Aus dem Bereich Sport- und Präventivmedizin

Klinische Medizin

der Medizinischen Fakultät

der Universität des Saarlandes, Homburg/Saar

End-spurt behaviour in long distance pool swimming

Dissertation zur Erlangung des Grades eines Doktors der Theoretischen Medizin

der Medizinischen Fakultät

der UNIVERSITÄT DES SAARLANDES

2024

vorgelegt von: Joshua E. Neuloh

geb. am: XXXXXXXX

DECLARATION

I Joshua E. Neuloh certify to the best of my knowledge and belief that this thesis does not:

i. Incorporate any material previously submitted for a degree or diploma in any institution of higher education without acknowledgement;

ii. Contain any material previously published or written by another person; where due reference is made in the text; or

iii. Contain any defamatory material.

I also grant permission for the library at Saarland University to produce duplicate copies of my thesis as required.

Saarbrücken, 13.06.2024 ____________________

Joshua E. Neuloh

Table of Content

For my family

Acknowledgement

This thesis would not have been started without a meeting with Prof. Dr. Tim Meyer and Dr. Sabrina Forster a long time ago. The encouragement and guidance received made me start this project and until today I am happy to have pursued a PhD at the Institute for Sports and Preventive Medicine at Saarland University.

This thesis would not have been possible without the guidance and help of several individuals, who in one way or another contributed to the completion of three publications. It is a pleasure to thank those, who made it possible. I am indebted to my supervisor Dr. Sabrina Forster, whose guidance, support, and expertise has enabled me to complete my PhD. A huge thank you is further extended to: Dr. Lex Mauger, Dr. Anne Hecksteden, Ingrid Lässig, Felix Weins, Dr. Sascha Schwindling.

Finally, this thesis would not have been finished without Dr. Andreas Venhorst. His valuable assistance in various aspects made this thesis a success, even during the worldwide corona pandemic. He knows how to bring “PS auf die Straße” (put the pedal to the metal). Thank you very much for your help.

Abbreviations

CI	Confidence interval
CP	Critical power
CTT	Head-to-head competition time trial
ES*	End-Spurt Indicator *used abbreviation in Study 1
ESI	End-Spurt Indicator
F	F-test
FAM	Familiarization time trial
FET	Forced even pacing through virtual pacing assistance time trial
m/s	Meter per second
p	P-value
PhD	Doctor of philosophy
RPE	Rate of perceived exertion
SD	Standard deviation
STT	Self-paced time trial
SVLL	Swim velocity of the last lap
SVMP	Swim velocity in the middle part of the race
VST	Virtual Swim Trainer

List of Publications

1. **Neuloh, Joshua E.*,** Skorski, Sabrina*, Mauger, Lex, Hecksteden, Anne & Meyer, Tim. (2020). Analysis of end-spurt behaviour in elite 800-m and 1500-m freestyle swimming. European Journal of Sport Science. 21. 1. 10.1080/17461391.2020.1851772; Published on 14 Dec 2020. *These authors contributed equally as first authors.
2. **Neuloh, Joshua E.,** Venhorst, Andreas, Forster, Sabrina, Mauger, Alexis & Meyer, Tim. (2022). The association of end-spurt behaviour with seasonal best time in long-distance freestyle pool swimming: End-spurt in freestyle swimming. European Journal of Sport Science. 23. 1-21. 10.1080/17461391.2022.2043943. Published on 6 Mar 2022.
3. **Neuloh, Joshua E.,** Venhorst, Andreas, Forster, Sabrina & Meyer, Tim. (2024). The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming. European Journal of Sport Science. 2024; 1-8; https://doi.org/10.1002/ejsc.12102. Published on 8 Apr 2024.

Abstract

Introduction: In 800 m and 1,500 m freestyle swimming an end-spurt has been observed, despite the more energetically optimal strategy being an even pace, particularly when moving a body through water. Even minor changes in speed are critical as they significantly impact energy expenditure**.** The ultimate goal of a competitive swimmer is to achieve completion of the race distance in the shortest possible time and beat all other competitors. The observation of end-spurt behaviour and the contradicting theoretical necessity determined the three main aims of this thesis: i) to develop an End-Spurt Indicator (ESI) to quantify and analyse end-spurt behaviour; ii) to analyse its relationship to finishing position and finishing times; and iii) to investigate the effects of an end-spurt compared to an energetically optimized pacing pattern and a race against a performance-matched opponent including its physiological underpinnings.

Method: i) To analyse the influence of distance, time point of competition, round and finishing position on end-spurt behaviour in 800 m and 1,500 m freestyle swimming from the last eight World Championships and five Olympic Games (1998–2016; including 1,433 races and 528 swimmers). The end-spurt for each race was determined by means of an ESI. Subsequently, ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for distance, time point of competition, round and finishing position. ii) To analyse the association of seasonal best time, distance, and different performance levels with end-spurt behaviour in 800 m and 1,500 m pool freestyle swimming in the season 2018/2019 (including 14,930 races and 2,650 swimmers). This time ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for seasonal best time, distance, and performance level amongst others. iii) To investigate the effect of forced even pacing through virtual pacing assistance and an opponent in a competitive setting on end-spurt behaviour in freestyle swimmers (including related physiological underpinnings), 27 competitive swimmers and triathletes were recruited and completed four 1,500 m freestyle trials: (i) familiarization time trial (FAM), (ii) self-paced time trial (STT), (iii) head-to-head competition time trial (CTT) and (iv) forced even pacing through virtual pacing assistance time trial (FET).

Eventually, 12 swimmers met the criteria for the CTT and FET to be included in the analysis. Changes in end-spurt behaviour, finishing time and physiological parameters (lactate, cortisol, noradrenaline, heart rate) were analysed using a linear mixed model with fixed effects for trials and a random effect for swimmer identity. A separate linear model was computed for competition outcome.

Results: i) An end-spurt was evident in most swims for both race distances. The finishing position within a race significantly affected the ESI ($P<.001$). Specifically, when analysing finals only, ESI was significantly greater in medallists compared to non-medallists ($P<.001$). ii) In 800 m and 1,500 m races swimmers showed a mean ESI of 2.08 and 3.68, respectively. There was a significant association between seasonal best time and ESI, with a better seasonal best time showing a greater ESI ($P<.001$, $f^2=0.04$). A significant effect on greater ESI was also observed for longer distance ($P<.001$, $f^2=0.06$) and higher performance level ($P<.001$, $f^2=0.02$). Elite swimmers had a mean ESI of 5.47, sub-elite swimmers of 3.74 and competitive swimmers of 2.41. iii) Swimmers demonstrated a significantly greater ESI in FET (+2,6; $P<.001$) and CTT (+1,4; $P<.022$) compared to STT. Blood lactate concentration in FET ($P<.001$) and CTT ($P<.001$) was significantly higher than in STT. Winners had a significantly greater ESI than losers in CTT ($P<.005$).

Conclusion: The first study used a newly developed ESI demonstrating that particularly medallists have a more pronounced end-spurt compared to non-medallists. The second study showed that a more pronounced end-spurt is associated with seasonal best time in long-distance pool swimming, higher performance level of the swimmer and longer race distance. The third study provided evidence that swimmers utilized a greater end-spurt through metabolically optimal forced even pacing by virtual pacing assistance and in a head-to-head competition due to a larger mobilization of anaerobic reserves as indicated by greater blood lactate concentrations. Winners had a significantly greater end-spurt than losers, despite similar metabolic disturbances. To summarize, swimmers use an end-spurt to a greater extent, when racing against a performance-matched competitor. Medallists and winners show a more pronounced end-spurt due to a larger mobilization of anaerobic reserve, as indicated by higher blood lactate concentrations. For future research, the sample size should be increased, and the data collection of psychological aspects is warrant.

1 Introduction

1.1 Pacing

Pacing in sport is crucial for achieving the desired outcome, whether that be reaching the finish line in the shortest amount of time or ahead of the competition. Regardless of the sport, athletes must maintain homeostasis to avoid catastrophic biological failure and premature fatigue, making pacing an essential skill for high-performance athletes (Abbiss and Laursen 2008). Developing successful pacing behaviour involves considering various factors such as the sport, environment, equipment, and the athlete's physiological and psychological characteristics (Foster et al. 1994). It is widely accepted that the brain plays a crucial role in processing and evaluating internal and external information to establish, maintain and adapt pacing behaviour during training and competition (Menting et al. 2022). The brain considers the remaining distance, current rate of energy consumption, energy reserves, and fatigue levels before determining the level of power output required to reach the finish line in the shortest possible time or outsprint an opponent (Smits et al. 2014).

However, the brain's calculation can be fallible, and poor pacing strategies and behaviour can have severe consequences, such as significant performance deterioration in the decisive moments of a race, thereby deciding the colour of the medal or not even finishing the race (Foster et al. 1994). Pacing, despite its complexities, is an essential skill for any sport performance that can make the difference between success and failure, as well as the difference between a good and a great performance (Abbiss and Laursen 2008). Therefore, having a better understanding of pacing strategies to optimise performance is essential for athletic performance. Focusing solely on performance outcomes without delving into the details of how it was achieved is futile for future athletic development. Coaches and athletes should explore the most effective pacing strategies and monitor the athlete’s pacing behaviour to ensure that individual swimmers achieve their potential.

The physiological aspects that underpin exercise performance have been extensively investigated in endurance sport (Stone et al. 2012). It is generally accepted that fatigue progressively develops during intense exercise, especially when near-maximal effort is exerted (Abbiss and Laursen 2008). Based on this theory, athletes should not be able to accelerate towards the end of exercise due to fatigue being at its highest levels (Azevedo et al. 2021). Fatigue occurs when the neuromuscular axis is no longer able to effectively drive the locomotor muscles, impeding power output and performance. The suggested causes, for example, include a deficit in energy-providing adenosine triphosphate and phosphocreatine and the accumulation of metabolic waste products in the muscle (Azevedo et al. 2021). The aerobic energy system plays a vital role in longer races, reducing the reliance on the anaerobic system. Such models suggest that metabolites associated with muscle fatigue reach an individual critical threshold at exhaustion, implying that fatigue progressively develops over time (Amann 2011). This highlights the necessity for athletes to set an individually optimized pace from the start, which can be maintained to the end of the race avoiding a critical rate of fatigue development, as an all-out effort cannot be sustained over longer distances and durations.

The relationship between time and power output has been well described in the concept of critical power (Jones 2017). It can be observed that the sustainable power output exponentially declines over time. Eventually, the power-duration curve begins to level off after roughly 20 minutes, which is termed critical power. It is a mesoscopic variable offering an integrative understanding skeletal muscle energetics, along with metabolic and cardiorespiratory reactions to exercise. Each physiological system receives efferent forward command from and provides afferent feedback to the central nervous system during exercise regulation. The cardiovascular system delivers oxygen to working muscles and removes waste products, while the respiratory system oxygenates the blood and exhales carbon dioxide. The muscular system produces force and maintains posture, and the metabolic system regulates energy supply. The central nervous systems integrate inputs from the different physiological systems to coordinate mechanical and metabolic responses.

The central governor model by Noakes posits that the brain functions as a safe-guard mechanisms during exercise, regulating physiological systems in order to prevent catastrophic failure (Noakes 1997). It is proposed that the brain adjusts neuromuscular recruitment of locomotor muscles in self-paced exercise in response to afferent feedback from muscles and organs. The power output created by the muscles during exercise is continuously adjusted to ensure the maintenance of homeostasis (Noakes 1997). Thus, exercise performance has been suggested to be regulated by a complex anticipatory system in the subconscious brain considering various factors such as oxygen delivery, glucose concentration and metabolic accumulation as well as psychological factors. Noakes & St Clair Gibson suggested that these factors amongst others affect the pace the athlete sets in a race to prevent catastrophic deterioration in exercise performance (Noakes and St Clair Gibson 2004). However, the concept of a central governor controlling physiological responses during exercise has faced scepticism due to instances of physiological catastrophes in athletes, suggesting a potential override of this safe-guard mechanism (Esteve-Lanao et al. 2008). Additionally, it is understood that athletes have a subjective awareness of their resource allocation (perception of effort) when exercising, controlling muscle fatigue and protecting against catastrophic failure (Marcora 2008). It is understood that the relationship between perception of effort, time and exhaustion can be explained more straightforwardly through mathematical adjustments rather than invoking complex physiological mechanisms (Marcora 2008).

It has been revealed that pacing is not only influenced by physiological factors, such as oxygen consumption and lactate accumulation, but also by psychological factors, such as motivation, perceived exertion, and goal-setting (Koning et al. 2011). For example, athletes who have clear goals and strategies for their races tend to pace themselves more effectively than those who do not (Abbiss and Laursen 2008).

The concept of teleoanticipation, is a fundamental tenet of theories in pacing. Ulmer suggested that before and during any race the brain takes into consideration various potential influencing factors. Critical factors for successful teleanticipation are knowledge of the endpoint and distance remaining (Ulmer 1996). To achieve effective teleanticipation, understanding both the endpoint and the remaining distance is crucial. Anticipating the duration of the planned race is significant as it prompts the brain to devise a pacing strategy for completing it. Teleoanticipation is based on the dynamic control and predictive regulation, which involves maintaining equilibrium and efficient allocation of resources to complete the race. The complex central regulation of exercise does not completely prevent homeostatic disturbances from occurring. It rather shows that a reserve exists in which skeletal muscle activation can be increased to cause increases in power output even in the presence of such peripheral changes (Tucker and Noakes 2009). The brain plans each race phase backward from the endpoint, aiming to both metabolic control and optimal race competition. Horstmann et al. found that psychophysiological judgements made early during exercise are reasonably accurate indicators of the time until exhaustion (Horstman et al. 1979). Research thereafter consistently demonstrated a strong relationship between effort perceptions and the adjustment of exercise, affirming the idea that the perception of effort is a primary determinant in the regulation of endurance performance. It is suggested that the scalar properties of perceived exertion (RPE) during exercise can predict the time to exhaustion (Noakes 2008). This guiding framework can dictate how the race is managed and conducted throughout its entire duration. In essence, there is a proactive planning approach to the activity, which serves two purposes. It facilitates successful race completion in the most efficient way, but at the same time preventing premature fatigue. Swart et al. found that enhanced familiarity with the exercise and a clear knowledge of its endpoint are linked to a more aggressive (i.e. linear) pacing strategy, leading to superior exercise performance (Swart et al. 2009).

The afferent feedback model (Amann 2011) includes both internal and external stimuli towards maintaining homeostasis during exercise (Ament 2001). It is suggested that receptors continuously monitor the physiological impact of the pace (Mauger 2014). Internal stimuli sensed by various receptors and external stimuli like a competitor or environmental shifts, contribute to the feedback loop. The feedback loop aims to regulate and restrict peripheral muscle fatigue, maintaining it below the individual critical threshold.

Psychological aspects of pacing have further yielded surprising and useful discoveries. A well-designed study by Stone et al. investigated whether athletes preserve an energy reserve for use only under extreme circumstances and whether their impressions of their energy levels are accurate (Stone et al. 2012). It was found that athletes reserve energy unconsciously even when pushing themselves to the limit (Stone et al. 2012). This raises the question of whether elite athletes can learn to access this reserve by training at high intensities or certain pacing strategies. As we gain a better understanding of pacing, we may be able to further push the boundaries of human performance, but the physical and psychological mechanisms involved remain complex.

2 Background

2.1 Pacing in swimming

The Olympic Games and World Championships are the ultimate platform for swimmers, with a rich history of pool and open water events. Most swimming competitions adhere to the heat, semi-final, and final format, where a swimmer's final time determines their qualification for subsequent rounds. Competing at this level demands unwavering commitment, dedication, and relentless physical and mental preparation, often leading to a solitary chance to compete for a medal. Swimming is a sport where victory and defeat often come down to slim margins, and the times required to win a gold medal are progressively getting faster with each Olympic Games and World Championships, often resulting in frequent World Record breakages (Pyne et al. 2004).

The scientific literature on swimming is vast and diverse, owing to the complex and multifaceted nature of swimming performance (McGibbon et al. 2018). However, research in certain areas is limited compared to many land-based sports due to the challenges associated with conducting research in an aquatic environment. For instance, measuring energy expenditure and metabolic responses, heart rate monitoring, kinematic analysis and sensory perceptions or other motivational aspects through questionnaires or scales during swimming in a pool can be as challenging to evaluate as externally controlling the pace in the pool (McGibbon et al. 2018). Considering that the smallest meaningful change in swimming performance in Olympic events is 0.4% (Pyne et al. 2004), a mere difference of 0.01 seconds can determine whether an elite athlete wins a gold or silver medal or qualifies for a final at the Olympic Games. Consequently, optimizing pacing behaviour is becoming increasingly important in maximizing swimming performance (Foster et al. 1994).

Due to the highly resistive properties of water, optimal pacing is arguably even more important in swimming than in other sports (Toussaint and Truijens 2006). Swimming is mechanically inefficient, because only 6-18% of the energy created from the metabolism is actually converted into mechanical work (McGibbon et al. 2018), compared to 18-24% in cycling (Coyle 1999). Therefore, an increase in swimming speed increases energy expenditure substantially (Batchelor 1999). Swimmers who fail to pace optimally may suffer poor race performances, because of a premature fatigue and subsequent loss of power output and swim speed. This is due to the high metabolic cost of swimming in a highly resistive medium and the drag caused by the swimmer becoming less streamlined, subsequently dropping deeper in the water (often at the hips) as fatigue ensues (Thompson et al. 2004). In addition, the more fatigued the swimmer becomes, the greater the technique deterioration (Naemi et al. 2010). This further increases metabolic energy cost and an even greater rate of accumulating fatigue.

Swimming is a sport where the frequency of strokes per minute determines the number of opportunities a swimmer can take a breath. When a swimmer becomes fatigued, they may be tempted to breathe more frequently, such as every stroke instead of every other stroke. This too can have a negative impact on streamlining, resulting in increased drag and energy expenditure (Barden and Barber 2022; Barbosa et al. 2010). As a result, a fatigued swimmer may need to slow down to finish the race without any chance of winning. Therefore, swimming requires a strong synchronization between technique and physiology, and pacing behaviour plays a crucial role in both areas.

Pacing patterns in swimming are often analysed by plotting split times or velocity for each lap of the event. Publicly accessible competition results allow for the calculation of mean lap velocity by dividing lap distance by split time (Mauger et al. 2012). Another method is to express lap velocity as a percentage of the overall mean race velocity. This concept of normalised velocity makes the variability of the mean race velocity comparable. It shows the fluctuation of velocity compared to the mean velocity in relative terms. These data offer insights into the pacing strategies of swimmers in competition, but it is unclear if these patterns are optimal for performance or reflect a deliberate pre-planned pacing strategy. Elite swimmers should be able to execute a pre-determined race plan, but also flexibly adjust pacing behaviour to changing race situations, such as modifying their initial pacing strategy to gain a tactical advantage or keeping pace with a competitor who is pulling away. To gain accurate pacing information, split times need to be measured every 5-10% of the race distance (Foster et al. 1994). This level of resolution has been achieved in swimming research, allowing for the identification of velocity changes in free swimming and non-swimming components such as the dive start, turns, and finish. Abbiss and Laursen have previously described and defined different pacing patterns in common sport performance (Abbiss and Laursen 2008). In swimming a positive, allout, parabolic, negative, variable and even pacing patterns have been observed (McGibbon et al. 2018).

2.2 Pacing pattern

A positive pacing pattern is present when the race velocity gradually declines throughout the duration of the event. A study on the impact of different pacing strategies on performance variables found that national and international 200 m breaststroke swimmers self-selected a positive pacing pattern (Thompson et al. 2004). However, it is unknown whether this pacing strategy is optimal for 200 m breaststroke swimming. Metabolic factors suggest that swimmers who adopt a positive pacing strategy have a higher post blood lactate level, respiratory gas exchange ratio, and RPE scores compared to those who use an even pacing strategy. Thompson et al. observed a positive pacing pattern in swimmers, although it was concluded that an even pacing strategy would be physiologically more advantageous, as using a positive pacing strategy could deplete metabolic reserves too early (Thompson et al. 2004). Indeed, Skorski et al. found that a faster first 100 m in a 400 m freestyle race resulted in a slower finishing time (Skorski et al. 2014a). Given the dive start in swimming, swimmers might adopt a positive pacing strategy to take advantage of the high swim velocity occurring through the starting procedure.

An all-out pacing pattern is predominantly present in 50 m swimming events, whereby the race velocity gradually declines throughout the race after the initial rapid acceleration at the start. Although this pacing pattern is also commonly described in 100 m events, a faster first lap initiated by the dive start means that the second lap is slower indicating a positive pacing pattern. In such short events, it is important for the swimmer to remain competitive (close to competitors), implying a fast start with only a slight drop off towards the end of the race. Accordingly, Robertson et al. found that successful elite swimmers showed faster lap times in the final stages of the race compared to less competitive swimmers (Robertson et al. 2009).

