine. 2009;43(10):789-95.

38. Rundell KW. Effects of drafting during short-track speed skating. Medicine and science in sports and exercise. 1996;28(6):765-71.

39. Edwards AM, Noakes TD. Dehydration. Sports Medicine. 2009;39(1):1-13.

40. Menting SGP, Elferink-Gemser MT, Huijgen BC, Hettinga FJ. Pacing in lane-based head-to-head competitions: A systematic review on swimming. Journal of sports sciences. 2019;37(20):2287-99. doi: 10.1080/02640414.2019.1627989.

Table 1. Number of included performances per age category.

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

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

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				

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

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				

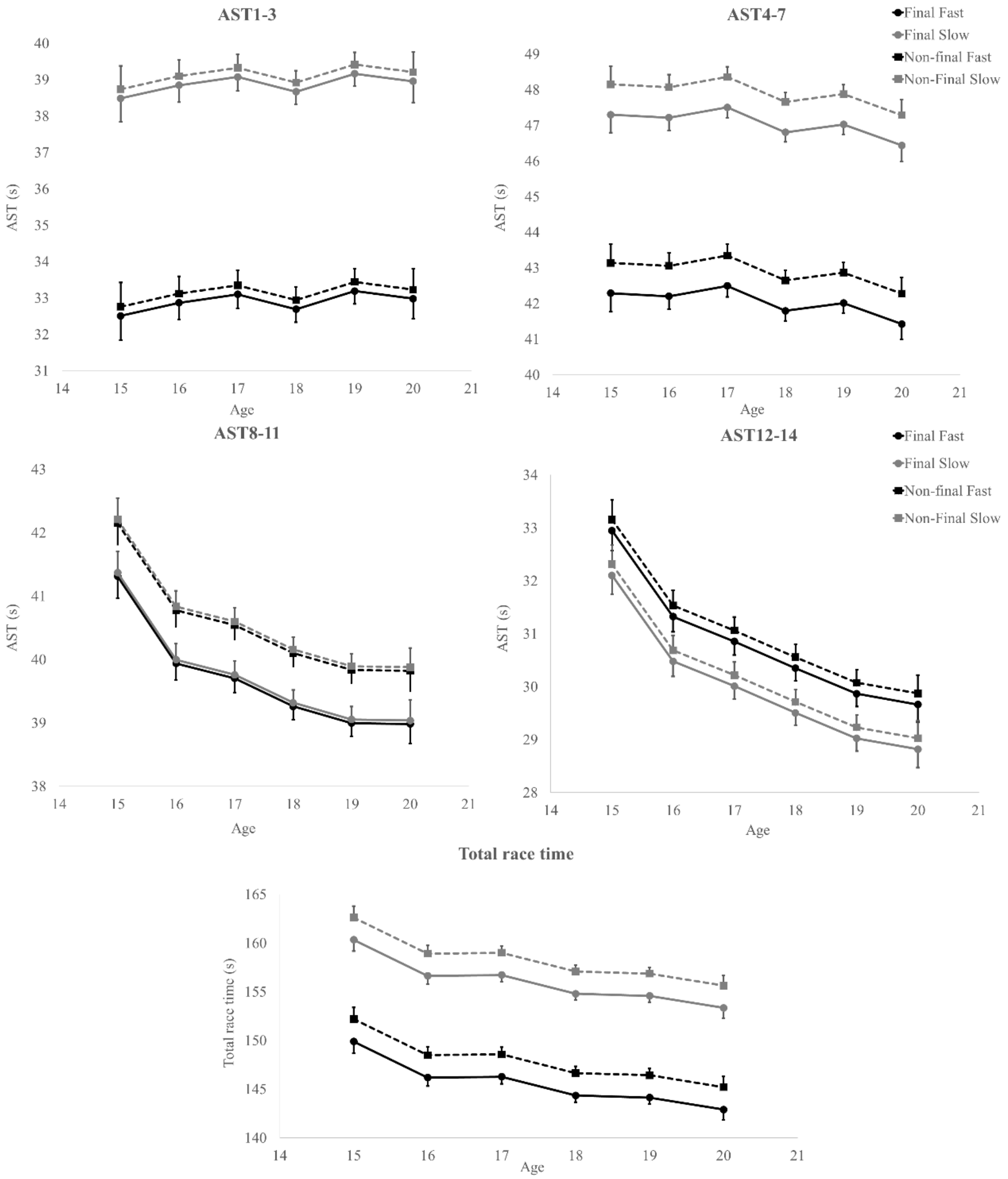

Figure 1. Predicted absolute section times (± 1 SE) per race section and total race time, presented for each age category. Symbols indicate; grey = slow races, black = fast races, circles = finals, squares = non-finals.