The most commonly used pacing pattern in elite middle distance freestyle swimming is parabolic, whereby the race velocity is approximately 10% above the average race velocity at the start of the race, levels off and stays on an even plateau until approximately 85% of the race has been completed, where the race velocity increases again towards 10% above average race velocity (Abbiss and Laursen 2008). A large sample size study by Mauger et al. analysing the 400 m freestyle races at elite national and international competitions revealed that a parabolic pacing patter is most frequently used (Mauger et al. 2012). Although no single pacing patterns yielded a statistically significant competitive advantage on 400 m freestyle performance, swimmers displaying a parabolic pacing pattern were on average 1.7 s faster compared to swimmers displaying a positive pacing pattern. Given the narrow margins between winning and losing in swimming, performance can be affected by differences of this magnitude and are therefore of practical relevance.

A negative pacing pattern is present when the race velocity is approximately 10% lower than the average race velocity in the start phase of the race and then gradually increases to 10% above average race velocity in the end phase of the race. A clear adoption of such a pacing strategy is rarely observed in swimming, although research showed it lowers fatigue-related metabolites in the start phase of the race (Abbiss and Laursen 2008). Similarly, Mattern et al. revealed that a negative pacing strategy was associated with lower blood lactate during the first half of a 20 km cycling time trial (Mattern et al. 2001). There was a significant increase in overall performance by adopting a negative pacing strategy with a reduced power output in the initial phase of the race by 15% compared to a self-selected pacing pattern. Thompson et al. also showed that heart rate response was significantly lower by utilising a negative pacing strategy compared to a positive or even pacing strategy in 200 m breaststroke swimming (Thompson et al. 2004). However, the study failed to demonstrate a lower mean blood lactate for the negative pacing strategy compared to the even pacing strategy. A negative and a parabolic pacing strategy have in common a controlled start and even pacing in the middle of the race, which conserves energy allowing to substantially increase speed in the final laps. Notably, it was shown that non-medallists expend more energy early on in the race, leaving no capacity left for an end-spurt compared to medallists, thereby emphasizing the importance of an end-spurt relative to the start phase of a race (Mytton et al. 2015).

A variable pacing pattern is present when the race velocity changes extensively during the race. In particular, water-resisted activities like swimming, as well as air-resisted exercises like cycling or ice-skating, can suffer from ineffective pacing behaviour, resulting in decreased performance outcomes (Abbiss and Laursen 2008). Whereas in swimming varying environmental factors are limited, the swimming technique and its effect on the level of water resistance makes pacing behaviour an important performance component. However, as the water resistance increases disproportional to the swimming velocity, acceleration may not be beneficial from a physiological perspective in swimming. The ineffectivity of a variable pacing strategy in swimming is supported by Thompson et al., who showed that an increase in swim velocity above the mean swim velocity results in a higher contribution of the anaerobic metabolism (Thompson et al. 2004). During a 102% trial with therefore increased mean swim velocity, the stroke rate and stroke count increased compared to the 98% trial with therefore reduced mean swim velocity, indicating that the higher mean velocity was due to an elevated stroke rate rather than an increase in stroke length. While RPE increased with mean swim velocity in connection with an increase in stroke rate, it was suggested that fatigue affected the swimming technique, indicating a loss in propulsion. Consequently, it was concluded that a change in swimming technique (i.e. increasing stroke rate) is a possible procedure to maintain swim velocity at the cost of a greater metabolic acidosis.

An even pacing pattern is present when the race velocity stays constant throughout the entire race with only minimal variability. An even pacing strategy is recommended when external conditions are constant (Foster et al. 1993). Though this strategy is mathematically and metabolically optimal for middle and long-distance freestyle events, it is not commonly observed in swimming (McGibbon et al. 2018). Swimmers often find themselves flexibly adapting their pacing strategy, responding to external factors such as a sprint of competitors in the final stages of a race. This adaptability introduces a strategic element to racing in swimming, where athletes must balance the benefits of even pacing with the need to respond to changing biopsychosocial circumstances. The interplay between a metabolically optimal even pacing strategy and interactive dynamics of a race highlights the complexity of regulating pacing behaviour in competitive middle-distance swimming.

2.3 Pacing in 800 m and 1,500 m freestyle pool swimming

Pacing strategies in swimming differ according to the distance of the event (McGibbon et al. 2018). In 800 m and 1,500 m freestyle pool swimming athletes generally display a parabolic pacing pattern with highest swimming velocities at the start and end of the race (Lara and Del Coso 2021; Lipińska 2009; Lipińska et al. 2016; Lipinska et al. 2016; McGibbon et al. 2021; Mytton et al. 2015; Menting et al. 2019). Elite female 800 m freestyle swimmers at the 2008 Olympic Games maintained an even swimming velocity in the middle part of the race after an initial fast start and followed by a substantial increase of swimming velocity on the last 100 m (Lipińska et al. 2016). Further studies repeatedly confirmed this pacing pattern in 800 m freestyle swimming, showing a fast start due to the dive followed by a gradual decrease towards the normalised velocity and with a sprint at the end of the race (Lipińska et al. 2016; McGibbon et al. 2018; Menting et al. 2019). Moreover, it was revealed that better placed swimmers showed less variation between lap times in the race compared to less experienced swimmers showing a decline in segmental velocity towards the end of the race (Lipińska et al. 2016).

An analysis of 173 national and international competitions between the years 2000 and 2014 indicated that a similar pacing pattern is utilised by swimmers in the 1,500 m freestyle pool swimming events (Lipinska et al. 2016). The pacing pattern was characterized by a fast start while the middle part of the race was swum with a reduced lap-to-lap variability. Improvements in finishing time may be possible by conserving energy in the middle part of the race for a faster final lap, which is typically demonstrated by better placed swimmers (Lipinska et al. 2016). A study analysing the 1,500 m freestyle races at World Championships between the years 2003 and 2019 showed that all finalists chose a parabolic pacing pattern (Lara and Del Coso 2021). It was concluded that a relatively slower start pace and an even paced middle part during the race may help to conserve energy for the decisive final stages of the race (McGibbon et al. 2021).

2.4 Reproducibility of pacing performance

Considering these different pacing strategies, researchers have examined the reproducibility of pacing patterns between and within athletes and competitions. Swimmers have a unique advantage over participants in cycling or running events as they compete in their own designated lanes, reducing the need to compete for drafting positions. This local separation from opponents and minimal interference from external factors contribute to a higher level of reliability within the sport compared to track running events of similar durations (Mytton et al. 2014). Accordingly, swimmers show a very stable pacing pattern in 800 m and 1,500 m freestyle events. The majority of elite swimmers tend to utilize similar pacing patterns in these two events irrespective of gender and final placing (Lipińska et al. 2016; Robertson et al. 2009). Theoretically, the pre-set conditions for a swimming race could allow athletes to use a pre-determined pacing strategy regardless of opponents and type of competition. However, some swimmers may swim strategically to gain a tactical advantage or respond to a certain pacing behaviour of a competitor. Swimmers develop their own pacing templates through years of repeated practice and competitions (Foster et al. 2009). Highly experienced athletes show a very stable pacing pattern suggesting that pacing variability is likely to stem from individual swimmers and to a lesser extent from influence of competitors (Skorski et al. 2014b). However, by looking at the final stages of a race it becomes obvious that opponents have an effect on the end-spurt of a competitor, although this was not subject of investigations so far. Thus, further research is needed to determine the impact of an opponent on pacing behaviour in swimming performance.

Regarding the within reproducibility in swimming performance, a study by Skorski et al. showed that elite swimmers have a stable pacing pattern within one event (Skorski et al. 2014b). It is suggested that prior experience decreases variability as younger and more inexperienced swimmers show a less stable pacing pattern (Skorski et al. 2013). However, swimmers with less expertise may also be more susceptible to being influenced by their opponents' actions, resulting in deviations from their planned pacing strategy and greater segmental velocity variability. There is also evidence suggesting that better swimmers can maintain more consistent turn performance, particularly in the decisive latter stages of a race (Veiga et al. 2014).

When evaluating reproducibility in the context of competition, elite swimmers exhibit consistent pacing patterns between different competitions (Skorski et al. 2013; Skorski et al. 2014b). However, the finishing time varies along the season, where faster times are reported towards the main peak of the season (Neuloh et al. 2022). The average improvement of finishing time is between 0.2 to 1.0% in one season depending on the time gap between competitions (Pyne et al. 2004). It is shown that elite swimmers improve their finishing time approximately by 1% within a year leading up to the Olympics (Pyne et al. 2004). Skorski et al. reported a performance improvement of 1.2% from heat to final in elite swimmers with a smaller variability at the start compared to the end of the race (Skorski et al. 2014b). This could indicate that the progression from heat to final influences the pacing variability towards the end of the race, suggesting that better swimmers might hold back in the heat to conserve energy and only show their peak performance in the final.

2.5 Real versus simulated competitions

Simulated and real swimming competitions have been compared in the literature to examine the similarities and differences between the two settings. Simulated competitions aim to replicate the conditions and atmosphere of real competitions, albeit in a controlled training or research environment. This allows swimmers to practice their skills, test their pacing strategies, and prepare themselves for the intensity and pressure of an actual race. Whereas pacing patterns have mainly been investigated in real competitions, manipulating factors influencing the pacing pattern have only been studied in simulated races. The analysis of an opponent in swimming in a controlled environment has been neglected so far.

Generally, swimmers tend to exhibit similar pacing patterns, maintaining relatively consistent speeds throughout the race, regardless of whether it is a simulation or an actual competition (Skorski et al. 2013). However, it has been noted that in real competitions, there is often a subtle rise in velocity as swimmers approach the final stages of the race. This suggests that the presence of an opponent and the desire to achieve optimal performance and ranking in a competition may influence swimmers to a greater increase in speed towards the end. Despite these slight but potentially decisive differences in velocity, swimmers appear to select their pacing strategies based on prior experience. This suggests that swimmers develop their own individualized pacing templates over time, which they rely on during races. Simulated competitions can be valuable tools for swimmers to practice and refine their pacing behaviour, providing more opportunities for younger or less experienced swimmers to develop their pacing skills and improve their performance. While simulated competitions offer a controlled environment for training, real competitions introduce additional factors that cannot easily be replicated. The presence of an audience, the adrenaline rush, and the pressure to perform at one's best against equally skilled opponents contribute to the unique experience of a real competition. These external factors can have a substantial psychological impact on swimmers and may significantly impact on their pacing behaviour.

2.6 Virtual pacing assistance

Science and technology play a huge role in optimizing swimming performance. Despite aquatic conditions, progress has been made to provide pacing feedback. Some of the current devices available allow for real time feedback. This is important as swimmers may misjudge their swimming pace (Bächlin and Tröster 2012). Research showed that it is not an easy task especially for non-elite swimmers to control their pace by themselves (Altavilla et al. 2018). Thus, researchers have developed a variety of devices that aid swimmers in different facets of their training. Zatoń and Szczepan have developed a wireless communication device that enhances the quality and flow of verbal information between coaches and swimmers (Zatoń and Szczepan 2014). Additionally, a submerged timer has been utilized as a visual medium for information transmission in a pool (Pérez et al. 2009). The combination of communication techniques with swimmers, along with the evaluation of movement and physiological parameters, has been shown to effectively enhance athletic performance. Various devices, including Virtual Swim Trainer (Indico Technologies Torino, Italy), Lider (Kuca, Poland), GBK-Pacer (GBK-Electronics, Portugal), Pace2Swim (FADEUP Porto, Portugal), and SwimLead (Synerte, Poland) utilize a beam of light that travels along the bottom of a swimming pool to provide real-time reporting of swimming speed (Proteau and Isabelle 2002).

The implementation of virtual pacing technology in swimming presents a new and inventive method for improving training routines and overall performance results in aquatic settings. The methodology involves the application of advanced sensors and augmented reality technology to provide swimmers with immediate feedback and guidance. The implementation of virtual pacing assistance facilitates the maintenance of a consistent and efficient tempo among swimmers during their practice routines (Szczepan et al. 2016). The dissemination of insightful feedback to athletes concerning their performance empowers them to pinpoint deficient areas and subsequently modify their approach. Optimizing pacing behaviour can enable elite swimmers to enhance their energy utilization and make strategic decisions during races, ultimately pushing the boundaries of their performance. The use of virtual pacing assistance has become a crucial tool for individuals seeking to attain outstanding performance in the competitive swimming domain (Szczepan et al. 2016).

Despite numerous obstacles associated with quantifying the kinematic and physiological data of swimmers, there are several studies demonstrating the methodology for accomplishing this task while being submerged in water. For example, Ohgi employed a wrist-mounted accelerometer to quantify the level of fatigue experienced by swimmers (Ohgi 2002). In 2005, Davey et al. affixed a sensor to the hip region of swimmers for the purpose of quantifying their swimming strokes (Davey et al. 2005). The authors Callaway et al. and Slawson et al. utilized an accelerometer in their assessment of the four distinct swimming strokes (Callaway et al. 2009; Slawson et al. 2008). Bächlin and Tröster developed a model that utilizes accelerometers and proposed a methodology for measuring the overall efficiency of swimming (Bächlin and Tröster 2012). The system conducts an analysis of the swimmer's stroke rate, pace, technique, and subsequently compares them to the established ideal standards. Upon receiving feedback from their visual interface, such as smart goggles or a heads-up display, the swimmer can adjust their stroke and tempo accordingly. The utilization of a virtual pacing aid in swimming can enhance efficiency, reduce fatigue indirectly (through a more optimal pacing pattern), and optimize performance through optimal pacing by providing prompt feedback and personalized pacing data.

In the year 2015 Indico Technologies in Torino introduced the Virtual Swim Trainer (VST). This system incorporates a light feedback mechanism consisting of waterproof

LED lights positioned along the bottom of the pool, spanning 50 m in the middle of the swim lane. To secure the LED stripe, small weights can be placed approximately every 4-5 m. The Swim Session Creator software by Indico Technologies can be used to pre-program the lights and import it into the control panel (VST 17) of the VST. LED stripes can be programmed to ensure consistent pacing for each 50 m split time, aligning with the pool's length. Each turn is indicated by a stationary white light positioned 1.5 m before the wall, while a static white light situated 7 m after the wall indicates the break out after the push-off. The light feedback duration during turns is generally set at 1.5 seconds for spinning and 3.6 seconds for push-offs. These settings adhere to the standard options available in the VST system for competitive swimmers and align with previous research findings (Weimar et al. 2019; Morais et al. 2019).

3 End-spurt

The end-spurt in swimming is a phenomenon that occurs during the final stages of a race (Abbiss and Laursen 2008; Hołub et al. 2023). It is characterized by a surge in speed, which can give a swimmer a decisive advantage over their rivals. It is especially noticeable in competitions like the 400 m, 800 m, and 1,500 m freestyle, where swimmers must maintain a high level of effort and stamina for a prolonged period. Elite swimmers are not the only ones who exhibit an end-spurt; swimmers of all ages and levels of competition do (as long as they are motivated). With the right instruction and awareness, even inexperienced swimmers can mobilize their reserves and perform a significant end-spurt during practice sessions or regional competitions. The concept of the end-spurt pertains to the inclination of athletes to intensify their efforts, such as velocity and power output, as they approach the end of a physical task (Noakes 2012; Edwards and Polman 2013). A combination of physical stamina, mental concentration, and tactical execution define the end-spurt. Athletes frequently use their reserves during an end-spurt, pushing their physical and mental boundaries and giving it their all to cross the finish line or accomplish a particular performance outcome. Athletes may be able to surpass rivals, set records, or win a sporting event because of this final increase of effort, which frequently determines the outcome in competitive events.

The parabolic shaped pattern, as described by Edwards and Polman (Edwards and Polman 2013), consists of athletes initially reducing their velocity during the middle phase of a physical task, followed by a subsequent increase in effort towards the race completion. The phenomenon known as the end-spurt has been consistently observed and documented across various endurance sports. These domains include running races ranging from 1,600 m to 10 km (Tucker et al. 2006), rowing events of 2,000 m (Garland 2005; Muehlbauer et al. 2010), swimming distances of 400 m to 25 km (McGibbon et al. 2018; Veiga et al. 2019), and cycling (Foster et al. 2004). As an illustration, a conventional 1600 m running race participant would initiate the race with a heightened velocity during the initial lap, subsequently reducing their velocity in the second and third laps. However, they would then increase their velocity once more during the final lap, thereby exhibiting an end-spurt that conforms to a parabolic shaped pattern (Tucker et al. 2006).

It is advisable for athletes to effectively allocate their energy expenditure in a manner that optimizes the utilization of all available energetic resources, while avoiding premature fatigue and a decline in speed (St Clair Gibson and Noakes 2004). An untimely increase in power generation could potentially lead to a suboptimal level of work output, thereby hindering the ability to enhance speed during the end-spurt. Hence, it can be inferred that the endpoint and remaining distance exert a stable and uniform influence on pacing behaviour (Venhorst et al. 2018b). It appears that athletes engage in energy conservation strategies during the middle phase of a long-distance event, thereby gradually building confidence to effectively utilize their remaining capacity for a final burst of speed as reaching the finish line becomes more certain (St Clair Gibson et al. 2006). Interestingly, athletes perform their highest velocity precisely when they are expected to encounter the greatest degree of muscular fatigue, indicating access to a previously inaccessible energy reserve. It is suggested that once athletes get closer to the finishing line, motivation to increase swim velocity is elevated (Förster et al. 1998).

In general, performance advantage of an end-spurt contrasts with the inherent water resistance-related fluctuations in swim velocity (Morais et al. 2019). As a result, there's limited support for the notion of utilizing an end-spurt based solely on biomechanical and aerobic energy supply considerations. The high resistance of water implies that even minor changes in swim velocity can lead to a significant rise in energy expenditure, potentially causing premature fatigue (Barbosa et al. 2010). Although biomechanically and physiologically, an even-paced approach with minimal lap-to-lap variability is generally considered optimal for long-distance pool swimming (Barbosa et al. 2010; Morais et al. 2019), successful swimmers have consistently demonstrated the ability to execute an end-spurt in various events (Lipińska 2009; Lipinska et al. 2016; Mytton et al. 2015; Neuloh et al. 2020; Neuloh et al. 2022). The critical power model suggests that maintaining an even pacing pattern for most of the race distance maximizes aerobic energy contribution. The concept shows the relationship between power output or speed and duration of swimming, whereas the slope of the relationship (critical power output) is defined as the threshold of fatigue. The sustainable power output decreases in relation to exercise duration, ultimately reaching a plateau, while the curvature of this relationships represents the work capacity available above critical power (CP) (Jones 2017). Therefore, it is speculated that maintaining an even pacing pattern for the majority of the race distance is optimal for aerobic energy contribution, it could lead to conserving anaerobic capacity for a potential end-spurt (Toussaint et al. 1998).

It is plausible that the control of work rate by the brain might better explain the presence of an end-spurt. The brain governs power output by regulating motor unit recruitment through information about the race's endpoint, past race experiences, and feedback from environmental and metabolic conditions (St Clair Gibson et al. 2006). The end-spurt involves tapping into the finite anaerobic reserve, a strategy potentially riskier to deploy early in the race due to uncertainty about the necessary power output to complete the race (Pyne and Sharp 2014). As the race progresses and the endpoint becomes more certain, the brain may release a higher output in the final lap. The metabolic requirements for completing the race without premature fatigue become more predictable towards the race's conclusion (Emanuel 2019). In this context the comparison of an even paced race with an end-spurt and a completely even paced race, where the anaerobic reserve from an end-spurt is equally distributed over the whole race distance becomes interesting. The effect of such an aggressive even pacing with a shallower linear increase of RPE should be investigated in swimming and its influence on the end-spurt examined.

Although the end-spurt in swimming is a relevant performance factor, it has not yet received the deserved attention in the literature. The importance of performing an end-spurt as a tactical tool is sometimes overshadowed by the emphasis on endurance and keeping a high steady pace throughout a race. Being a relatively brief burst of speed, the end-spurt is sometimes disregarded as a negligible component of performance improvement. Thus, coaches may erroneously focus on aerobic capacity of athletes in longer pool races without giving the mobilization of anaerobic energy reserves the necessary attention. There seems to be a lack of appropriate training methods and approaches designed to maximize the athlete’s end-spurt. For example, continuous swimming or interval training, which largely focuses on aerobic endurance, are frequent focal points in traditional training science. Specific drills and workouts aimed at enhancing the explosive power and speed necessary for the end-spurt are not given enough attention (Neuloh et al. 2020). End-spurt in swimming is a phenomenon with enormous potential that is yet not fully appreciated by conventional training approaches. Swimmers can gain a competitive advantage, both emotionally and physically, by understanding the significance of a burst of speed, as an end-spurt or in a tactical situation with a competitor during a race. Athletes may maximize their performance and produce outstanding results by combining specific training activities and the end-spurt into racing plans. To achieve greater levels of success in this sport, coaches and swimmers should work to better comprehend, appreciate, and harness the power of the end-spurt.

4 Aims of the PhD-Thesis

The aim of this thesis was to examine end-spurt behaviour in long distance pool swimming. This work presents a novel End-Spurt Indicator (ESI), which can quantify end-spurt behaviour in swimming. It was used to analyse different effects of the end-spurt to get a better understanding of how it can influence swimming performance. In this regard, it tries to close the scientific gap on optimal pacing in the last stages of a race.

The aim of the first study was to design an ESI to quantify and analyse end-spurt behaviour in 800 m and 1,500 m freestyle swimming races from the last eight World Championships and five Olympic Games (1998–2016). The influence of distance, time point of competition, round and finishing position was investigated. The second study analysed the association of seasonal best time, distance, and different performance levels with end-spurt behaviour over one swimming season. Finally, the third study examined the effect of an end-spurt in association with an energetically more optimal even-paced pacing pattern and a race against a performance-matched opponent including its physiological underpinnings.

5 Study overview

5.1 Study 1: Analysis of end-spurt behaviour in elite 800 m and 1,500 m freestyle swimming

Neuloh, Joshua E., Skorski, Sabrina, Mauger, Lex, Hecksteden, Anne & Meyer, Tim. (2020); Eur J Sport Sci. 2021 Dec; 21 (12): 1628-1636. Published on 14 Dec 2020.

Introduction: An end-spurt has been typically described in head-to-head competitions, where success is determined by performing marginally better than other competitors to achieve a better finishing position. To better understand end-spurt behaviour in swimming the influence of distance, time point of competition, round and finishing position was analysed.

Methods: Race results in 800 m and 1,500 m freestyle swimming from the last eight World Championships and five Olympic Games (1998-2016) including 1,433 races and 528 swimmers were obtained. The end-spurt for each race was determined by means of an End-Spurt Indicator (ESI). The ESI was calculated by dividing the difference between the swim velocity of the last lap (SVLL) and the mean swim velocity of the middle part of the race (SVMP) by the respective individual standard deviation of SVMP. Subsequently, ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for distance, time point of competition, round and finishing position.

Results: An end-spurt was evident in most swims for both race distances. The mean change in swim velocity between the middle part of the race and the last lap was 0.06±0.02 m/s (1.2±0.2 s) in the 800 m and 0.07±0.02 m/s (1.5±0.2 s) in the 1,500 m. The finishing position within a race significantly affected the ESI ($P<.001$, t=7.28). Specifically, when analysing finals only, ESI was significantly greater in medallists (5.76; quantile: 3.61 and 8.06) compared to non-medallists (4.06; quantile: 1.83 and 6.82; $P=.001$). The between-subject standard deviation was 1.66 (CI: 1.42 to 1.97) with a relative variance component of 23%, while 77% of ESI variance remained unexplained.

Conclusion: This is the first study using a newly developed indicator of end-spurt behavior demonstrating that particularly medallists have a more pronounced end-spurt compared to non-medallists.

5.2 Study 2: The association of end-spurt behaviour with seasonal best time in long-distance freestyle pool swimming

Neuloh, Joshua E., Venhorst, Andreas, Forster, Sabrina, Mauger, Alexis & Meyer, Tim. (2022); Eur J Sport Sci. 2023 Apr ;23 (4): 469-477. Published on 6 Mar 2022.

Introduction: Most of the pacing literature has analysed end-spurts among elite swimmers without assessing their intra-seasonal best time progression. Although the ultimate goal at a competition is to beat all competitors and win the gold medal, it has been suggested that swimmers simultaneously may need to improve their seasonal best time to stay in contention for a medal.

Method: Race results in 800 m and 1,500 m pool freestyle swimming in the season 2018/2019 including 14,930 races and 2,650 swimmers were obtained. The end-spurt for each race was determined by means of an End-Spurt Indicator (ESI). Subsequently, ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for seasonal best time, distance, and performance level amongst others.

Results: In the 800 m and 1,500 m races swimmers showed a mean ESI of 2.08 (95% CI: 2.02 to 2.13) and 3.68 (95% CI: 3.59 to 3.76), respectively. There was a significant association between seasonal best time and ESI, with a better seasonal best time showing a greater ESI (F=70.5, P<.001, f^2=0.04). A significant effect on greater ESI was also observed for longer distance (F=1067.5, P<.001, f^2=0.06) and higher performance level (F=91.1, P<.001, f^2=0.02). Elite swimmers had a mean ESI of 5.47 (95% CI: 4.91 to 6.03), sub-elite swimmers of 3.74 (95% CI: 3.53 to 3.95) and competitive swimmers of 2.41 (95% CI: 2.37 to 2.46).

Conclusion: It was shown and quantified that competitive, sub-elite and elite swimmers execute an end-spurt in freestyle long-distance pool swimming races over

800 m and 1,500 m. A greater end-spurt was associated with better seasonal best time, higher performance level of the swimmer, longer race distance and being closer to the main peak of the season.

5.3 Study 3: The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming

Neuloh, Joshua E., Venhorst, Andreas, Forster, Sabrina & Meyer, Tim. (2024). The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming. Eur J Sport Sci. 2024; 1–8. Published on 8 Apr 2024.

Introduction: Swimmers typically perform an end-spurt in 1,500 m freestyle with the magnitude being affected by the anticipated finishing position and the importance of the race. Greater end-spurts have been reported in head-to-head races in which success is determined by marginally performing better than the opponents. In this case, swimmers seem to be able to mobilize greater fractions of anaerobic reserves to outsprint the competitor during the final meters.

Method: Twenty-seven competitive swimmers and triathletes were recruited and completed four 1,500 m freestyle trials: (i) familiarization time trial (FAM), (ii) self-paced time trial (STT), (iii) head-to-head competition time trial (CTT) and (iv) virtual pacing assistance time trial (FET). Eventually, 12 swimmers met the criteria for the CTT and FET to be included in the analysis. Changes in end-spurt behaviour, finishing time and physiological parameters (cortisol, noradrenaline, lactate, heart rate) were analysed using a linear mixed model with fixed effects for trials and a random effect for swimmer identity. A separate linear model was computed for competition outcome. The end-spurt for each race was determined by means of an End-Spurt-Indicator (ESI; ESI >0 greater end-spurt).

Results: Swimmers demonstrated a significantly greater ESI in CTT (+1,40; $P<.022$) and FET (+2,65; $P<.001$) compared to STT. Winners had a significantly greater ESI (+1.68) than losers in CTT ($P<.005$). Blood lactate concentration in CTT (+1.67 $mmol.l^{-1}$; $P<.001$) and FET (+1.01 $mmol.l^{-1}$; $P<.001$) was significantly higher than in STT.

Conclusion: Swimmers seem to experience a positive stimulus from a real opponent and virtual pacing assistance and can execute a greater end-spurt due to a higher metabolic tolerance level. A head-to-head race is won by a greater end-spurt, although the loser is experiencing a similar metabolic disturbance as the winner. It is speculated that the presence of a real opponent leads to access to an anaerobic energy reserve through a command based on the motivational stimulus of a head-to-head race.

6 Discussion of findings

Swimmers have been observed to execute an end-spurt in 800 m (Lipińska et al. 2016; Lipińska 2009; Nikolaidis and Knechtle 2017) and 1,500 m (Lipinska et al. 2016) races. However, so far, such studies did not contain a clear definition based on an explicit statistical rationale for end-spurt behaviour and only accounted for overall statistical significance, when analysing the effect on a variety of different factors. Further, the main portion of the existing pacing literature has focused on analysing end-spurts within the context of elite swimmers (Hecksteden et al. 2015; Konings and Hettinga 2020; Lipińska 2009; Mytton et al. 2015; Neuloh et al. 2020), but without considering their seasonal best times and different performance levels. While the primary objective in a competition is to outperform all rivals and secure a gold medal, it has been proposed that swimmers might also need to enhance their seasonal best times to remain competitive for medals (Pyne et al. 2004). Additionally, when a competitor is present, the emphasis often shifts from executing an energetically efficient to an even-paced pacing pattern to attain the best medal placing (Foster et al. 1994; Mauger et al. 2012; Abbiss and Laursen 2008). This scenario holds relevance in significant races such as World Championships or the Olympic Games, where success is primarily measured by the medal's colour.

Therefore, this PhD-Thesis aimed to design an ESI to quantify end-spurt behaviour and analyse different effects such as distance, time point of competition, round, finishing position, different performance levels, seasonal best time, performance outcome and the effect of an opponent and the related physiological underpinnings.

The first study in this thesis (Neuloh et al. 2020) was to analyse end-spurt behaviour in elite 800 m and 1,500 m freestyle swimming by applying and evaluating the ESI to investigate the influence of potential determinants such as distance, time point of competition, round, and race ranking. The retrospective analysis of elite competitions during 1998-2017 revealed that swimmers seem to consistently execute an end-spurt in both the 800 m and 1,500 m races. To the authors´ knowledge, this was the first attempt to quantify an end-spurt statistically and to estimate potential influencing factors. The current results expand on previous research, which mainly assessed mean differences within the velocity pattern (Lipińska et al. 2016; Lipinska et al. 2016), by developing an indicator that considers different variance components as well as within-subject variability during the middle part of the race. The presence of an end-spurt in the 800 m and 1,500 m is in accordance with previous research (Lipińska et al. 2016; Lipinska et al. 2016) and expectations. In a recent review, Mc Gibbon et al. summarised that similar to middle-distance events, parabolic pacing is typically observed in freestyle events of 800 m or above with the highest swimming velocity at the start and the end of the race (McGibbon et al. 2018). Lipinska et al. reported a 3.6% and 5.8% faster last lap compared to the middle part in 800 m and 1,500 m competitions over a period of 13 years (Lipińska et al. 2016; Lipinska et al. 2016). Whilst the change in pace in the 800 m was like our analysis, the last lap in the 1,500 m was only 4.2% faster. This discrepancy in the 1,500 m could be related to the fact that Lipinska et al. only included the fastest race at a competition into their analysis, leaving out performances in heats or slower races (Lipińska et al. 2016).

Moreover, the first study of this thesis (Neuloh et al. 2020) also examined the effect of finishing position. The association of ESI and finishing position was significant. Specifically, in finals the ESI was significantly greater in medallists compared to non-medallists. The observation that medal placement was significantly associated with ESI aligns with other research. For instance, Lopez-Belmonte et al. showed that the last lap was the fastest compared to the middle part of the race in 400 m, 800 m and 1,500 m freestyle swimming and medallist had a higher coefficient of variation and performance progression versus non-medallists from heat to final (López-Belmonte et al. 2021). Mytton et al. also observed that medal winners exhibited a more pronounced surge in speed during the concluding phase of a 400 m freestyle race in comparison to non-medallists (Mytton et al. 2015; Neuloh et al. 2024). This discrepancy seemed to be the key factor distinguishing those who won medals from those who didn't. On the other hand, it is plausible that some non-medallists may not have executed an end-spurt due to diminished prospects of winning a medal. Therefore, elite athletes are better equipped to mobilize their reserve capacity to a greater extent for the end-spurt. Conversely, swimmers with lower fitness levels might already be pushing themselves to their limits to keep up with faster competitors (i.e., medallists) during the midsection of the race. One possible explanation is that medallists experience fewer physiological disruptions during the race's initial and middle stages, as they use fractionally less of their higher capacity compared to non-medallists. As a result, they may maintain a greater anaerobic reserve for the decisive end-spurt (Mytton et al. 2015).

The second study in this thesis (Neuloh et al. 2022) aimed to measure and examine the characteristics of the end-spurt in pool-based swimming competitions, along with its correlation to factors such as seasonal best time. It was found that the ESI increased from the Pre-Season over the Main-Season to the Main-Peak-Season (Neuloh et al. 2022). In broader terms, a more pronounced end-spurt correlated with swimmers achieving faster seasonal best times. Specifically, the end-spurt was more prominent among swims falling within the first to third categories of personal seasonal best times, in contrast to those categorized as fourth or beyond. In the first study of this thesis (Neuloh et al. 2020), it was observed that there is a connection between the magnitude of the end-spurt and finishing position among elite swimmers. This study highlighted that medal-winning athletes displayed a more pronounced end-spurt compared to those who did not win medals (Neuloh et al. 2020). Collectively, these findings suggest that swimmers perform an end-spurt not only to contend for medals in major sporting events like the Olympic Games or World Championships but also to potentially enhance their seasonal best times. Nevertheless, it is important to acknowledge that aiming for new seasonal best times during competitions is not always the primary objective for swimmers. Their central focus often lies in surpassing all competitors to secure the gold medal (Mujika et al. 2019). As a result, it is reasonable to infer that a potent end-spurt significantly contributes to securing medals, which secondarily may facilitate improvements in seasonal best times. However, it is worth noting that winning a medal does not consistently align with achieving a new seasonal best time, as these two objectives may not always coincide. In a different investigation, it was discovered that swimmers could potentially experience a moderate enhancement in their overall performance by reducing their swim velocity at the start of the race (Lipińska 2009). This strategy allows to conserve the finite anaerobic energy capacity to be later employed in the end-spurt during the decisive moments of swimming competitions. Consequently, it is suggested that a more pronounced end-spurt aligns with improved finishing positions and better finishing times.

In the third study of this thesis (Neuloh et al. 2024), it was found that swimmers execute a greater end-spurt in the presence of an opponent compared to self-pacing and this was associated with a larger mobilization of anaerobic reserves as indicated by greater blood lactate concentrations. The discovery that swimmers utilize a more pronounced end-spurt during head-to-head competitions aligns with the findings in the first study of this thesis (Neuloh et al. 2020). This earlier study established a link between the end-spurt, finishing position, and medal-winning performance, particularly within head-to-head races (Neuloh et al. 2022). This trend of a heightened end-spurt due to the presence of an opponent has now been established in swimming and also aligns with findings in other sports (Williams et al. 2015; Wilmore 1968; Tomazini et al. 2015). The consensus is that athletes tend to perform better in head-to-head contests in cycling (Williams et al. 2015; Wilmore 1968) and running (Tomazini et al. 2015) compared to self-paced exercises, indicating that head-to-head competitions serve as motivational trigger that impacts performance and pacing behaviour including the end-spurt. On the contrary, it is recognized that an even pacing pattern is considered energetically optimal in swimming (Thompson et al. 2004), due to the high resistive forces of water. Even small changes in swim velocity are critical, as any increase in velocity raises energy expenditure substantially (Lipinska et al. 2016). The contrast between real-world observations and theoretical models might be resolved by examining energy expenditure during simulated competitions. Foster et al. demonstrated that cyclists conserve some anaerobic energy during races, highlighting that athletes strategically manage their energy resources to optimize performance (Foster et al. 2003). In the context of the third study in this thesis (Neuloh et al. 2024), where two swimmers competed head-to-head with the goal of outsprinting the opponent in the final 200 m to secure victory, both athletes were motivated to transition from even pacing to an end-spurt strategy. This transition could be facilitated by a larger mobilization of the available anaerobic energy reserves, as indicated by elevated blood lactate concentrations.

Another layer of support for the motivational aspect driving a more substantial end-spurt lies in the observation that winners displayed a more pronounced end-spurt compared to losers, despite similar metabolic disturbances (Neuloh et al. 2024). In the context of a head-to-head competition, the primary objective is to outperform the opponent, therefore no improvement in finishing time was found. It is suggested that there is an anaerobic energy reserve that could potentially be accessed through motivation-triggered commands, as previously suggested by Corbett et al. (Corbett et al. 2012). Within this framework, it is understood that winners exhibit heightened motivation due to leading (Iso-Ahola and Dotson 2016), while losers experience a dampened motivation owing to the prospect of losing the race, which eventually enables winners to tap into their anaerobic reserves more extensively. The result is a more pronounced end-spurt without a competitor. These findings align with two cycling studies conducted over distances of 16.1 km (Williams et al. 2015) and 70 km (Venhorst et al. 2018b). Both studies demonstrated a delineation between perceived effort and performance outcome. It can be speculated that winners exhibited an upsurge in affect and motivation in contrast to their individual trials, simultaneously diminishing their attention to or intensity of perceived effort. In contrast, losers demonstrated a negative affective state and a shift in mindset indicative of disengaging from their initial goals (Williams et al. 2015; Venhorst et al. 2018b). These distinct responses correspond with variations in endocrinological stress responses and performance outcomes (Venhorst et al. 2018a). There appears to exist an intricate interplay between exercise intensity and affective-motivational states (Corbett et al. 2012). The elevation in anaerobic energy production seems to be rooted in the notion of a metabolic reserve that is centrally regulated. This underscores the potential influence of psychological factors in the regulation of exercise intensity, related to the dynamic interaction between interoceptive and cognitive elements within affective-motivational states (Ekkekakis et al. 2011).

Coaches and sports scientists should acknowledge that an end-spurt is a prevalent tactic among most swimmers, especially among those who secure medals. A greater end-spurt was associated with better seasonal best time, higher performance level of the swimmer, longer race distance, and being closer to the main peak of the season. Swimmers appear to derive a positive stimulus from an opponent, enabling them to execute a more pronounced end-spurt by increasing their metabolic tolerance level. Notably, even though both winners and losers in a head-to-head race experience comparable metabolic disturbance, the race is often decided by the greater end-spurt executed by the winner. It is conjectured that the presence of an opponent triggers access to an anaerobic energy reserve, facilitated through a command activated by the motivational stimulus inherent to a head-to-head competition.

7 Future research and directions

The ongoing aim remains to find the most effective pacing behaviour in swimming and to improve overall performance. The investigation of end-spurt behaviour is the first step to get a better understanding on optimal pacing. However, further steps will have to follow.

The design of the ESI allows researcher to investigate the end-spurt with a clear statistical rational. It was shown that swimmers generally execute an end-spurt and medallists in particular show a greater end-spurt compared to non-medallists. A greater end-spurt is also associated with a better finishing time. This is also the case when they swim against an opponent or receive virtual pacing assistance. It seems that swimmers experience a positive stimulus from a performance-matched opponent and virtual pacing assistance due to a higher metabolic tolerance level. A head-to-head race is won by a greater end-spurt, although losers were experiencing a similar metabolic disturbance compared to winners. In this thesis, it is speculated that the presence of a performance-matched opponent facilitates the mobilization of anaerobic energy reserves through a central command based on the motivational stimulus of a head-to-head race.

For future research, it is suggested to account for individual differences in physiological and psychological factors to gain a better understanding of why a performance-matched opponent facilitates a greater end-spurt in swimming. Although the access to swimmers for extensive research is limited, it is recommended to increase participants for future studies and also investigate different race distances.

8 References

Abbiss, Chris R.; Laursen, Paul B. (2008): Describing and understanding pacing strategies during athletic competition. In Sports medicine (Auckland, N.Z.) 38 (3), pp. 239–252. DOI: 10.2165/00007256-200838030-00004.

Altavilla, Cesare; Cejuela, Roberto; Caballero-Pérez, Pablo (2018): Effect of Different Feedback Modalities on Swimming Pace: Which Feedback Modality is Most Effective? In Journal of human kinetics 65, pp. 187–195. DOI: 10.2478/hukin-2018-0026.

Amann, Markus (2011): Central and peripheral fatigue: interaction during cycling exercise in humans. In Medicine and science in sports and exercise 43 (11), pp. 2039–2045. DOI: 10.1249/MSS.0b013e31821f59ab.

Ament, Willem (2001): Exercise and Fatigue. Zugl.: Gronningen, Univ., Diss., 2001.

Azevedo, Rafael de Almeida; Silva-Cavalcante, Marcos David; Lima-Silva, Adriano Eduardo; Bertuzzi, Romulo (2021): Fatigue development and perceived response during self-paced endurance exercise: state-of-the-art review. In European journal of applied physiology 121 (3), pp. 687–696. DOI: 10.1007/s00421-020-04549-5.

Bächlin, Marc; Tröster, Gerhard (2012): Swimming performance and technique evaluation with wearable acceleration sensors. In Pervasive and Mobile Computing 8, pp. 68–81. DOI: 10.1016/j.pmcj.2011.05.003.

Barbosa, Tiago M.; Bragada, José A.; Reis, Víctor M.; Marinho, Daniel A.; Carvalho, Carlos; Silva, António J. (2010): Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. In Journal of science and medicine in sport 13 (2), pp. 262–269. DOI: 10.1016/j.jsams.2009.01.003.

Barden, John M.; Barber, Mike V. (2022): The Effect of Breathing Laterality on Hip Roll Kinematics in Submaximal Front Crawl Swimming. In Sensors (Basel, Switzerland) 22 (6). DOI: 10.3390/s22062324.

Batchelor, George Keith (1999): An introduction to fluid dynamics. 2nd pbk. ed. Cambridge, U.K and New York, NY: Cambridge University Press (Cambridge mathematical library). Available online at http://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=511005.

Callaway, Andrew J.; Jon E Cobb; Ian Jones (2009): A Comparison of Video and Accelerometer Based Approaches Applied to Performance Monitoring in Swimming. In International Journal of Sports Science & Coaching 4 (1), pp. 139–153. DOI: 10.1260/1747-9541.4.1.139.

Corbett, Jo; Barwood, Martin J.; Ouzounoglou, Alex; Thelwell, Richard; Dicks, Matthew (2012): Influence of competition on performance and pacing during cycling exercise. In Medicine and science in sports and exercise 44 (3), pp. 509–515. DOI: 10.1249/MSS.0b013e31823378b1.

Coyle, E. F. (1999): Physiological determinants of endurance exercise performance. In Journal of science and medicine in sport 2 (3), pp. 181–189. DOI: 10.1016/s1440-2440(99)80172-8.

Davey, Neil; Shephard, Megan; James, Daniel (2005): An accelerometer based system for elite athlete swimming performance analysis. In Proceedings of SPIE - The International Society for Optical Engineering 5649. DOI: 10.1117/12.582264.

Edwards, A. M.; Polman, R. C. J. (2013): Pacing and awareness: brain regulation of physical activity. In Sports medicine (Auckland, N.Z.) 43 (11), pp. 1057–1064. DOI: 10.1007/s40279-013-0091-4.