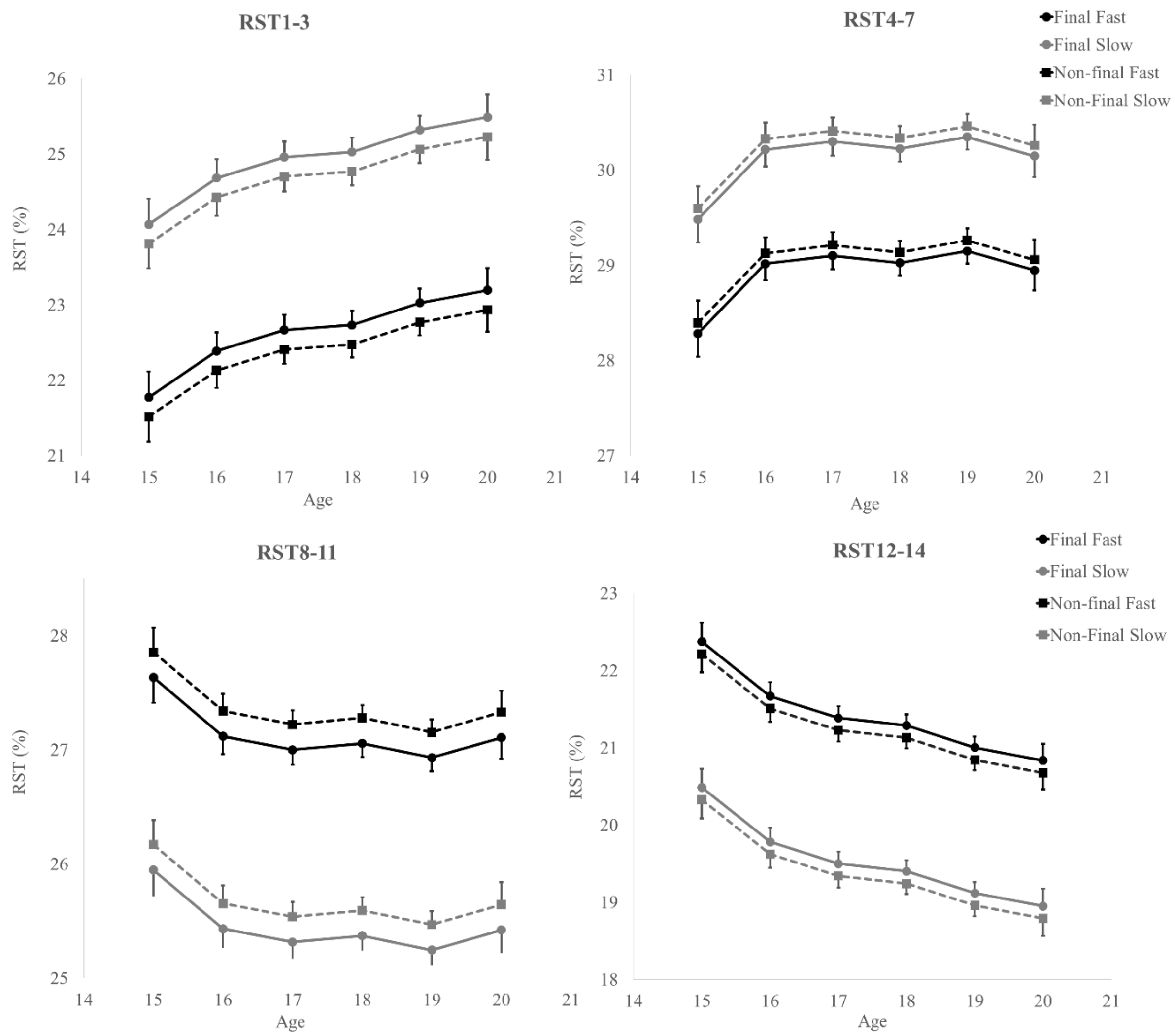

Figure 2. Predicted relative section times (± 1 SE) per race section, presented for each age category. Symbols indicate; grey = slow races, black = fast races, circles = finals, squares = non-finals.