Ekkekakis, Panteleimon; Parfitt, Gaynor; Petruzzello, Steven J. (2011): The pleasure and displeasure people feel when they exercise at different intensities: decennial update and progress towards a tripartite rationale for exercise intensity prescription. In Sports medicine (Auckland, N.Z.) 41 (8), pp. 641–671. DOI: 10.2165/11590680-000000000-00000.

Emanuel, Aviv (2019): Perceived Impact as the Underpinning Mechanism of the End-Spurt and U-Shape Pacing Patterns. In Frontiers in psychology 10, p. 1082. DOI: 10.3389/fpsyg.2019.01082.

Esteve-Lanao, Jonathan; Lucia, Alejandro; deKoning, Jos J.; Foster, Carl (2008): How do humans control physiological strain during strenuous endurance exercise? In PLoS ONE 3 (8), e2943. DOI: 10.1371/journal.pone.0002943.

Förster, J.; Higgins, E. T.; Idson, L. C. (1998): Approach and avoidance strength during goal attainment: regulatory focus and the "goal looms larger" effect. In Journal of personality and social psychology 75 (5), pp. 1115–1131. DOI: 10.1037//0022-3514.75.5.1115.

Foster, C.; deKoning, J. J.; Hettinga, F.; Lampen, J.; Dodge, C.; Bobbert, M.; Porcari, J. P. (2004): Effect of competitive distance on energy expenditure during simulated competition. In International journal of sports medicine 25 (3), pp. 198–204. DOI: 10.1055/s-2003-45260.

Foster, C.; Hendrickson, K. J.; Peyer, K.; Reiner, B.; deKoning, J. J.; Lucia, A. et al. (2009): Pattern of developing the performance template. In British journal of sports medicine 43 (10), pp. 765–769. DOI: 10.1136/bjsm.2008.054841.

Foster, C.; Koning, Jos J. de; Hettinga, Floor; Lampen, Joanne; La Clair, Kerry L.; Dodge, Christopher et al. (2003): Pattern of energy expenditure during simulated competition. In Medicine and science in sports and exercise 35 (5), pp. 826–831. DOI: 10.1249/01.MSS.0000065001.17658.68.

Foster, C.; Schrager, M.; Snyder, A. C.; Thompson, N. N. (1994): Pacing strategy and athletic performance. In Sports medicine (Auckland, N.Z.) 17 (2), pp. 77–85. DOI: 10.2165/00007256-199417020-00001.

Foster, C.; Snyder, A. C.; Thompson, N. N.; Green, M. A.; Foley, M.; Schrager, M. (1993): Effect of pacing strategy on cycle time trial performance. In Medicine and science in sports and exercise 25 (3), pp. 383–388.

Garland, S. W. (2005): An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing. In British journal of sports medicine 39 (1), pp. 39–42. DOI: 10.1136/bjsm.2003.010801.

Hecksteden, Anne; Kraushaar, Jochen; Scharhag-Rosenberger, Friederike; Theisen, Daniel; Senn, Stephen; Meyer, Tim (2015): Individual response to exercise training - a statistical perspective. In Journal of applied physiology (Bethesda, Md. : 1985) 118 (12), pp. 1450–1459. DOI: 10.1152/japplphysiol.00714.2014.

Hołub, Maciej; Prajzner, Arkadiusz; Stanula, Arkadiusz (2023): Pacing Strategy Models in 1500 m Male Freestyle Long-Course Swimming on the Basis of the All-

Time Ranking. In International journal of environmental research and public health 20 (6). DOI: 10.3390/ijerph20064809.

Horstman, D. H.; Morgan, W. P.; Cymerman, A.; Stokes, J. (1979): Perception of effort during constant work to self-imposed exhaustion. In Perceptual and motor skills 48 (3 Pt 2), pp. 1111–1126. DOI: 10.2466/pms.1979.48.3c.1111.

Iso-Ahola, Seppo E.; Dotson, Charles O. (2016): Psychological Momentum-A Key to Continued Success. In Frontiers in psychology 7, p. 1328. DOI: 10.3389/fpsyg.2016.01328.

Jones, Andrew M. (2017): The ‘Critical Power’ Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. In Sports medicine 47 (1), pp. 65–78. DOI: 10.1007/s40279-017-0688-0.

Koning, Jos J. de; Foster, Carl; Bakkum, Arjan; Kloppenburg, Sil; Thiel, Christian; Joseph, Trent et al. (2011): Regulation of pacing strategy during athletic competition. In PLoS ONE 6 (1), e15863. DOI: 10.1371/journal.pone.0015863.

Konings, Marco J.; Hettinga, Florentina J. (2020): Preexercise Cycling Protocol Alters Pacing Behavior in Competitive Time Trials. In International journal of sports physiology and performance, pp. 1–6. DOI: 10.1123/ijspp.2019-0763.

Lara, Beatriz; Del Coso, Juan (2021): Pacing Strategies of 1500 m Freestyle Swimmers in the World Championships According to Their Final Position. In International journal of environmental research and public health 18 (14). DOI: 10.3390/ijerph18147559.

Lipinska, Patrycja; Allen, Sian V.; Hopkins, Will G. (2016): Relationships Between Pacing Parameters and Performance of Elite Male 1500-m Swimmers. In International journal of sports physiology and performance 11 (2), pp. 159–163. DOI: 10.1123/ijspp.2015-0117.

Lipińska, Patrycja (2009): Kinematic Tactics in the Women’s 800 m Freestyle Swimming Final at the Beijing 2008 Olympic Games. In Baltic Journal of Health and Physical Activity 1. DOI: 10.2478/v10131-009-0010-0.

Lipińska, Patrycja; Allen, Sian V.; Hopkins, Will G. (2016): Modeling parameters that characterize pacing of elite female 800-m freestyle swimmers. In European journal of sport science 16 (3), pp. 287–292. DOI: 10.1080/17461391.2015.1013996.

López-Belmonte, Óscar; Párraga, Ana; Ruiz-Navarro, Jesús; Cuenca-Fernández, Francisco; González-Ponce, Ángela; Arellano, Raul (2021): Pacing profiles, variability and progression in 400, 800 and 1500-m freestyle swimming events at the 2021 European Championship. In International Journal of Performance Analysis in Sport 22, pp. 1–12. DOI: 10.1080/24748668.2021.2010318.

Marcora, Samuele M. (2008): Do we really need a central governor to explain brain regulation of exercise performance? In European journal of applied physiology 104 (5), 929-31; author reply 933-5. DOI: 10.1007/s00421-008-0818-3.

Mattern, C. O.; Kenefick, R. W.; Kertzer, R.; Quinn, T. J. (2001): Impact of starting strategy on cycling performance. In International journal of sports medicine 22 (5), pp. 350–355. DOI: 10.1055/s-2001-15644.

Mauger, Alexis R. (2014): Factors affecting the regulation of pacing: current perspectives. In Open access journal of sports medicine 5, pp. 209–214. DOI: 10.2147/OAJSM.S38599.

Mauger, Alexis R.; Neuloh, Joshua; Castle, Paul C. (2012): Analysis of pacing strategy selection in elite 400-m freestyle swimming. In Medicine and science in sports and exercise 44 (11), pp. 2205–2212. DOI: 10.1249/MSS.0b013e3182604b84.

McGibbon, Katie E.; Pyne, D. B.; Shephard, M. E.; Thompson, K. G. (2018): Pacing in Swimming: A Systematic Review. In Sports medicine (Auckland, N.Z.) 48 (7), pp. 1621–1633. DOI: 10.1007/s40279-018-0901-9.

McGibbon, Katie E.; Pyne, David B.; Heidenreich, Laine E.; Pla, Robin (2021): A Novel Method to Characterize the Pacing Profile of Elite Male 1500-m Freestyle Swimmers. In International journal of sports physiology and performance 16 (6), pp. 818–824. DOI: 10.1123/ijspp.2020-0375.

Menting, Stein Gerrit Paul; Edwards, Andrew Mark; Hettinga, Florentina; Elferink-Gemser, Marije Titia (2022): Pacing Behaviour Development and Acquisition: A Systematic Review. In Sports medicine - open 8 (1), pp. 1–17. DOI: 10.1186/s40798-022-00540-w.

Menting, Stein Gerrit Paul; Elferink-Gemser, Marije Titia; Huijgen, Barbara Catharina; Hettinga, Florentina Johanna (2019): Pacing in lane-based head-to-head competitions: A systematic review on swimming. In Journal of sports sciences 37 (20), pp. 2287–2299. DOI: 10.1080/02640414.2019.1627989.

Morais, Jorge E.; Marinho, Daniel A.; Arellano, Raul; Barbosa, Tiago M. (2019): Start and turn performances of elite sprinters at the 2016 European Championships in swimming. In Sports biomechanics 18 (1), pp. 100–114. DOI: 10.1080/14763141.2018.1435713.

Muehlbauer, Thomas; Panzer, Stefan; Schindler, Christian (2010): Pacing pattern and speed skating performance in competitive long-distance events. In Journal of strength and conditioning research 24 (1), pp. 114–119. DOI: 10.1519/JSC.0b013e3181c6a04a.

Mujika, Iñigo; Villanueva, Luis; Welvaert, Marijke; Pyne, David B. (2019): Swimming Fast When It Counts: A 7-Year Analysis of Olympic and World Championships Performance. In International journal of sports physiology and performance 14 (8), pp. 1132–1139. DOI: 10.1123/ijspp.2018-0782.

Mytton, Graham J.; Archer, David T.; St Clair Gibson, Alan; Thompson, Kevin G. (2014): Reliability and stability of performances in 400-m swimming and 1500-m running. In International journal of sports physiology and performance 9 (4), pp. 674–679. DOI: 10.1123/ijspp.2013-0240.

Mytton, Graham J.; Archer, David T.; Turner, Louise; Skorski, Sabrina; Renfree, Andrew; Thompson, Kevin G.; St Clair Gibson, Alan (2015): Increased variability of lap speeds: differentiating medalists and nonmedalists in middle-distance running and swimming events. In International journal of sports physiology and performance 10 (3), pp. 369–373. DOI: 10.1123/ijspp.2014-0207.

Naemi, Roozbeh; Easson, William J.; Sanders, Ross H. (2010): Hydrodynamic glide efficiency in swimming. In Journal of science and medicine in sport 13 (4), pp. 444–451. DOI: 10.1016/j.jsams.2009.04.009.

Neuloh, Joshua E.; Skorski, Sabrina; Mauger, Lex; Hecksteden, Anne; Meyer, Tim (2020): Analysis of end-spurt behaviour in elite 800-m and 1500-m freestyle swimming. In European journal of sport science, pp. 1–9. DOI: 10.1080/17461391.2020.1851772.

Neuloh, Joshua E.; Venhorst, Andreas; Forster, Sabrina; Mauger, Alexis R.; Meyer, Tim (2022): The association of end-spurt behaviour with seasonal best time in long-distance freestyle pool swimming. In European journal of sport science, pp. 1–9. DOI: 10.1080/17461391.2022.2043943.

Neuloh, Joshua E.; Venhorst, Andreas; Skorski, Sabrina; Meyer, Tim (2024): The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming. In European journal of sport science. DOI: 10.1002/ejsc.12102.

Nikolaidis, Pantelis T.; Knechtle, Beat (2017): Pacing in age-group freestyle swimmers at The XV FINA World Masters Championships in Montreal 2014. In Journal of sports sciences 35 (12), pp. 1165–1172. DOI: 10.1080/02640414.2016.1213412.

Noakes, T. D. (2008): Rating of perceived exertion as a predictor of the duration of exercise that remains until exhaustion. In British journal of sports medicine 42 (7), pp. 623–624.

Noakes, T. D.; St Clair Gibson, A. (2004): Logical limitations to the "catastrophe" models of fatigue during exercise in humans. In British journal of sports medicine 38 (5), pp. 648–649. DOI: 10.1136/bjsm.2003.009761.

Noakes, Timothy (1997): 1996 J.B. Wolffe Memorial Lecture. Challenging beliefs: ex Africa semper aliquid novi. In Medicine and science in sports and exercise 29, pp. 571–590.

Noakes, Timothy David (2012): Fatigue is a Brain-Derived Emotion that Regulates the Exercise Behavior to Ensure the Protection of Whole Body Homeostasis. In Frontiers in physiology 3, p. 82. DOI: 10.3389/fphys.2012.00082.

Ohgi, Y. (2002): Microcomputer-based acceleration sensor device for sports biomechanics -stroke evaluation by using swimmer’s wrist acceleration. In Proceedings of IEEE Sensors 1, 699-704 vol.1.

Pérez, Pedro; Llana, Salvador; Brizuela, Gabriel; Encarnación, Alberto (2009): Effects of three feedback conditions on aerobic swim speeds. In Journal of sports science & medicine 8 (1), pp. 30–36.

Proteau, Luc; Isabelle, Geneviève (2002): On the role of visual afferent information for the control of aiming movements toward targets of different sizes. In Journal of motor behavior 34 (4), pp. 367–384. DOI: 10.1080/00222890209601954.

Pyne, David; Trewin, Cassie; Hopkins, William (2004): Progression and variability of competitive performance of Olympic swimmers. In Journal of sports sciences 22 (7), pp. 613–620. DOI: 10.1080/02640410310001655822.

Pyne, David B.; Sharp, Rick L. (2014): Physical and energy requirements of competitive swimming events. In International journal of sport nutrition and exercise metabolism 24 (4), pp. 351–359. DOI: 10.1123/ijsnem.2014-0047.

Robertson, Eileen; Pyne, David; Hopkins, Will; Anson, Judith (2009): Analysis of lap times in international swimming competitions. In Journal of sports sciences 27 (4), pp. 387–395. DOI: 10.1080/02640410802641400.

Skorski, S.; Faude, O.; Rausch, K.; Meyer, T. (2013): Reproducibility of pacing profiles in competitive swimmers. In International journal of sports medicine 34 (2), pp. 152–157. DOI: 10.1055/s-0032-1316357.

Skorski, Sabrina; Faude, Oliver; Abbiss, Chris R.; Caviezel, Seraina; Wengert, Nina; Meyer, Tim (2014a): Influence of pacing manipulation on performance of juniors in simulated 400-m swim competition. In International journal of sports physiology and performance 9 (5), pp. 817–824. DOI: 10.1123/ijspp.2013-0469.

Skorski, Sabrina; Faude, Oliver; Caviezel, Seraina; Meyer, Tim (2014b): Reproducibility of pacing profiles in elite swimmers. In International journal of sports physiology and performance 9 (2), pp. 217–225. DOI: 10.1123/ijspp.2012-0258.

Slawson, Sian; Justham, Laura; West, Andrew; Conway, Paul; Caine, Mike; Harrison, Robert; Estivalet, Margaret (2008): Accelerometer Profile Recognition of Swimming Strokes (P17). In, vol. 7, pp. 81–87.

Smits, Benjamin L. M.; Pepping, Gert-Jan; Hettinga, Florentina J. (2014): Pacing and decision making in sport and exercise: the roles of perception and action in the regulation of exercise intensity. In Sports medicine (Auckland, N.Z.) 44 (6), pp. 763–775. DOI: 10.1007/s40279-014-0163-0.

St Clair Gibson, A.; Noakes, T. D. (2004): Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. In British journal of sports medicine 38 (6), pp. 797–806. DOI: 10.1136/bjsm.2003.009852.

St Clair Gibson, Alan; Lambert, Estelle V.; Rauch, Laurie H. G.; Tucker, Ross; Baden, Denise A.; Foster, Carl; Noakes, Timothy D. (2006): The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. In Sports medicine (Auckland, N.Z.) 36 (8), pp. 705–722. DOI: 10.2165/00007256-200636080-00006.

Stone, Mark Robert; Thomas, Kevin; Wilkinson, Michael; Jones, Andrew M.; St Clair Gibson, Alan; Thompson, Kevin G. (2012): Effects of deception on exercise performance: implications for determinants of fatigue in humans. In Medicine and science in sports and exercise 44 (3), pp. 534–541. DOI: 10.1249/MSS.0b013e318232cf77.

Swart, J.; Lamberts, R. P.; Lambert, M. I.; Lambert, E. V.; Woolrich, R. W.; Johnston, S.; Noakes, T. D. (2009): Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. In British journal of sports medicine 43 (10), pp. 775–781. DOI: 10.1136/bjsm.2008.056036.

Szczepan, Stefan; Zatoń, Krystyna; Klarowicz, Andrzej (2016): The Effect of Concurrent Visual Feedback on Controlling Swimming Speed. In Polish Journal of Sport and Tourism 23. DOI: 10.1515/pjst-2016-0001.

Thompson, Kevin G.; MacLaren, Donald P. M.; Lees, Adrian; Atkinson, Greg (2004): The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. In Journal of sports sciences 22 (2), pp. 149–157. DOI: 10.1080/02640410310001641467.

Tomazini, Fabiano; Pasqua, Leonardo A.; Damasceno, Mayara V.; Silva-Cavalcante, Marcos D.; Oliveira, Fernando R. de; Lima-Silva, Adriano E.; Bertuzzi, Rômulo (2015): Head-to-head running race simulation alters pacing strategy, performance, and mood state. In Physiology & behavior 149, pp. 39–44. DOI: 10.1016/j.physbeh.2015.05.021.

Toussaint, H. M.; Wakayoshi, K.; Hollander, A. P.; Ogita, F. (1998): Simulated front crawl swimming performance related to critical speed and critical power. In Medicine and science in sports and exercise 30 (1), pp. 144–151. DOI: 10.1097/00005768-199801000-00020.

Toussaint, Huub M.; Truijens, Martin (2006): Power requirements for swimming a world-record 50-m front crawl. In International journal of sports physiology and performance 1 (1), pp. 61–64. DOI: 10.1123/ijspp.1.1.61.

Tucker, R.; Noakes, T. D. (2009): The physiological regulation of pacing strategy during exercise: a critical review. In British journal of sports medicine 43 (6), e1. DOI: 10.1136/bjsm.2009.057562.

Tucker, Ross; Lambert, Michael I.; Noakes, Timothy D. (2006): An analysis of pacing strategies during men's world-record performances in track athletics. In International journal of sports physiology and performance 1 (3), pp. 233–245.

Ulmer, H. V. (1996): Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. In Experientia 52 (5), pp. 416–420. DOI: 10.1007/BF01919309.

Veiga, Santiago; Mallo, Javier; Navandar, Archit; Navarro, Enrique (2014): Effects of different swimming race constraints on turning movements. In Human movement science 36, pp. 217–226. DOI: 10.1016/j.humov.2014.04.002.

Veiga, Santiago; Rodriguez, Luis; González-Frutos, Pablo; Navandar, Archit (2019): Race Strategies of Open Water Swimmers in the 5-km, 10-km, and 25-km Races of the 2017 FINA World Swimming Championships. In Frontiers in psychology 10, p. 654. DOI: 10.3389/fpsyg.2019.00654.

Venhorst, Andreas; Micklewright, Dominic; Noakes, Timothy D. (2018a): Modelling the process of falling behind and its psychophysiological consequences. In British journal of sports medicine 52 (23), pp. 1523–1528. DOI: 10.1136/bjsports-2017-097632.

Venhorst, Andreas; Micklewright, Dominic P.; Noakes, Timothy D. (2018b): The Psychophysiological Determinants of Pacing Behaviour and Performance During Prolonged Endurance Exercise: A Performance Level and Competition Outcome Comparison. In Sports medicine (Auckland, N.Z.) 48 (10), pp. 2387–2400. DOI: 10.1007/s40279-018-0893-5.

Weimar, Wendi; Sumner, Andrea; Romer, Braden; Fox, John; Rehm, Jared; Decoux, Brandi; Patel, Jay (2019): Kinetic Analysis of Swimming Flip-Turn Push-Off Techniques. In Sports 7 (2). DOI: 10.3390/sports7020032.

Williams, Emily L.; Jones, Hollie S.; Andy Sparks, S.; Marchant, David C.; Midgley, Adrian W.; Mc Naughton, Lars R. (2015): Competitor presence reduces internal attentional focus and improves 16.1km cycling time trial performance. In Journal of science and medicine in sport 18 (4), pp. 486–491. DOI: 10.1016/j.jsams.2014.07.003.

Wilmore, J. H. (1968): Influence of motivation on physical work capacity and performance. In Journal of applied physiology 24 (4), pp. 459–463. DOI: 10.1152/jappl.1968.24.4.459.

Zatoń, Krystyna; Szczepan, Stefan (2014): The impact of immediate verbal feedback on the improvement of swimming technique. In Journal of human kinetics 41, pp. 143–154. DOI: 10.2478/hukin-2014-0042.

Curriculum Vitae

The curriculum vitae was removed from the electronic version of the doctoral thesis for reasons of data protection.

Tag der Promotion: 07.04.2025

Dekan: Univ.-Prof. Dr. med. dent. Matthias Hannig

Berichterstatter: Prof. Dr. Tim Meyer (erster Berichterstatter) und Prof. Dr. Bergita Ganse (zweiter Berichterstatter)

Appendix

The appendix includes the original manuscripts in the following order:

1. The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming.
2. The association of end-spurt behaviour with seasonal best time in long-distance freestyle pool swimming: End-spurt in freestyle swimming.
3. Analysis of end-spurt behaviour in elite 800-m and 1500-m freestyle swimming.

Received: 13 June 2023 | Revised: 6 March 2024 | Accepted: 10 March 2024

DOI: 10.1002/ejsc.12102

ORIGINAL PAPER

Official ECSS Journal Open Access WILEY

The effect of forced even pacing and an opponent on end-spurt behaviour in freestyle pool swimming

Joshua E. Neuloh | Andreas Venhorst | Sabrina Skorski | Tim Meyer

Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany

Correspondence
Joshua E. Neuloh, Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken 66123, Germany.
Email: j.neuloh@mail.com

Abstract

To investigate the effect of forced even pacing through virtual pacing assistance and an opponent in a competitive setting on end-spurt behaviour in freestyle swimmers, including related physiological underpinnings. Twenty-seven competitive swimmers and triathletes were recruited. There were four 1500 m freestyle trials: (i) familiarisation time trial, (ii) self-paced time trial (STT), (iii) head-to-head competition time trial (CTT) and (iv) forced even pacing through virtual pacing assistance time trial (FET). Eventually, 12 swimmers met the criteria for the CTT and FET to be included in the analysis. Changes in end-spurt behaviour, finishing time and physiological parameters (lactate, cortisol, noradrenaline and heart rate) were analysed using a linear mixed model with fixed effects for trials and a random effect for swimmer identity. A separate linear model was computed for competition outcome. The end-spurt for each race was determined by means of an end-spurt indicator (ESI; ESI > 0 greater end-spurt). Swimmers demonstrated a significantly greater ESI in FET (+2.6; $p < 0.001$) and CTT (+1.4; $p = 0.022$) compared to STT. Blood lactate concentration in FET (+1.0 mmol L^{-1}; $p < 0.001$) and CTT (+1.6 mmol L^{-1}; $p < 0.001$) was significantly higher than in STT. Winners had a significantly greater ESI than losers in CTT (+1.6 and $p = 0.005$). Swimmers utilised a greater end-spurt through metabolically optimal forced even pacing by virtual pacing assistance and in a head-to-head competition due a larger mobilisation of anaerobic reserves as indicated by greater blood lactate concentrations. Winners had a significantly greater end-spurt than losers despite similar metabolic disturbances.

KEYWORDS
competition, opponent, pacing strategy, sports performance, water

Highlights

- Compared to a self-paced time trial, swimmers in a forced even pacing trial by virtual pacing assistance and in a head-to-head competition execute a greater end-spurt.
- The larger end-spurt is associated with larger mobilisation of anaerobic reserves as indicated by greater blood lactate concentrations.
- Winners had a significantly greater end-spurt than losers despite similar metabolic disturbances.

1 | INTRODUCTION

The presence of an end-spurt in 1500 m freestyle pool races has been well described previously (Lipinska et al., 2016; Mytton et al., 2015; Neuloh et al., 2020). Figueiredo et al. (2011) analysed the energy contribution of each 50 m lap during simulated competitions finding that the energy costs in the last lap was second highest after the start lap in 200 m freestyle. Still, a more even pacing strategy is considered energetically optimal in swimming (Thompson et al., 2004) due to the high restive forces of water. Even small changes in the swim velocity are accepted to be very critical as any increase in velocity raises energy expenditure substantially (Lipinska et al., 2016). However, Skorski et al. (2014) found that moderate manipulation through an opponent in 400 m freestyle swimming races had a positive impact in the final stages of the race (Skorski et al., 2014). Particularly, the winners and medallists in elite competitive events seem to be able to mobilise greater fractions of anaerobic reserves to outsprint their competitors during the final metres (Neuloh et al., 2020). The presence of a competitor shifts the focus towards beating the opponent rather than utilising the energetically optimal even pacing strategy to achieve the fastest possible finishing time (Abbiss et al., 2008; Foster et al., 1994; Mauger et al., 2012). As such, the primary goal of a swimmer during competitions is to achieve the best possible position, whilst achieving a personal best time may become a secondary objective (Menting et al., 2019). This might be especially true in important races, such as World championships or Olympic Games, where success is rated by the colour of the medal. To evaluate the end-spurt scientifically, an 'End-spurt indicator' (ESI; arbitrary units) was designed by Neuloh et al. (2020). To define an individual ESI per race and subject, the difference between the swim velocity in the last lap and the corresponding velocity of the middle part of the race is divided by the respective individual standard deviation of the swim velocity in the middle part of the race (For further details, see Neuloh et al., 2020). Swimmers typically perform an end-spurt in 1500 m freestyle with the magnitude being affected by the anticipated finishing position and the importance of the race (Neuloh et al., 2020). Consequently, greater end-spurts have been reported in head-to-head races in which success is determined by marginally performing better than the opponents (Neuloh et al., 2022) but only when the athletes believe they can beat the opponent (Crivoi do Carmo et al., 2022).

Multiple studies in cycling (Crivoi do Carmo et al., 2022; Konings et al., 2016; Konings et al., 2017; Venhorst et al., 2018b; Williams et al., 2015; Wilmore, 1968) and running (Tomazini et al., 2015) showed that an opponent is an essential determinant of pacing regulation. It was found that the presence of an opponent in cycling influenced end-spurt behaviour with the magnitude of the end-spurt depending on the performance goal (Crivoi do Carmo et al., 2022). For example, Corbett et al. (2012) observed an increased anaerobic energy supply (indicated by higher maximal blood lactate concentrations) when cyclists competed in virtual competitions against an opponent, which could not be mobilised in individual time trials. However, racing and losing against a faster opponent can negatively impact end-spurt behaviour through decreased self-efficacy and motivation in the final stages of the race (Crivoi do Carmo et al., 2022). Falling behind an opponent clearly is a negative affective event in goal-striving associated with a greater endocrinological distress response as indicated using higher levels of cortisol and noradrenaline concentrations in losers compared to winners during head-to-head-competitions (Venhorst et al., 2018b). Thus, the presence of opponents per se and the competition outcome are important factors in the decision-making process to execute an end-spurt (Hettinga et al., 2017; Konings et al., 2018; Renfree et al., 2014).

So far, the pacing literature in swimming has retrospectively analysed end-spurt behaviour in 800 and 1500 m in competitions (Neuloh et al., 2022). The direct influence of forced even pacing through virtual pacing assistance (assumingly energetically optimal) and an opponent on end spurt behaviour in swimming is still unknown. Moreover, the physiological underpinnings of an end-spurt considering differential responses in winners have not yet been investigated.

Therefore, the aim of the current study was to investigate the effect of forced even pacing through virtual pacing assistance and an opponent on swimmers' end-spurt behaviour, including related physiological underpinnings. It was hypothesised that forced even pacing through virtual pacing assistance and an opponent leads to a greater end-spurt compared to an individual time trial due to greater mobilisation of anaerobic energy reserves. Furthermore, it was hypothesised that the head-to-head competition would elicit a greater stress response and that winners would demonstrate an absolute (and relative to a self-paced time trial [STT]) greater end-spurt than losers.

2 | METHODS

2.1 | Participants

Twenty-seven competitive swimmers and triathletes (11 female; age: 18 ± 2.54 years, height: 181.6 ± 7.8 cm and weight: 70.2 ± 8.20 kg) were recruited. All participants were highly trained and competed at the national level in their respective sport (mean: 549.90 ± 81.25, min: 476.37 and max: 650.99 Swimming Points by World Aquatics for their 1500 m freestyle personal best time) corresponding to Tier 3 in a novel participation classification framework of McKay et al. (2022).

Out of 27 swimmers, six participants dropped out at various points during the study due to injury or illness. Therefore, only 21 swimmers completed all trials. Due to strict matching and performance criteria, 9 swimmers were excluded and eventually 12 swimmers (11 pool swimmers and one triathlete) met the criteria for the head-to-head competition and the forced even pacing time trial (FET) and were subsequently included in the analysis. To ensure a competitive environment during the end-spurt, pairs with a gap of more than one body length (i.e. ~1.7 s) apart at the 1300 m turn were excluded. During the FET, athletes who were more than 10.5 s behind the set pace at the 1450 m turn have also been excluded to ensure that the swimmer followed the pre-set even pacing pattern. This benchmark is based on a mean difference of 10 s between first and third finishing place at the World Championships 2003–2019 in

1500 m freestyle (Lara et al., 2021). Anthropometric and performance data of swimmers included in the study can be found in Table 1. All participants provided prior written informed consent to the procedures used in this study, which were approved by the local ethics committee (Kenn-Nr. 34/21) and carried out in accordance with the Declaration of Helsinki.

2.2 | Study design

All participants completed four trials with 1 week between sessions. The first trial was a baseline STT for familiarisation (FAM). Thereafter, swimmers completed three 1500 m trials in set order: a STT, a head-to-head competition time trial (CTT) and a FET using the Virtual Swim Trainer System (VST). The FAM test acted as a familiarisation time trial (FAM), and the STT was a STT without an opponent. The fastest of both finishing times (FAM and STT) was used to match swimmers for the CTT to ensure that swimmers were matched on their best performance capabilities. The finishing times and matches were not shared with the participants until the start of the CTT. The finishing time from CTT was the evenly distributed set pace for FET. Accordingly, no randomisation of the trial sequence was possible. Swimmers were asked to log their training, recovery training and diet before the first trial and replicate it accordingly for subsequent trials. All trials were completed at the same time of day to minimise diurnal biological variation (in assessed physiological parameters). The participants have been advised to reduce the training load 48 h prior to each session and prepare in the same manner as they would for a competition. The warm-up before the trials consisted of 800 m self-selected training followed by an ~20 min delayed start. The participants completed all trials in freestyle, as this is the only stroke offered in swimming competitions for 1500 m.

2.3 | Session 1—FAM

In session 1, swimmers completed a 1500-m freestyle solo swim from a push start. The push start has been used to ease following the pacing lights from the start, and therefore, all time trials have been started with the same technique.

TABLE 1 Anthropometric and performance level data.

	Male ($n = 8$)	Female ($n = 4$)
Anthropometric data		
Age (years)	17 ± 2	17 ± 3
Stature (cm)	184 ± 9	171 ± 5
Body mass (kg)	74.8 ± 7.8	60.6 ± 4.5
Performance level data		
Personal best time (min:ss.hh)	17:39.41 ± 48.86	20:44.17 ± 109.79
Swimming Points	561.91 ± 70.00	420.90 ± 109.66

2.4 | Session 2—STT

In session 2, swimmers completed a 1500-m freestyle solo swim from a push start equal to session one.

2.5 | Session 3—Head-to-head CTT

In session 3, swimmers completed a 1500 m head-to-head competition. To ensure a head-to-head-competition with uncertain outcomes, swimmers were matched as closely as possible in pairs based on the fastest finishing time of the slower swimmer from FAM and STT. The mean difference of all pairs was 5.92 ± 6.30 s (maximum 19.56 s, minimum: 0 s). This mean difference is considerably lower than the mean difference of 10 s between first and third finishing place at the World Championships 2003–2019 in 1500 m freestyle (Lara et al., 2021). The time was programmed into the VST (Indico Technologies; see below) evenly and both swimmers followed the lights for the first 1300 m. For the last 200 m, the VST was stopped and both swimmers were encouraged to race each other and beat the opponent without any pacing feedback. The separation of 200 m was based on previous findings revealing the lowest mean swim velocity at around 1300 m and leaving enough room for tactical considerations by the swimmers before the end-spurt (Neuloh et al., 2022). As a secondary goal, swimmers were encouraged to finish the trial in the shortest possible time independent of the head-to-head competition outcome.

2.6 | Session 4—FET

In session four, swimmers had to complete a 1500 m trial with a forced even pacing. The pace was set based on their finishing time from CTT with the VST being programmed to distribute the CTT finishing time evenly among the 1500 m. This trial was conducted as a solo swim. Swimmers were encouraged to keep up with the target light until 1450 m without falling behind the LED lights by more than one body length and were then allowed to out sprint the pacing lights on the last 50 m if possible.

2.7 | Virtual Swim Trainer system

The VST (Indico Technologies) was used in the CTT and FET trials. The light feedback system comprised of waterproof LED lights placed on the bottom of the pool throughout 50 m in the middle of the swim lane. The LED stripe was held down by small weights placed every ~4–5 m. The lights have been pre-programmed through the Swim Session Creator (Indico Technologies) and imported into the control panel (VST 17) of the Virtual Swim Trainer. For all testing sessions, including the lights condition, the LED stripes were programmed for even pacing on all 50 m split times according to the length of the pool (50 m). Every turn was indicated by a static white light 1.5 m before the wall and every push-off the wall by a static white light by 7 m after the wall. The light feedback through the turn was set for all swimmers at 1.5 s for the spin and 3.6 s for the push-off, which is the standard selection in the VST for competitive swimmers and in accordance with previous findings (Morais et al., 2019; Weimar et al., 2019).

2.8 | Measurements

Before the warm-up of the first trial, each participant had their age and body mass recorded. During each time trial, split times were taken every 50 m using handheld stopwatches (Interval 2000, Nielsen Kellermann) by skilled swim coaches to ensure the pacing was precise and to account for individual end-spurt behaviour.

Heart rate was measured constantly through Polar OH1 optical heart rate sensor (Polar Electro Oy), which was placed under the swim cap at the temple. Heart rate data were collected from all sessions and stored in the internal memory of the devices. After completion of each session, data were uploaded to Polar Flow (Polar Electro Oy) and then exported to Microsoft Excel (Microsoft software, Microsoft Corporation).

Venous blood samples from a superficial antecubital vein were taken in a supine position for (a) cortisol 1 min before swim start at rest and 15 min after each trial, (b) noradrenaline 1 min before swim start at rest and 1 min after each trial and (c) haemoglobin 1 min before swim start at rest and 1 min after each trial. The blood samples were placed into pre-chilled vacutainers containing K_2-ethylenediaminetetraacetic acid for the analysis of noradrenaline and red blood cell count and serum clot activator for the analysis of cortisol. Where appropriate, samples were inverted four times, immediately centrifuged at 3000 rpm for 10 min, plasma/serum pipetted off and kept cool until stored at −80°C for subsequent analysis. Noradrenaline was analysed by means of a chemical and enzymatic derivatisation linked to an immunosorbent assay (2-Cat ELISA) (Beckmann Coulter). Cortisol was determined through chemiluminescence immunoassay using an Access 2 (Beckmann Coulter). The degree of haemoconcentration was calculated, and all blood samples were subsequently corrected for plasma volume changes (Dill et al., 1974). Capillary blood (5 μL) was collected from an earlobe 1 min before the start and 3 min after each trial to determine peak lactate concentration and placed into a glass capillary (20 μL), which was then stored in a container with haemolysing solution. Subsequently, blood lactate concentrations (mmol L^{-1}) were analysed through an enzymatically amperometric procedure using Super GL (Greiner DiaSys).

2.9 | Statistical analysis

Statistical analyses were conducted using SPSS 21 (IBM). Data were tested for normality, equality of variances, equality of covariance matrices and sphericity. When the assumption of sphericity was violated, Greenhouse–Geisser correction was performed. Results are reported as mean ± *SD* and α-error of $p < 0.05$ was accepted as the level of significance. Changes in ESI, finishing time and physiological parameters (lactate, cortisol, noradrenaline and heart rate) were analysed using a linear mixed model with fixed effects for trials (three levels: STT, CTT and FET) and a random effect for swimmer identity. Due to the limited sample size, a separate linear model was computed with winner/loser (based on outcome of CTT) to further isolate the difference found and investigate interaction effects. A calculation of effect size was made using Cohen's *d* with thresholds of ≤0.50 for small, ≥0.50 for medium and ≥0.80 for large. The sample size estimation revealed that 41 participants will be necessary to observe a significant interaction effect (two-tailed alpha of >0.05, $\beta > 0.80$ and $d = 0.41$, G*Power, Version 3.1.9.7). This calculation is based on the effect size found between medallists (finishing place 1–3) and non-medallists (finishing place 4–8) in ESI at finals at World Championships and Olympic Games (Neuloh et al., 2020). The limited resources were the primary reason (limited access to national and international level swimmers) for the choice of the sample size collected (Lakens, 2022).

3 | RESULTS

3.1 | End-spurt indicator

The main effect on ESI was significant (see Table 2 for all data; $F = 11.0$ and $p < 0.001$). The ESI in FET and CTT was significantly higher compared to STT with large effect sizes ([$p < 0.001$ and $d = 1.90$] and [$p = 0.022$ and $d = 1.12$], respectively). The ESI in the FET and CTT was on average 2.65 and 1.40 higher than in the STT, respectively. The ESI in FET was 1.25 higher compared to CTT. This difference was significant ($p = 0.037$ and $d = 0.079$). The interaction effect of trial and CTT outcome (winner/loser) was significant ($F = 6.0$, $p < 0.001$) with winners showing a significantly greater ESI (+1.68) than losers in CTT ($p = 0.005$ and $d = 1.44$). Losers had a significantly higher ESI (+1.70) in FET compared to CTT ($p = 0.018$ and $d = 1.08$), whereas winners showed no significant differences in ESI between the two trials (+0.36, $p = 0.701$ and $d = 0.26$).

3.2 | Finishing time

Total times from all sessions are shown in Table 2. There was no significant difference in finishing time between trials ($F = 0.5$, $p = 0.600$). The best mean finishing time was reported in FET with a difference of 3.66 s to STT and 3.15 s to CTT. The mean difference between STT and CTT was 0.51 s.

3.3 | Haematological data

The main effect on blood lactate concentration was significant ($F = 11.5$ and $p < 0.001$). The blood lactate concentrations in FET and CTT were significantly higher than in STT. The difference between FET and STT was 1.01 mmol L^{-1} ($p < 0.001$; $d = 0.04$) and between CTT and STT 1.67 mmol L^{-1} ($p < 0.001$; $d = 0.58$). There was no

TABLE 2 Summary of result in all sessions, main effects and haematological measurements.

(n)	STT 12	CTT 12	FET 12		Main effect	p value[a]	Cohen's d
ESI	0.93 ± 0.95	2.33 ± 1.48	3.58 ± 1.65	STT/CTT	<0.001	0.022	1.12
	102.15 (CV)	63.52 (CV)	46.08 (CV)	STT/FET		<0.001	1.90
				CTT/FET		0.037	0.79
Finishing time (mm:ss.hh)	18:29.71 ± 1:40.34	18:29.21 ± 1:33.66	18:26.06 ± 1:36.72	STT/CTT	>0.600	-	-
	9.04 (CV)	8.44 (CV)	8.74 (CV)	STT/FET			
				CTT/FET			
Heartrate Ø	168.60 ± 24.89	161.75 ± 29.44	162.26 ± 28.43	STT/CTT	>0.279	-	-
	14.76 (CV)	18.20 (CV)	17.52 (CV)	STT/FET			
				CTT/FET			
Lactate (mmol L^{-1})	4.24 ± 1.81	5.19 ± 1.41	5.26 ± 1.64	STT/CTT	<0.001	<0.001	0.58
	42.69 (CV)	27.17 (CV)	31.18 (CV)	STT/FET		0.008	0.04
				CTT/FET		0.076	0.59
Cortisol (μg/dL)	6.23 ± 3.00	8.70 ± 3.24	7.18 ± 2.69	STT/CTT	>0.07	-	-
	48.15 (CV)	37.24 (CV)	37.47 (CV)	STT/FET			
				CTT/FET			
Noradrenaline	3.43 ± 1.31	2.95 ± 1.03	2.62 ± 1.22	STT/CTT	>0.205	-	-
	38.19 (CV)	34.92 (CV)	46.56 (CV)	STT/FET			
				CTT/FET			

Abbreviations: CTT, competition time trial; CV, coefficient of variance; ESI, end-spurt indicator; FET, forced even pacing time trial; STT, self-paced time trial.

[a]Post hoc test.

significant difference between FET and CTT (0.65 mmol L^{-1} and $p = 0.118$). We found a significant interaction effect between trial and winner/loser ($F = 4.6$ and $p < 0.001$). On average, swimmers had a significantly higher blood lactate concentration in CTT than in STT ($p = 0.003$) and FET ($p = 0.010$), respectively. There was no significant difference between winner/loser in CTT ($p = 0.216$). The main effect on heart rate ($F = 1.4$ and $p = 0.279$), cortisol ($F = 3.0$ and $p = 0.073$) and noradrenaline ($F = 1.7$ and $p = 0.205$) was not significant. Although it did not reach the significance level ($p = 0.07$), blood cortisol concentrations were 2.47 μg/dL higher in CTT compared to STT ($d = 2.74$).

4 | DISCUSSION

The main findings of the present study were (i) swimmers execute a greater end-spurt through forced even pacing by virtual pacing assistance and in the presence of an opponent as compared to self-pacing, (ii) this is paralleled with a larger mobilisation of anaerobic reserves as indicated by greater blood lactate concentrations and (iii) winners had a significantly greater end-spurt than losers despite similar metabolic disturbances.