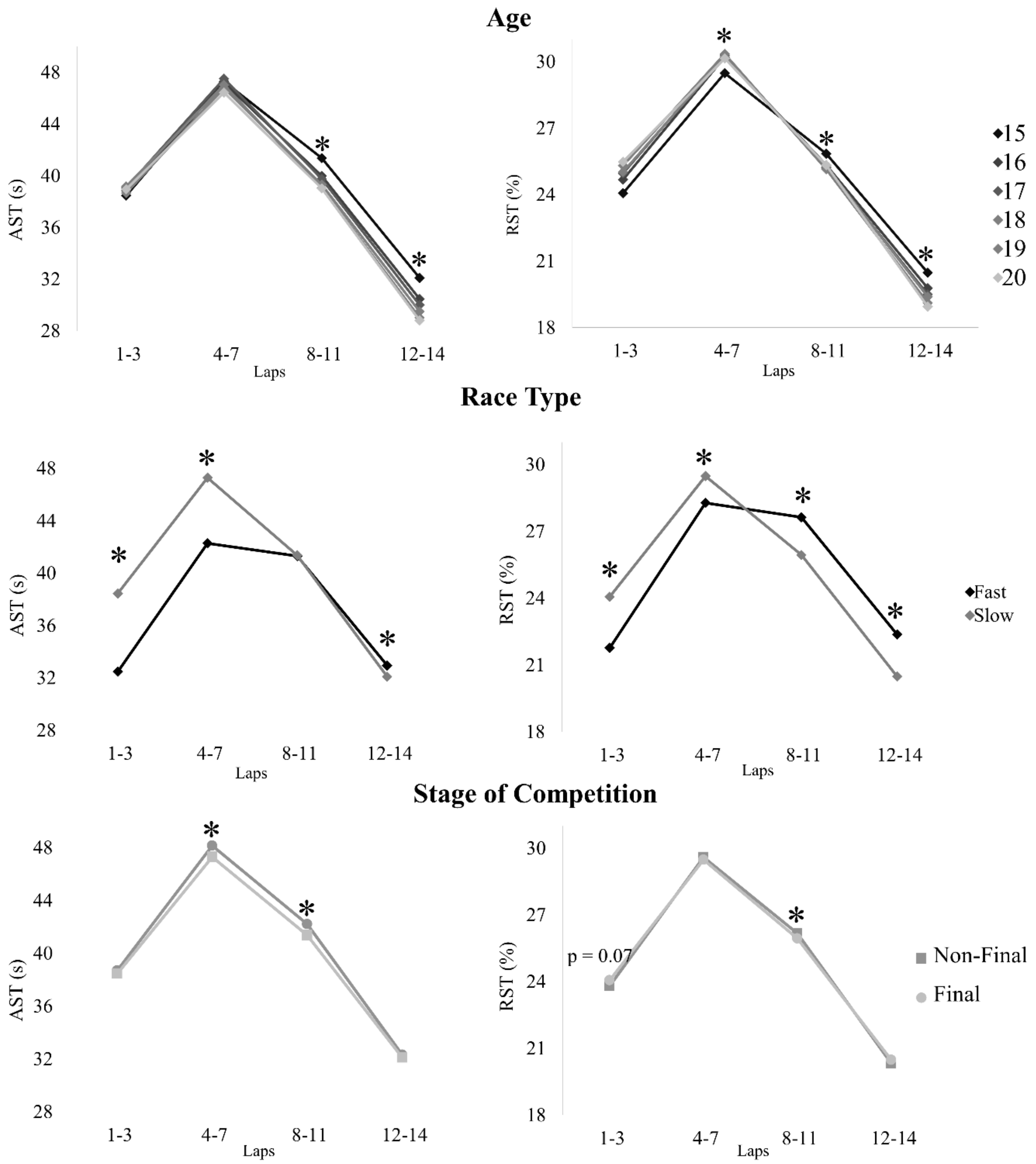

Figure 3. Absolute and normalized velocity distribution of skaters: the predicted values for the absolute and relative section times per race section for each age category, race type and stage of competition. *p<0.05