Swimmers showed a greater end-spurt through forced even pacing by using virtual pacing assistance and predicted greater tolerance of metabolic disturbance, which is supported by higher blood lactate concentrations. Swimmers were guided to evenly pace the first 1450 m and then outsprint the pacing lights where possible. As there was no competitive opponent in FET opposed to CTT, we suggest that swimmers were able to perform an end-spurt and access the anaerobic reserves to a greater extend by profiting from a more energetically optimal even pace in the first stages of the trial. It is generally accepted that mathematically and energetically an even pacing pattern in 1500 m freestyle swimming is optimal (McGibbon et al., 2018) and even small variations in the pacing strategy may have a substantial influence on the performance outcome (de Koning et al., 1999). Looking at the energy expenditure during virtual even pacing assistance in cycling, it was found that athletes had a higher power output assisted by greater anaerobic energy contribution in the end-spurt, whereas the aerobic energy yield remained unchanged (Corbett et al., 2012). Foster et al. (2003) also showed that cyclists reserve some anaerobic energy during simulated competition, and it is understood that athletes monitor their energetic resources in a manner designed to optimise performance outcome. We propose that there is a positive effect through forced even pacing by virtual pacing assistance influencing the degree of metabolic stress that can be tolerated by swimmers.

Another argument could be the focus on achieving a better finishing time rather than beating an opponent. The external guidance (through the VST) can be assumed to represent a motivational factor for the swimmer, where the knowledge of being able to swim at the set pace and visual confirmation of it improves end-spurt (Corbett et al., 2012). Although there are no supporting studies in swimming, it can be suggested from our findings and studies in other sports (Noakes et al., 2004; Williams et al., 2015) that forced even pacing by virtual pacing assistance through the VST also could have a motivational effect. In cycling, it was found that a simulated avatar serving as an opponent but actually representing the fastest previous performance of the athlete, improved time trial performance and end spurt (Williams et al., 2015). It was suggested that an increase in motivation positively influenced the willingness to exert the required effort, tolerate the associated physical discomfort of intensified performance and overcome negative factors, such as fatigue (Noakes et al., 2004; Williams et al., 2015).

It is generally accepted that athletes perform better in head-to-head competitions (Tomazini et al., 2015; Williams et al., 2015; Wilmore, 1968) than when exercising alone. The finding that swimmers showed a greater end-spurt, while swimming in a head-to-head competition compared to a self-paced trial is also in agreement with a recent study by Neuloh et al. (2020), who found that the end-spurt is associated with the finishing position and that medallists performed a more pronounced end-spurt than non-medallists (Neuloh et al., 2020). As suggested by Corbett et al. (2012), the anaerobic energy reserve seems to be mobilised to a higher degree during competitions and needs to be accompanied by a greater tolerance of the metabolic stress (i.e., higher blood lactate concentrations) and associated physical discomfort. Konings et al. (2018) suggested that the behaviour of opponents is an essential determinant in the regulation of exercise intensity. It was shown that the competitive environment and the current internal state of the athlete influence the pacing behaviour related to an opponent. Thus, the decision-making process of the athlete to elicit an end-spurt or not is underpinned by biopsychosocial interactions.

In the current study, two swimmers were competing head-to-head against a closely matched competitor. Given an uncertain outcome as indicated by the (trend for a) higher blood cortisol concentrations in the CTT, both swimmers were motivated to change their pacing strategy from even to an end-spurt and outsprint the opponent to win the race. The main aim in the CTT was to beat the opponent. It can reasonably be assumed that the winner in CTT felt motivated by being ahead and losers demotivated by the prospect of losing the race. Accordingly, winners were willing to access anaerobic reserves to a greater extent (as indicated by higher blood lactate concentrations) resulting in a greater end-spurt compared losers and their own STT.

On the other hand, falling behind a performance matched competitor can clearly be conceived as a demotivational and negative affective event in goal-striving in competitive athletes (Venhorst et al., 2018b). Accordingly, it has been shown that losers of head-to-head competition disengage from their initially set goal of winning and settle for a lesser goal, such as merely finishing the race (Crivoi do Carmo et al., 2022). This also explains the slightly better mean finishing time of all swimmers in FET compared to CTT as the motivational effect of winning is diminished by the demotivational effect of losing. Accordingly, Crivoi do Carmo et al. (2022) found that the presence of an opponent did not change overall performance, but differentially influenced pacing behaviour depending on the perceived outcome of winning or losing a race against an opponent and the respective maintenance or loss of self-confidence.

5 | LIMITATIONS AND SCOPE

The main limitation of the current study is the sample size as it is inherently difficult to recruit national level competitive swimmers. Due to dropouts and the application of strict matching criteria to ensure a competitive environment, all swimmers being more than 1.7 s behind the opponent in the CTT or 10.5 s behind the pacing light in FET were excluded from the analysis further reducing sample size. Moreover, the problem of imperfect matching of swimmers cannot be evaded. This is highlighted by the fact that winners in CTT also have been the swimmers with the faster time in FAM or STT, though there is always going to be one swimmer with a faster best time going into a matched head-to-head race. To prevent the confounder that swimmers may have changed their performance outcome in FAM or STT based on tactical reasons (to receive a slower opponent in CTT) was prevented by not sharing results and matching criteria. In fact, the trend for higher blood cortisol concentrations in CTT is indicative of a heightened stress response due to uncertain competition outcomes. The greater end-spurt in FET compared to CTT is due to the fact of comparing group means, where losers had a lower or no end-spurt in CTT, which affects the group mean of CTT when compared to FET. Losers were tapering off in CTT once they realised that they will lose.

It is generally accepted that a race against an opponent leads to greater motivation and that losing against a performance matched opponent is a demotivational and distressful event (Venhorst et al., 2018a). Given the objective difficulties in assessing motivational aspects through questionnaires or scales in swimming, there was no data collection on psychological aspects.

6 | CONCLUSION

This study investigated the influence of forced even pacing through virtual pacing assistance and an opponent on end-spurt behaviour and its physiological underpinnings. Swimmers performed a greater end-spurt through metabolically optimal forced even pacing by virtual pacing assistance and in the presence of an opponent due a larger mobilisation of anaerobic reserves as indicated by greater blood lactate concentrations. Winners had a significantly greater end-spurt than losers despite similar metabolic disturbances.

ACKNOWLEDGEMENTS

The authors would like to thank the swimmers involved in this study for their time. The authors report that Saarland University paid the publication charge for this article.

CONFLICT OF INTEREST STATEMENT

No potential conflict of interest was reported by the authors(s).

ORCID

Joshua E. Neuloh https://orcid.org/0000-0001-8914-7460

REFERENCES

Abbiss, C. R., and P. B. Laursen. 2008. "Describing and Understanding Pacing Strategies during Athletic Competition." *Sports Medicine* 38(3): 239–52. https://doi.org/10.2165/00007256-200838030-00004.

Corbett, J., M. J. Barwood, A. Ouzounoglou, R. Thelwell, and M. Dicks. 2012. "Influence of Competition on Performance and Pacing during Cycling Exercise." *Medicine & Science in Sports & Exercise* 44(3): 509–15. https://doi.org/10.1249/MSS.0b013e31823378b1.

Crivoi do Carmo, E., A. Renfree, C. Y. Nishimura Vieira, D. D. S. Ferreira, G. A. Truffi, and R. Barroso. 2022. "Effects of Different Goal Orientations and Virtual Opponents Performance Level on Pacing Strategy and Performance in Cycling Time Trials." *European Journal of Sport Science* 22(4): 491–8. https://doi.org/10.1080/17461391.2021.1880645.

de Koning, J. J., M. F. Bobbert, and C. Foster. 1999. "Determination of Optimal Pacing Strategy in Track Cycling with an Energy Flow Model." *Journal of Science and Medicine in Sport* 2(3): 266–77. https://doi.org/10.1016/s1440-2440(99)80178-9.

Dill, D. B., and D. L. Costill. 1974. "Calculation of Percentage Changes in Volumes of Blood, Plasma, and Red Cells in Dehydration." *Journal of Applied Physiology* 37(2): 247–8. https://doi.org/10.1152/jappl.1974.37.2.247.

Figueiredo, P., P. Zamparo, A. Sousa, J. P. Vilas-Boas, and R. J. Fernandes. 2011. "An Energy Balance of the 200 m Front Crawl Race." *European Journal of Applied Physiology* 111(5): 767–77. https://doi.org/10.1007/s00421-010-1696-z.

Foster, C., J. J. de Koning, F. Hettinga, J. Lampen, K. L. La Clair, C. Dodge, M. Bobbert, and J. P. Porcari. 2003. "Pattern of Energy Expenditure during Simulated Competition." *Medicine & Science in Sports & Exercise* 35(5): 826–31. https://doi.org/10.1249/01.MSS.0000065001.17658.68.

Foster, C., M. Schrager, A. C. Snyder, and N. N. Thompson. 1994. "Pacing Strategy and Athletic Performance." *Sports Medicine* 17(2): 77–85. https://doi.org/10.2165/00007256-199417020-00001.

Hettinga, F. J., M. J. Konings, and G.-J. Pepping. 2017. "The Science of Racing against Opponents: Affordance Competition and the Regulation of Exercise Intensity in Head-To-Head Competition." *Frontiers in Physiology* 8: 118. https://doi.org/10.3389/fphys.2017.00118.

Konings, M., J. Parkinson, I. Zijdewind, and F. Hettinga. 2017. "Racing an Opponent Alters Pacing, Performance and Muscle Force Decline, but Not RPE." *International Journal of Sports Physiology and Performance* 28: 1–24. https://doi.org/10.1123/ijspp.2017-0220.

Konings, M. J., and F. J. Hettinga. 2018. "Pacing Decision Making in Sport and the Effects of Interpersonal Competition: A Critical Review." *Sports Medicine* 48(8): 1829–43. https://doi.org/10.1007/s40279-018-0937-x.

Konings, M. J., P. P. J. M. Schoenmakers, A. J. Walker, and F. J. Hettinga. 2016. "The Behavior of an Opponent Alters Pacing Decisions in 4-km Cycling Time Trials." *Physiology & Behavior* 158: 1–5. https://doi.org/10.1016/j.physbeh.2016.02.023.

Lakens, D. 2022. "Sample Size Justification." *Collabra: Psychology* 8(1): 33267. https://doi.org/10.1525/collabra.33267.

Lara, B., and J. Del Coso. 2021. "Pacing Strategies of 1500 m Freestyle Swimmers in the World Championships According to Their Final Position." *International Journal of Environmental Research and Public Health* 18(14): 7559. https://doi.org/10.3390/ijerph18147559.

Lipinska, P., S. V. Allen, and W. G. Hopkins. 2016. "Relationships between Pacing Parameters and Performance of Elite Male 1500-m Swimmers." *International Journal of Sports Physiology and Performance* 11(2): 159–63. https://doi.org/10.1123/ijspp.2015-0117.

Mauger, A. R., J. Neuloh, and P. C. Castle. 2012. "Analysis of Pacing Strategy Selection in Elite 400-m Freestyle Swimming." *Medicine & Science in Sports & Exercise* 44(11): 2205–12. https://doi.org/10.1249/MSS.0b013e3182604b84.

McGibbon, K. E., D. B. Pyne, M. E. Shephard, and K. G. Thompson. 2018. "Pacing in Swimming: A Systematic Review." *Sports Medicine* 48(7): 1621–33. https://doi.org/10.1007/s40279-018-0901-9.

McKay, A. K. A., T. Stellingwerff, E. S. Smith, D. T. Martin, I. Mujika, V. L. Goosey-Tolfrey, J. Sheppard, and L. M. Burke. 2022. "Defining Training and Performance Caliber: A Participant Classification Framework." *International Journal of Sports Physiology and Performance* 17(2): 317–31. https://doi.org/10.1123/ijspp.2021-0451.

Menting, S. G. P., M. T. Elferink-Gemser, B. C. Huijgen, and F. J. Hettinga. 2019. "Pacing in Lane-Based Head-To-Head Competitions: A Systematic Review on Swimming." *Journal of Sports Sciences* 37(20): 2287–99. https://doi.org/10.1080/02640414.2019.1627989.

Morais, J. E., D. A. Marinho, R. Arellano, and T. M. Barbosa. 2019. "Start and Turn Performances of Elite Sprinters at the 2016 European Championships in Swimming." *Sports Biomechanics* 18(1): 100–14. https://doi.org/10.1080/14763141.2018.1435713.

Mytton, G. J., D. T. Archer, L. Turner, S. Skorski, A. Renfree, K. G. Thompson, and A. S. C. Gibson. 2015. "Increased Variability of Lap Speeds: Differentiating Medalists and Nonmedalists in Middle-Distance Running and Swimming Events." *International Journal of Sports Physiology and Performance* 10(3): 369–73. https://doi.org/10.1123/ijspp.2014-0207.

Neuloh, J. E., S. Skorski, L. Mauger, A. Hecksteden, and T. Meyer. 2020. "Analysis of End-Spurt Behaviour in Elite 800-m and 1500-m Freestyle Swimming." *European Journal of Sport Science* 21(12): 1–9. https://doi.org/10.1080/17461391.2020.1851772.

Neuloh, J. E., A. Venhorst, S. Forster, A. R. Mauger, and T. Meyer. 2022. "The Association of End-Spurt Behaviour with Seasonal Best Time in Long-Distance Freestyle Pool Swimming." *European Journal of Sport Science* 23(4): 1–9. https://doi.org/10.1080/17461391.2022.2043943.

Noakes, T. D., and A. St Clair Gibson. 2004. "Logical Limitations to the "catastrophe" Models of Fatigue during Exercise in Humans." *British Journal of Sports Medicine* 38(5): 648–9. https://doi.org/10.1136/bjsm.2003.009761.

Renfree, A., L. Martin, D. Micklewright, and A. St Clair Gibson. 2014. "Application of Decision-Making Theory to the Regulation of Muscular Work Rate during Self-Paced Competitive Endurance Activity." *Sports Medicine* 44(2): 147–58. https://doi.org/10.1007/s40279-013-0107-0.

Skorski, S., O. Faude, C. R. Abbiss, S. Caviezel, N. Wengert, and T. Meyer. 2014. "Influence of Pacing Manipulation on Performance of Juniors in Simulated 400-m Swim Competition." *International Journal of Sports Physiology and Performance* 9(5): 817–24. https://doi.org/10.1123/ijspp.2013-0469.

Thompson, K. G., D. P. M. MacLaren, A. Lees, and G. Atkinson. 2004. "The Effects of Changing Pace on Metabolism and Stroke Characteristics during High-Speed Breaststroke Swimming." *Journal of Sports Sciences* 22(2): 149–57. https://doi.org/10.1080/02640410310001641467.

Tomazini, F., L. A. Pasqua, M. V. Damasceno, M. D. Silva-Cavalcante, F. R. de Oliveira, A. E. Lima-Silva, and R. Bertuzzi. 2015. "Head-to-head Running Race Simulation Alters Pacing Strategy, Performance, and

Mood State." *Physiology & Behavior* 149: 39–44. https://doi.org/10.1016/j.physbeh.2015.05.021.

Venhorst, A., D. Micklewright, and T. D. Noakes. 2018a. "Modelling the Process of Falling behind and its Psychophysiological Consequences." *British Journal of Sports Medicine* 52(23): 1523–8. https://doi.org/10.1136/bjsports-2017-097632.

Venhorst, A., D. P. Micklewright, and T. D. Noakes. 2018b. "The Psychophysiological Determinants of Pacing Behaviour and Performance during Prolonged Endurance Exercise: A Performance Level and Competition Outcome Comparison." *Sports Medicine* 48(10): 2387–400. https://doi.org/10.1007/s40279-018-0893-5.

Weimar, W., A. Sumner, B. Romer, J. Fox, J. Rehm, B. Decoux, and J. Patel. 2019. "Kinetic Analysis of Swimming Flip-Turn Push-Off Techniques." *Sports (Basel)* 7(2): 32. https://doi.org/10.3390/sports7020032.

Williams, E. L., H. S. Jones, S. Andy Sparks, D. C. Marchant, A. W. Midgley, and L. R. Mc Naughton. 2015. "Competitor Presence Reduces Internal Attentional Focus and Improves 16.1km Cycling Time Trial Performance." *Journal of Science and Medicine in Sport* 18(4): 486–91. https://doi.org/10.1016/j.jsams.2014.07.003.

Wilmore, J. H. 1968. "Influence of Motivation on Physical Work Capacity and Performance." *Journal of Applied Physiology* 24(4): 459–63. https://doi.org/10.1152/jappl.1968.24.4.459.

EUROPEAN JOURNAL OF SPORT SCIENCE
2023, VOL. 23, NO. 4, 469–477
https://doi.org/10.1080/17461391.2022.2043943

Routledge
Taylor & Francis Group

ORIGINAL INVESTIGATION

The association of end-spurt behaviour with seasonal best time in long-distance freestyle pool swimming

Joshua E. Neuloh [a], Andreas Venhorst[a], Sabrina Forster[a], Alexis R. Mauger[b] and Tim Meyer[a]

[a]Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany; [b]School of Sport and Exercise Sciences, University of Kent, Canterbury, UK

ABSTRACT

To analyse the association of seasonal best time, distance and different performance levels with end-spurt behaviour in one swimming season. Race results in 800 and 1500 m pool freestyle swimming in the season 2018/2019 including 14,930 races and 2650 swimmers were obtained. The end-spurt for each race was determined by means of an End-Spurt Indicator (ESI). Subsequently, ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for seasonal best time, distance, and performance level amongst others. In the 800 and 1500 m races swimmers showed a mean ESI of 2.08 (95% CI: 2.02–2.13) and 3.68 (95% CI: 3.59–3.76), respectively. There was a significant association between seasonal best time and ESI, with a better seasonal best time showing a greater ESI ($F = 70.5$, $P < .001$, $f^2 = 0.04$). A significant effect on greater ESI was also observed for longer distance ($F = 1067.5$, $P < .001$, $f^2 = 0.06$) and higher performance level ($F = 91.1$, $P < .001$, $f^2 = 0.02$). Elite swimmers had a mean ESI of 5.47 (95% CI: 4.91–6.03), sub-elite swimmers of 3.74 (95% CI: 3.53–3.95) and competitive swimmers of 2.41 (95% CI: 2.37–2.46). A more pronounced end-spurt is associated with seasonal best time in long-distance pool swimming, higher performance level of the swimmer and longer race distance.

KEYWORDS
Pacing strategy; consistency; swim velocity; water; sports performance

Highlights

- Swimmers of all performance levels execute an end-spurt in 800 and 1500 m freestyle races.
- A greater end-spurt was associated with faster seasonal best time and longer race distance
- Swimmers of higher performance level have greater end-spurts

Introduction

In order to reach an endurance event's endpoint in the fastest time possible, athletes need to appropriately distribute their energy expenditure in a way that all available energetic resources are used, but not too early so as to avoid premature fatigue and a loss of speed (St Clair Gibson & Noakes, 2004). In competitions where the aim is to cover a given race distance in the fastest time possible, this regulation of speed, power or energy expenditure is an important factor for the optimisation of performance (Tucker & Noakes, 2009). Pacing is considered to be regulated by complex interactions between the brain and other physiological systems (McGibbon et al., 2018). Besides internal factors such as biomechanical and physiological influences on pacing, external psychological factors such as competitors might also affect an athlete's pacing by eliciting changes in race tactics (Konings et al., 2020). It has been shown that the reproducibility of pacing profiles in simulated and real competition trials is good except for the last part of the race, where the absolute variability increased in real competitions and when a competitor was present (Skorski et al., 2013). Thus, the presence of competitors may shift the goal from achieving the fastest possible time to the best possible finishing position by beating direct opponents (Abbiss & Laursen, 2008; Foster et al., 1994; Mauger et al., 2012; Tucker et al., 2006).

Pacing in long-distance swimming pool competitions is considered an important determinant of success, especially in the presence of similar individual performance levels in elite swimmers (Baldassarre et al., 2019; Lipińska, 2009; Lipińska et al., 2016a, 2016b; Mauger et al., 2012; Rodriguez & Veiga, 2018). It is important that swimmers make systematic use of available energetic resources as swimming is regarded more inefficient than other sports (Barbosa et al., 2010; Lipińska, 2009).

CONTACT Joshua E. Neuloh j.neuloh@mail.com Institute of Sports and Preventive Medicine, Saarland University, 66123 Saarbrücken, Germany

This is due to the high resistive properties of the water and the low mechanical efficiency (de Koning et al., 2011). Even the front crawl arm pull itself increases active drag, as the swim velocity changes during the stroke (Morais et al., 2020). Whereas the mechanical efficiency of swimming varies between 6–18% (McGibbon et al., 2018), 18–24% of energy generated in cycling is converted into mechanical work (Coyle, 1999). Thus, even small changes in swim velocity can result in a substantial increase in energy expenditure and premature fatigue (Thompson et al., 2004).

In long-distance freestyle pool events, a parabolically shaped pacing pattern is consistently observed (McGibbon et al., 2018), including a fast start, an even middle part and an increase in speed during the last stages of the race (Skorski et al., 2014). However, it is not yet completely understood what effect turn stability has on this pacing pattern (Morais et al., 2019). Indeed, it was found that elite long-distance male swimmers showed a varying turn pattern in the 800 m freestyle race, although the effect on their final race time is not clear yet (Morais et al., 2020). On the other hand, it is evident that in such competitions elite swimmers execute an end-spurt and medallists show a greater end-spurt than non-medallists (Neuloh et al., 2020). A pronounced end-spurt has also been described in competitions (McGibbon et al., 2018), where success is determined by performing marginally better than other competitors to achieve a better finishing position. In such events, athletes seem to retain a reserve of energy required for an end-spurt to possibly outsprint an opponent on the last few metres (Foster et al., 1993).

The majority of the pacing literature has analysed end-spurts among elite swimmers (Hecksteden et al., 2015; Konings et al., 2020; Lipińska, 2009; Mytton et al., 2015; Neuloh et al., 2020) without assessing their seasonal best time. Although the ultimate goal at a competition is to beat all competitors and win the gold medal, it has been suggested that swimmers simultaneously may need to improve their seasonal best time to stay in contention for a medal (Pyne et al., 2004). Further, it was found that swimmers improve their seasonal best time as the season advances towards the main peak competitions (Pyne et al., 2004). Thus, considering seasonal best time might help elucidating if the end-spurt is an important determinant of overall performance itself or only follows general performance changes in swimmers (Hecksteden et al., 2015; Konings et al., 2020; Lipińska, 2009; Mytton et al., 2015; Neuloh et al., 2020).

Whereas the literature has mainly focused on end-spurt behaviour in elite swimmers, other performance levels have not been closely investigated so far. It has been suggested that competitive and sub-elite swimmers have more room for improving their pacing skills due to their lesser experience in racing (Menting et al., 2019). This leads to the assumption that a lack of maximum performance capacity (as it is required for certain pacing strategies) in competitive and sub-elite swimmers might result in an end-spurt of smaller magnitude.

In order to analyse end-spurt behaviour in swimming it has been suggested to make use of the End-Spurt-Indicator (ESI) (Neuloh et al., 2020). This ESI is based on the mean swim velocity (m/s) and the respective standard deviation (SD) of each individual swimmer. To define an individual ESI per race and subject, the difference between the swim velocity in the last lap (SVLL) and the corresponding velocity of the middle part of the race (SVMP) is divided by the respective individual SD of SVMP (Neuloh et al., 2020). An evaluation of group means as often done in the current pacing literature is of little value with respect to the individual athlete (Neuloh et al., 2020). When analysing the end-spurt behaviour within one athlete it is beneficial to consider the intra-individual variability during the middle part of the individual race, which is consistent with research on individual responses to exercise training (Atkinson & Batterham, 2015; Hecksteden et al., 2015).

Therefore, the current study aimed to quantify and analyse end-spurt behaviour in long-distance pool swimming events and its relationship with seasonal best time, distance and performance level by use of the ESI. It was hypothesised that a greater ESI is positively associated with better overall performance, longer race distance and higher performance level.

Methods

Subjects

The database www.swimranking.net (Splash Software Ltd., Switzerland; 2 April 2020) holds complete race information on 45,967 swim races in 800 m freestyle and 22,669 ones in 1500 m freestyle during the season 2018/2019 (1 September 2018–31 August 31 2019). These data were used to classify swimmers into three groups (elite swimmers: >900 FINA points; sub-elite swimmers: 800–899.99 FINA points; competitive swimmers: <799.99 FINA points) by identifying their best performance in the season based on FINA points. The FINA points metric is based on the world record and calculated accordingly. The total race time of elite, sub-elite, and competitive swimmers stays below 110%, between 110% and 120%, and above 120% of the world record, respectively (Menting et al., 2019). All swimmers with less than three registered competitions over the whole season were removed (minimum requirement for meaningful intra-individual variability) from this analysis, leaving 177 elite, 1006 sub-elite and 13,747 competitive swimmers races, with 10,614 races in the 800 m and 4316 races in the 1500 m, respectively (Table 1). The mean of competitions by each swimmer was 4.05 (1.39) and a maximum of 13 competitions in the 800 m and 3.72 (1.04) and a maximum of 9 competitions in the 1500 m.

All procedures in this study were in accordance with the declaration of Helsinki. It was not necessary to obtain informed consent from swimmers because only publicly accessible information was utilised, and all data were anonymised before conducting the analysis.

End-spurt indicator

To evaluate the end-spurt, the "End-Spurt Indicator" (ESI; arbitrary units) suggested by Neuloh et al. (2020) was used (Neuloh et al., 2020). This ESI is based on the mean swim velocity (m/s) and the respective standard deviation (SD) of each individual swimmer. Due to the rapid acceleration caused by the diving start, the first 50 m split is not included when calculating mean swim velocity. The last lap was also excluded as it was used as the reference split for the ESI calculation (Morais et al., 2019, 2020). Therefore, the velocity of the middle part (SVMP) of the race was calculated using the individual mean (SD) speed in the laps 2–15, and 2–29 in the 800 and 1500 m race, respectively. To define an individual ESI per race and subject, the difference between the swim velocity in the last lap (SVLL) and the corresponding SVMP was divided by the respective individual SD of SVMP [see Neuloh et al. (2020) for additional information] (Neuloh et al., 2020). In the current study, the following fixed threshold value was used: ESI was defined when the value was > 0.

Events

Overall, the current analysis included 513 national and 15 international competitions. The total number of races (800 m: $n = 10,614$; 1500 m: $n = 4316$) included 11,215 (800 m: $n = 8013$; 1500 m: $n = 3202$) heat and 3715 (800 m: $n = 2601$; 1500 m: $n = 1114$) final performances. Race data in the www.swimrankings.net database are based on information from the European Swimming Federation (LEN) database and the results from the Belgian, Canadian, Dutch, Polish, Portuguese, and Swiss federations. Each race report includes a subject identification number for each swimmer, the name and date of the competition, distance, 50 m split times (s) and the total completion time (s). To examine intra-seasonal differences in ESI, the 2018/2019 season was divided into three season cycles. The Pre-Season (1 September 2018–31 January 2019), Main-Season (1 February 2019–31 May 2019) and Main-Peak-Season (1 June 2019–31 August 2019) included 1659, 7369, and 5902 races, respectively. These season cycles are typical for the European competition calendar in swimming, where the season starts in September with a general preparation phase, followed by a specific training phase and ends with main peak competitions in June, July, or August (typically when the main event occurs, e.g. National, European and World Championships). All events were swum in a long-course (50 m) pool. In all events semi- or full-automatic officiating equipment was used under the supervision of appointed officials and recorded to one-hundredth of a second to determine total times, as well as 50 m split times (according to FINA swimming rules).

Statistical analysis

Statistical analyses were conducted using SPSS 21 (IBM, New York, USA). A Kolmogorov–Smirnov-Test demonstrated that overall performance data were normally distributed. Thus, data are presented as means and standard deviation (SD) and analysed using parametric tests. Because ESI within individual subjects was not normally distributed descriptive data are presented as medians.

Changes in ESI were analysed using a linear mixed model with fixed effects for distance (two levels: 800 and 1500 m), sex (two levels: male and female), performance level (three levels: elite, sub-elite and competitive), season cycle (three levels: Pre-, Main-, and Main- Peak-Season), competition level (two levels: national and international), round (two levels: heat and final) and seasonal best time (thirteen levels: best time, second-best

Table 1. Number of races repeated by all subjects.

		Number of competitions (n)								
	Subjects (n)	Three	Four	Five	Six	Seven	Eight	Nine	Ten	≥Eleven
800 m	2623	1247	674	350	173	94	44	23	12	4
1500 m	1160	660	285	127	58	20	7	1	–	–

time, third-best time etc.) and a random effect for swimmer identity. The number of levels for seasonal best time refers to the maximum number of swims per athlete. A separate linear mixed model was computed with seasonal best times allocated to two performance categories as an additional effect (two levels: A: first to third seasonal best time; B: ≥fourth seasonal best time) to further isolate the differences found. An α-error of $P < .05$ was accepted as the level of significance. A calculation of effect size was made using Cohen's f^2 based on the work by Selya et al. (2012). Thresholds of ≥0.02 small, ≥0.15 medium and ≥0.35 large were used to assess the practical relevance for the fixed factors (Selya et al., 2012).

Results

Overall results

Total times in 800 and 1500 m races for males and females in heats and finals are shown in Table 2. On average, elite swimmers achieved 889.4 (42.1) FINA points, sub-elite swimmers 805.4 (41.4) FINA points, and competitive swimmers 590.5 (95.0) FINA points, which approximately fits the above criteria. Most of the best times in the season 2018/2019 were swum in the Main-Peak-Season (n = 2021) and fewer in the Main-Season (n = 1571) and Pre-Season (n = 190). Competitions were on average 43.7 (37.3) and 49.6 (36.7) days apart in the 800 and 1500 m, respectively. Most swimmers 74.67% (n = 11,346 races) competed in three registered competitions whereas 25.33% (n = 3584 races) competed in more than three competitions (Table 1).

End-spurt indicator

In the 800 and 1500 m races swimmers showed a mean ESI of 2.08 (95% CI: 2.02–2.13) and 3.68 (95% CI: 3.59–3.76), respectively. Male swimmers had a lower mean ESI (2.48; 95% CI: 2.41–2.55) than female swimmers (2.61; 95% CI: 2.55–2.68). Elite swimmers had a mean ESI of 5.47 (95% CI: 4.91–6.03), sub-elite swimmers of 3.74 (95% CI: 3.53–3.95) and competitive swimmers of 2.41 (95% CI: 2.37–2.46). The EIS increased from 2.46 (95% CI: 2.60–2.32) in the Pre-Season to 2.53 (95% CI: 2.60–2.47) in the Main-Season and 2.57 (95% CI: 2.64–2.49) in the Main-Peak-Season. A total of 3141 races (21%) revealed a negative ESI of −0.93 (0.65) on average, which indicates the absence of an end-spurt. The median ESI for all swimmers was 1.64 (min: −5.75; max: 24.77) in the 800 m and 3.17 (min: −4.04; max: 25.79) in the 1500 m.

A significant but small effect on ESI was observed for distance ($F = 1067.5$, $P < .001$, $f^2 = 0.06$) and performance level ($F = 91.1$, $P < .001$, $f^2 = 0.02$). The effect of season cycle ($F = 22.3$, $P < .001$, $f^2 = 0.00$) and sex ($F = 59.3$, $P < .001$, $f^2 = 0.00$) was also significant. Seasonal best time was significantly (small effect) associated with ESI with a faster seasonal best time indicating a greater ESI ($F = 70.5$, $P < .001$, $f^2 = 0.04$). No significant effect on ESI was found for competition level ($F = 1.2$, $P = .28$, $f^2 = 0.00$) and round ($F = 2.1$, $P = .15$, $f^2 = 0.00$). Between subject standard deviation was 1.17 (95% CI: 1.11–1.23); relative variance component subject ID = 17.94%, while 82.06% of ESI variance remained unexplained. When analysing seasonal best time in two categories (A: first to third seasonal best time; B: ≥fourth seasonal best time), ESI was significantly greater among category A (2.74; 95% CI: 2.69–2.79) compared to B (1.90; 95% CI: 1.81–1.99; $P < .001$, $f^2 = 0.02$).

Table 2. Number of races and age at competition for all subjects (n = 2650; n in table reflects number of races included).

	Age (years)	Heat total time (min)	Final total time (min)
		Male (n = 8140)	
800 m (n = 5296)	17.2 (4.1)	9:06.18 (44.01)	8:59.58 (38.84)
1500 m (n = 2844)	17.1 (2.6)	16:57.78 (59.39)	16:50.78 (53.44)
		Female (n = 6790)	
800 m (n = 5318)	16.4 (3.7)	9:41.99 (37.25)	9:40.18 (40.46)
1500 m (n = 1472)	16.9 (3.2)	18:15.45 (59.91)	17:59.95 (60.40)

Data is shown as mean and standard deviation (SD).

Discussion

This study was designed to analyse end-spurt behaviour in long-distance freestyle pool swimming by investigating the influence of seasonal best time, performance level, distance, sex, season cycle, round, and competition level on end-spurt behaviour within one season. The main findings were (i) a greater end-spurt is associated with faster seasonal best times, (ii) swimmers show a greater end-spurt in the 1500 m than in the 800 m, and (iii) elite swimmers have a greater end-spurt than sub-elite and competitive swimmers.

End-spurt and seasonal best time

In general, a greater end-spurt was associated with faster seasonal best times, and the end-spurt was greater among swims with the first to third personal seasonal best time compared to swims classed ≥fourth seasonal best time. Recently, Neuloh et al. (2020) found that the end-spurt is associated with finishing position in elite swimmers, and that medallists performed a more pronounced end-spurt than non-medallists (Neuloh et al., 2020). Collectively, these findings suggest that swimmers not only execute a pronounced end-spurt when the primary aim is to win a medal at Olympic Games or World Championships it may also assist in achieving new seasonal best time. However, it is understood that achieving a new seasonal best time in competitions is not always the primary goal of the swimmers, but to beat all competitors and win the gold medal (Mujika et al., 2019). Therefore, it can be assumed that a strong end-spurt is important for winning a medal and may indirectly contribute to an improvement of seasonal best times, although winning a medal is not always related to a new seasonal best time.

The performance advantage of an end-spurt stands in contrast with fluctuations in swim velocity due to the high resistive properties of water (Morais et al., 2020), where even small changes in swim velocity can result in a substantial increase in energy expenditure and thus premature fatigue (Barbosa et al., 2010). It is generally accepted that even-pacing with minimal lap-to-lap variability is biomechanically and physiologically optimal for long-distance pool swimming (Barbosa et al., 2010; Morais et al., 2020). This is despite successful swimmers showing the ability to produce an end-spurt at the end of the race in a range of different events (Lipińska, 2009; Lipinska et al., 2016b; Mytton et al., 2015). Accordingly, there seems to be little support for realising an end-spurt based on biomechanical, and physiological grounds. Instead, the control of work rate by the brain may explain the underlying cause of an end-spurt. It is recognised that an important factor in selecting certain pacing strategies is knowledge of the endpoint of the race (St Clair Gibson et al., 2006). The brain controls the power output by regulating motor unit recruitment based on knowledge of the endpoint, experience from similar past races and feedback from environmental and metabolic conditions (St Clair Gibson et al., 2006). The end-spurt requires greater utilisation of the finite anaerobic reserve, which would be riskier to use in the first part of the race due to uncertainty of the remaining required power output (Pyne & Sharp, 2014). The increasing certainty of the endpoint towards the end of the race leads to a command of higher output in the final lap, as the metabolic requirements to finish the race without premature fatigue are now more safely predictable (Emanuel, 2019). Besides psychological, there are also physiological tenets underpinning the presence of an end-spurt (Mytton et al., 2015). It is speculated that based on the critical power model an even pacing strategy for most of the race distance increases aerobic energy contribution and spares anaerobic capacity for a possible end-spurt (Toussaint et al., 1998). A recent study found that swimmers may achieve moderate improvement in overall performance by decreasing swim velocity at the start of the race (Lipińska, 2009), saving higher relative energy costs, which could spare a greater anaerobic capacity for the end-spurt. Thus, it can be noted that an end-spurt of greater magnitude is associated with higher finishing positions and better times, but a higher finishing position is not always related to a new seasonal best time.

End-spurt and distance

Swimmers showed a significantly greater end-spurt in the 1500 m than swimmers in the 800 m. This is in agreement with the literature on pacing in swimming, revealing that the pacing profile changes from being positive to more parabolic as the race distance increases (Menting et al., 2019). The main difference between 800 and 1500 m is that in the 1500 m it takes longer before the sudden increase in power output (end-spurt) occurs. Therefore, swimmers need to maintain a level of physiological reserve for longer than over shorter race distances due to an extended uncertainty about what power output is required to finish the race. This suggests that the reserve capacity is accessed when premature fatigue becomes more unlikely and peripheral fatigue can be overridden (Noakes et al., 2009; Sandals et al., 2006). An increase in power output too early could cause a lower than optimal work rate and a subsequent loss of the ability to increase swim velocity for the end-spurt or other opponent-driven challenges. It is therefore suggested that remaining distance and endpoint have a set and constant influence on pacing behaviour (Venhorst et al., 2018). The fact that swimmers swim the fastest (end-spurt) when they should experience the most muscle fatigue seems to indicate that they conserve energy in the middle part of a long-distance pool event and become increasingly certain to fully use remaining capacity for the end-spurt as the finish looms larger. The longer the distance of the race, the more challenging it becomes to evenly distribute the overall capacity of power output (Casado et al., 2020). This assumption is further supported by the greater difference in ESI among sub-elite and competitive swimmers compared to elite swimmers regarding distance, highlighting the importance of expert knowledge and race experience for optimal pacing and end-spurts. Indeed, Neuloh et al. (2020) revealed no effect of distance on ESI for elite swimmers only at Olympic Games and World Championships. In general, overall performance in 1500 m freestyle pool swimming benefits from regularly racing this event and at the same time developing one's physiological capacities (McGibbon et al., 2020).

End-spurt and performance level

Swimmers with a higher performance level show a greater end-spurt. Elite swimmers showed a mean ESI of 5.47, which is in accordance with previous findings in other studies (Hecksteden et al., 2015; Lipińska, 2009; Neuloh et al., 2020). It has been assumed that swimmers of a higher performance level demonstrate a reduced lap-to-lap variability (as well as swimming closer to their optimal work rate for the whole distance) in the middle part of the race to preserve a capacity to increase the swim velocity at the end of the race (Lipińska, 2009). Another point could be that elite swimmers have greater experience in which work rate is required to finish the race within the context of the overall pacing strategy due to more race exposure and advanced training. Swimmers with a lower performance level may have greater uncertainty about the endpoint of the race due to a lack of race experience and therefore may keep a greater reserve and reduce power output to ascertain finishing the race and avoid catastrophic failure of any physiological system (St Clair Gibson et al., 2006). The possible lack of certainty in a race of lower performance swimmers is supported by a study on sub-elite swimmers showing a greater variability in speed in 800 m freestyle races (Skorski et al., 2013). Therefore, it can be concluded that swimmers with a higher performance level have a more pronounced end-spurt than swimmers with a lower performance level and this may be due to elite swimmers having greater race experience and subsequently less uncertainty about the endpoint of the race.

Other findings

Regarding the effect of season cycle, it was found that along the overall improvement over time (Pyne et al., 2004), the magnitude of the end-spurt increased from the Pre-Season over the Main-Season towards the Main-Peak-Season. This supports the notion that swimmers develop their physiological capacity for better overall performance during the season towards their main season events, and particularly preserve a greater anaerobic capacity available for the end-spurt (Pyne et al., 2004). This necessitates that swimmers have to endure greater levels of unpleasantness and discomfort elicited by the greater work rate. This tolerance may be facilitated by a greater level of motivation during the main events of their season (Mujika et al., 2002).

The effect of round and competition level revealed that there is no modification in the end-spurt between heat and final races or between different competition levels, which was expected based on previous research (Neuloh et al., 2020). The random between-subject and random within-subject variability of the ESI seemed fairly consistent between and within competitions suggesting that pacing strategies are in fact relatively stable between and within events. This is also in accordance with the literature revealing stable pacing profiles between and within swimmers in simulated and real competitions (McGibbon et al., 2018; Skorski et al., 2013, 2014). As the random within-subject variability of ESI was higher than the random between-subject variability it can be concluded that the variation in ESI comes from the variability of the swimmers themselves rather than from different external factors.

The effect of sex showed that female swimmers have a significantly greater end-spurt than male swimmers in the current study. This contrasts with another study revealing no sex difference in end-spurt behaviour (Neuloh et al., 2020). Given a difference of 0.2 ESI and a trivial effect size of $f^2 = 0.00$ between female and male swimmers in the current study this is likely to be of no practical relevance.

Limitations and scope

To the authors' knowledge, this is the first attempt to establish the effect of end-spurt behaviour in a large-scale and field-based study on performance in swimmers of different performance levels. The current results expand on previous research which mainly assessed mean differences within the velocity pattern (Hecksteden et al., 2015; Lipińska, 2009) or only included elite swimmers at Olympic Games and World Championships without accounting for seasonal best time effects (Neuloh et al., 2020). Still, the current investigation was purely observational and retrospective. Influencing factors such as training load, periodisation (swimmers could have had different periodisation as suggested), motivation, shaving or different swimming suits could not be controlled for. Thus, only assumptions can be made on the current results. However, the large sample size makes up for some confounders as they can be assumed to be evenly distributed. Furthermore, the complexities such as the position of a competitor within the race during different time points may alter the ESI which should be the subject of future research as well as the underlying physiological/psychological mechanism.

Implications for practice

This study provides an insight into the end-spurt behaviour of competitive, sub-elite and elite swimmers in association with seasonal best time. The end-spurt is increased by the majority of swimmers when they swim faster races, despite fluctuations in swim velocity creating greater relative energy costs (Abbiss & Laursen, 2008). It can be therefore explained that end-spurt behaviour is linked to the knowledge of the end-point of the race and its certainty or uncertainty thereof. Consequently, coaches and sport scientists should include practice of different pacing pattern into the training based on the specific race distance through the use of visual or auditory pacing feedback for example (Altavilla et al., 2018). Further, swimmers might benefit from using pacing training sessions while simulating specific race distances throughout the season to accommodate yield from an end-spurt, establishing better knowledge and certainty about the end-point of the race. Last, they should consider that optimal performance requires high levels of aerobic capacity for the even-paced middle part of the race and sparing anaerobic capacity for the end-spurt, which needs to be trained.

Conclusion

It was shown and quantified that competitive, sub-elite and elite swimmers execute an end-spurt in freestyle long-distance pool swimming races over 800 and 1500 m. A greater end-spurt was associated with better seasonal best time, higher performance level of the swimmer, longer race distance and being closer to the main peak of the season. Therefore, swimmers should build their capacities to execute an end-spurt.

Acknowledgements

The authors would like to thank swimranking.net for granting access and permission to use their race report data. The results of the current study do not constitute an endorsement of the product by the authors or the journal.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Joshua E. Neuloh http://orcid.org/0000-0001-8914-7460

References

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Medicine*, *38*(3), 239–252. https://doi.org/10.2165/00007256-200838030-00004

Altavilla, C., Cejuela, R., & Caballero-Pérez, P. (2018). Effect of different feedback modalities on swimming pace: Which feedback modality is most effective? *Journal of Human Kinetics*, *65*, 187–195. https://doi.org/10.2478/hukin-2018-0026

Atkinson, G., & Batterham, A. M. (2015). True and false interindividual differences in the physiological response to an intervention. *Experimental Physiology*, *100*(6), 577–588. https://doi.org/10.1113/EP085070

Baldassarre, R., Bonifazi, M., & Piacentini, M. F. (2019). Pacing profile in the main international open-water swimming competitions. *European Journal of Sport Science*, *19*(4), 422–431. https://doi.org/10.1080/17461391.2018.1527946

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, *13*(2), 262–269. https://doi.org/10.1016/j.jsams.2009.01.003

Casado, A., Hanley, B., Jiménez-Reyes, P., & Renfree, A. (2020). Pacing profiles and tactical behaviors of elite runners. *Journal of Sport and Health Science*, *10*(5), 537–549. https://doi.org/10.1016/j.jshs.2020.06.011

Coyle, E. F. (1999). Physiological determinants of endurance exercise performance. *Journal of Science and Medicine in Sport*, *2*(3), 181–189.https://doi.org/10.1016/S1440-2440(99)80172-8

de Koning, J. J., Foster, C., Lucia, A., Bobbert M. F., Hettinga F. J., Porcari J. P. (2011). Using modeling to understand how athletes in different disciplines solve the same problem: Swimming versus running versus speed skating. International Journal of Sports Physiology and Performance, *6*(2), 276–280. https://doi.org/10.1123/ijspp.6.2.276

Emanuel, A. (2019). Perceived impact as the underpinning mechanism of the End-spurt and U-shape pacing patterns. *Frontiers in Psychology*, *10*, 1082. https://doi.org/10.3389/fpsyg.2019.01082

Foster, C., Schrager, M., Snyder, A. C., Thompson N. N. (1994). Pacing strategy and athletic performance. *Sports Medicine*, *17*(2), 77–85. https://doi.org/10.2165/00007256-199417020-00001

Foster, C., Snyder, A. C., Thompson, N. N., Green, M. A., Foley, M., & Schrager, M. (1993). Effect of pacing strategy on cycle time trial performance. *Medicine & Science in Sports &*

Exercise, 25(3), 383–388. https://doi.org/10.1249/00005768-199303000-00014

Hecksteden, A., Kraushaar, J., Scharhag-Rosenberger, F., Theisen, D., Senn, S., & Meyer, T. (2015). Individual response to exercise training – a statistical perspective. *Journal of Applied Physiology (Bethesda, MD: 1985)*, *118*(12), 1450–1459. https://doi.org/10.1152/japplphysiol.00714.2014

Konings, M. J., Foulsham, T., Micklewright, D., & Hettinga, F. J. (2020). Athlete-Opponent interdependency alters pacing and information-seeking behavior. *Medicine & Science in Sports & Exercise*, *52*(1), 153–160. https://doi.org/10.1249/MSS.0000000000002101

Lipińska, P. (2009). Kinematic tactics in the women's 800 m freestyle swimming final at the Beijing 2008 Olympic games. *Baltic Journal of Health and Physical Activity*, *1*. https://doi.org/10.2478/v10131-009-0010-0

Lipińska, P., Allen, S. V., & Hopkins, W. G. (2016a). Modeling parameters that characterize pacing of elite female 800-m freestyle swimmers. *European Journal of Sport Science*, *16*(3), 287–292. https://doi.org/10.1080/17461391.2015.1013996

Lipinska, P., Allen, S. V., & Hopkins, W. G. (2016b). Relationships between pacing parameters and performance of elite male 1500-m swimmers. *International Journal of Sports Physiology and Performance*, *11*(2), 159–163. https://doi.org/10.1123/ijspp.2015-0117

Mauger, A. R., Neuloh, J., & Castle, P. C. (2012). Analysis of pacing strategy selection in elite 400-m freestyle swimming. *Medicine & Science in Sports & Exercise*, *44*(11), 2205–2212. https://doi.org/10.1249/MSS.0b013e3182604b84

McGibbon, K. E., Pyne, D. B., Heidenreich, L. E., & Pla, R. (2020, Dec 8). "A novel method to characterize the pacing profile of elite male 1500-m freestyle swimmers". *Int J Sports Physiol Perform*, *6*(6), 818–824. doi:10.1123/ijspp.2020-0375. PMID: 33291067.

McGibbon, K. E., Pyne, D. B., Shephard, M. E., & Thompson, K. G. (2018). Pacing in swimming: A systematic review. *Sports Medicine (Auckland, N.Z.)*, *48*(7), 1621–1633. https://doi.org/10.1007/s40279-018-0901-9

Menting, S. G. P., Elferink-Gemser, M. T., Huijgen, B. C., & Hettinga, F. J. (2019). Pacing in lane-based head-to-head competitions: A systematic review on swimming. *Journal of Sports Sciences*, *37*(20), 2287–2299. https://doi.org/10.1080/02640414.2019.1627989

Morais, J. E., Barbosa, T. M., Forte, P., Bragada, J. A., Castro, F., & Marinho, D. A. (2020). Stability analysis and prediction of pacing in elite 1500 m freestyle male swimmers. *Sports Biomechanics*, 1–18.

Morais, J. E., Barbosa, T. M., Neiva, H. P., & Marinho, D. A. (2019). Stability of pace and turn parameters of elite long-distance swimmers. *Human Movement Science*, *63*, 108–119. https://doi.org/10.1016/j.humov.2018.11.013

Morais, J. E., Sanders, R. H., Papic, C., Barbosa, T. M., & Marinho, D. A. (2020). The influence of the Frontal surface area and swim velocity variation in Front crawl active drag. *Medicine & Science in Sports & Exercise*, *52*(11), 2357–2364. https://doi.org/10.1249/MSS.0000000000002400

Mujika, I., Padilla, S., & Pyne, D. (2002). Swimming performance changes during the final 3 weeks of training leading to the Sydney 2000 Olympic games. *International Journal of Sports Medicine*, *23*(8), 582–587. https://doi.org/10.1055/s-2002-35526

Mujika, I., Villanueva, L., Welvaert, M., & Pyne, D. B. (2019). Swimming fast when it counts: A 7-year analysis of Olympic and World Championships performance. *International Journal of Sports Physiology and Performance*, *14*(8), 1132–1139. https://doi.org/10.1123/ijspp.2018-0782

Mytton, G. J., Archer, D. T., Turner, L., Skorski S., Renfree A., Thompson K. G., St Clair Gibson A. (2015). Increased variability of lap speeds: Differentiating medalists and nonmedalists in middle-distance running and swimming events. *International Journal of Sports Physiology and Performance*, *10*(3), 369–373. https://doi.org/10.1123/ijspp.2014-0207

Neuloh, J. E., Skorski, S., Mauger, L., Hecksteden, A., & Meyer, T. (2020). Analysis of end-spurt behaviour in elite 800-m and 1500-m freestyle swimming. *European Journal of Sport Science* 21(12), 1–9.

Noakes, T. D., Lambert, M. I., & Hauman, R. (2009). Which lap is the slowest? An analysis of 32 world mile record performances. *British Journal of Sports Medicine*, *43*(10), 760–764. https://doi.org/10.1136/bjsm.2008.046763

Pyne, D., Trewin, C., & Hopkins, W. (2004). Progression and variability of competitive performance of Olympic swimmers. *Journal of Sports Sciences*, *22*(7), 613–620. https://doi.org/10.1080/02640410310001655822

Pyne, D. B., & Sharp, R. L. (2014). Physical and energy requirements of competitive swimming events. *International Journal of Sport Nutrition and Exercise Metabolism*, *24*(4), 351–359. https://doi.org/10.1123/ijsnem.2014-0047

Rodriguez, L., & Veiga, S. (2018). Effect of the pacing strategies on the open-water 10-km World Swimming Championships performances. *International Journal of Sports Physiology and Performance*, *13*(6), 694–700. https://doi.org/10.1123/ijspp.2017-0274

Sandals, L. E., Wood, D. M., Draper, S. B., & James, D. V. B. (2006). Influence of pacing strategy on oxygen uptake during treadmill middle-distance running. *International Journal of Sports Medicine*, *27*(1), 37–42. https://doi.org/10.1055/s-2005-837468

Selya, A. S., Rose, J. S., Dierker, L. C., Hedeker, D., & Mermelstein, R. J. (2012). A practical guide to calculating Cohen's f(2), a measure of local effect size, from PROC MIXED. *Frontiers in Psychology*, *3*(111).

Skorski, S., Faude, O., Caviezel, S., & Meyer, T. (2014). Reproducibility of pacing profiles in elite swimmers. *International Journal of Sports Physiology and Performance*, *9*(2), 217–225. https://doi.org/10.1123/ijspp.2012-0258

Skorski, S., Faude, O., Rausch, K., & Meyer, T. (2013). Reproducibility of pacing profiles in competitive swimmers. *International Journal of Sports Medicine*, *34*(2), 152–157.

St Clair Gibson, A., Lambert, E. V., Rauch, L. H. G., Tucker R., Baden D. A., Foster C., Noakes T. D. (2006). The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Medicine (Auckland, N.Z.)*, *36*(8), 705–722. https://doi.org/10.2165/00007256-200636080-00006

St Clair Gibson, A., & Noakes, T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, *38*(6), 797–806. https://doi.org/10.1136/bjsm.2003.009852

Thompson, K. G., MacLaren, D. P. M., Lees, A., & Atkinson, G. (2004). The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. *Journal of Sports Sciences*, *22*(2), 149–157. https://doi.org/10.1080/02640410310001641467

Toussaint, H. M., Wakayoshi, K., Hollander, A. P., & Ogita, F. (1998). Simulated front crawl swimming performance related to critical speed and critical power. *Medicine & Science in Sports & Exercise*, *30*(1), 144–151. https://doi.org/10.1097/00005768-199801000-00020

Tucker, R., Lambert, M. I., & Noakes, T. D. (2006). An analysis of pacing strategies during men's world-record performances in track athletics. *International Journal of Sports Physiology and Performance*, *1*(3), 233–245. https://doi.org/10.1123/ijspp.1.3.233

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: A critical review. *British Journal of Sports Medicine*, *43*(6), e1. https://doi.org/10.1136/bjsm.2009.057562

Venhorst, A., Micklewright, D., & Noakes, T. D. (2018). Towards a three-dimensional framework of centrally regulated and goal-directed exercise behaviour: A narrative review. *British Journal of Sports Medicine*, *52*(15), 957–966. https://doi.org/10.1136/bjsports-2016-096907

European Journal of Sport Science, 2021
Vol. 21, No. 12, 1628–1636, https://doi.org/10.1080/17461391.2020.1851772

Routledge
Taylor & Francis Group

ORIGINAL ARTICLE

Analysis of end-spurt behaviour in elite 800-m and 1500-m freestyle swimming

JOSHUA E. NEULOH [1]*, SABRINA SKORSKI[1]*, LEX MAUGER[2], ANNE HECKSTEDEN[1], & TIM MEYER[1]

[1]*Institute of Sports and Preventive Medicine, Saarland University, Saarbrücken, Germany &* [2]*School of Sport and Exercise Sciences, University of Kent, Chatham, Kent, England, UK*

Abstract
To analyse the influence of distance, time point of competition, round and finishing position on end-spurt behaviour in swimming. Race results in 800-m and 1500-m freestyle swimming from the last 8 World Championships and 5 Olympic Games (1998–2016) including 1433 races and 528 swimmers were obtained. The end-spurt for each race was determined by means of an End-Spurt Indicator (ESI). The ESI was calculated by dividing the difference between the swim velocity of the last lap (SVLL) and the mean swim velocity of the middle part of the race (SVMP) by the respective individual standard deviation of SVMP. Subsequently, ESI was used as a dependent variable and influences were analysed using a linear mixed model with fixed effects for distance, time point of competition, round and finishing position. An end-spurt was evident in most swims for both race distances. The mean change in swim velocity between the middle part of the race and the last lap was 0.06 ± 0.02 m/s (1.2 ± 0.2 s) in the 800-m and 0.07 ± 0.02 m/s (1.5 ± 0.2 s) in the 1500-m. The finishing position within a race significantly affected the ESI ($P < .001$, $t = 7.28$). Specifically, when analysing finals only, ESI was significantly greater in medallists (5.76; quantile: 3.61 and 8.06) compared to non-medallists (4.06; quantile: 1.83 and 6.82; $P = .001$). The between-subject standard deviation was 1.66 (CI: 1.42–1.97) with a relative variance component of 23%, while 77% of ESI variance remained unexplained. This is the first study using a newly developed indicator of end-spurt behaviour demonstrating that particularly medallists have a more pronounced end-spurt compared to non-medallists.

Keywords: *pacing strategy, swim velocity, water, elite swimmers, tactics*

Highlights

- Swimmers seem to consistently execute an end-spurt in both the 800-m and 1500-m races.
- Coaches and sport scientists should take into account that an increase in velocity is utilized particularly by medallists.
- Swimmers might benefit from utilising pacing training sessions to accommodate yield from an end-spurt.

Introduction

In order to reach an endurance event's endpoint in the fastest time possible, athletes should appropriately distribute their energy expenditure in a way that all available energetic resources are used but not too early so as to avoid premature fatigue and a loss of speed (St Clair Gibson & Noakes, 2004). In competitions when the aim is to cover a given race distance in the fastest time possible, this regulation of speed, power or energy expenditure is extremely important for the optimisation of performance (Tucker & Noakes, 2009). Based on current research, pacing appears to be regulated by complex interactions between the brain and other physiological systems (McGibbon, Pyne, Shephard, & Thompson, 2018). Despite biomechanical and physiological influences on pacing, competitors might further affect an athlete's pacing by changes in their race tactics, and their presence means that the ultimate goal is to beat them rather than post the fastest time (Abbiss & Laursen, 2008; Foster, Schrager, Snyder, & Thompson, 1994; Mauger,

*These authors contributed equally as first authors.
Correspondence: Joshua E. Neuloh, Institute of Sports and Preventive Medicine, Saarland University, 66123 Saarbrücken, Germany. E-mail: j.neuloh@mail.com

Neuloh, & Castle, 2012; Tucker, Lambert, & Noakes, 2006).

Pacing in long-distance swimming in pool competitions is considered an important determinant of success, especially in the case of very similar individual capacities between swimmers (Baldassarre, Bonifazi, & Piacentini, 2019; Lipinska, Allen, & Hopkins, 2016; Lipińska, 2009; Lipińska, Allen, & Hopkins, 2016; Mauger et al., 2012; Rodriguez & Veiga, 2018; Veiga, Rodriguez, González-Frutos, & Navandar, 2019). Indeed, due to the high resistive properties of the water and the low mechanical efficiency, pacing is likely to be more critical in swimming compared to other endurance-based sports (Thompson, MacLaren, Lees, & Atkinson, 2004). It is suggested that even small changes in swim velocity can result in a substantial increase in energy expenditure and thus premature fatigue (Lipinska et al., 2016). A swimmer's distribution of speed throughout the race might be especially important in order to use available energetic resources efficiently (Barbosa et al., 2010; Lipinska et al., 2016). In long distance freestyle pool events of 800-m and above, a parabolic shaped pacing pattern is usually used (McGibbon et al., 2018), including a fast start, an even middle part and an increase in speed in the last stages of the race, which is suggested to be consistent throughout different competitions and between heat and final races (Skorski, Faude, Caviezel, & Meyer, 2014). Such an increase in speed or power at the end of the race is generally called end- or final spurt. It has been typically described in head-to-head competitions, where success is determined by performing marginally better than other competitors in order to achieve a better finishing position. In such events, athletes seem to retain a reserve of energy required for an end-spurt to possibly outsprint an opponent in the last few meters (Foster et al., 1993).

The vast majority of the pacing literature considers an end-spurt to be a statistically significant mean difference between the last and the penultimate split. However, an evaluation of group means is of little value with respect to the individual athlete. Moreover, when analysing the end-spurt behaviour within one athlete it seems beneficial to consider the intra-individual variability during the middle part of the individual race. The relevant considerations are consistent with research on individual responses to exercise training (Atkinson & Nevill, 1998). Specifically, a deviation in mean velocity may be interpreted in the context of random variability, which in this case would mean that an athlete has performed an end-spurt if the last lap is performed faster than the middle part of the race by more than the intra-individual variability (Hecksteden et al., 2015; Senn, 2004). Consequently, we propose the difference between the last lap and the middle part of the race divided by the respective standard deviation as an end-spurt indicator (ESI). Thus, the ESI used in this work is directly based on the above rationale.

Therefore, the aim of the current study was to analyse the end-spurt behaviour in long-distance pool swimming events in relation to distance, time point of competition, round and finishing position using this newly ESI. It was hypothesised that the ESI magnitude is related to the swimmerś finishing position, distance, but not time point of competition or round.

Methods

Subjects

All procedures were in accordance with the declaration of Helsinki. It was not considered necessary to obtain informed consent from swimmers because only publicly accessible information was used and all data were anonymised during the entire analysis. Races from all swimmers participating in the World Championships and Olympic Games between 1998 and 2016 were analysed. One hundred and twenty-nine races were excluded since finishing position for heats or finals were not accessible. Therefore, a total of 1433 races from 528 different elite swimmers (1115 heats; 318 finals) over 800-m (men: $n = 283$; age: 21.6 ± 3.1 years, women: $n = 448$; age: 21.0 ± 3.7 years) and 1500-m (men: $n = 497$; age 21.9 ± 3.2, women: $n = 205$; age: 21.1 ± 4.0 years) freestyle were retrospectively analysed. Semi-finals do not exist for these race distances in swimming, thus heats and finals only were analysed. Several swimmers competed in more than one competition ($n = 220$) and/or distance ($n = 199$; Table I) resulting in an unequal number of races per swimmer.

Events

Overall, the current analysis examined eight World Championships and five Olympic Games between 1998 and 2016. Race data were obtained using the web site www.swimrankings.net (Splash Software Ltd., Switzerland; 20 December 2017), which is based on information from the European Swimming Federation (LEN) database and the results from the Belgian, Canadian, Dutch, Polish, Portuguese and Swiss federations. Each race report included a subject identification number for each swimmer, the name of the competition, distance, round (heat vs. final), overall finishing position, 50-m split times (s) and the total completion time (s). All events were swum in a long-course (50-m) pool. Total and all 50-m split times were downloaded from the

Table I. Number of races repeated by all subjects

	Subjects (*n*)	Number of competitions (*n*)								
		One	Two	Three	Four	Five	Six	Seven	Eight	Nine
800-m	273	111	74	21	26	11	8	4	6	4
1500-m	255	102	64	28	22	15	5	3	1	3

official site www.swimrankings.net. In all events automatic officiating equipment was used under the supervision of appointed officials and recorded to 0.01 s to determine total times, as well as 50-m split times (according to FINA swimming rules).

End-spurt indicator

To evaluate the end-spurt an "End-Spurt Indicator" (ESI; arbitrary units) was designed by the authors. This ESI was based on the mean swim velocity (m/s) and the respective standard deviation (SD*)* of each individual swimmer. Due to the rapid acceleration caused by the diving start, swimmers typically complete the first 50-m faster than any other section of the race (Skorski et al., 2014; Veiga & Roig, 2017). Thus, the first 50-m split was not included when calculating mean swim velocity. The last lap was also excluded as it was used as the reference split for the ESI calculation. The first and final lap is reported to be an important parameter to characterise pacing in swimming (Lipinska et al., 2016), whereas medallists swim a relatively faster last lap than non-medallists (Mytton et al., 2015). Therefore, the velocity of the middle part (SVMP) of the race was calculated using the individual mean (±SD) speed in the laps 2–15 and 2–29 in the 800-m and 1500-m race, respectively. To define an individual ESI per race and subject, the difference between the swim velocity in the last lap (SVLL) and the corresponding SVMP was divided by the respective individual SD of SVMP.

$$ESI = \frac{SVLL - meanSVMP}{meanSVMP\ SD}$$

For example, if the final lap was swam in 2.0 m/s and lap 2–15 had a mean swim velocity of 1.5 m/s with a mean SD of 0.5 m/s in the 800-m, an ESI of 1.0 would have been calculated. The approach to define ESI as the difference between the last lap and mean swim velocity divided by the individual standard deviation is similar to methods used when analysing individual response, e.g. in medicine (Hecksteden et al., 2015). The standard deviation provides an estimate of gross variability in the mean SVMP. Similarly to the classification of responders and non-responders, the definition of ESI can be based on different rationales (Hecksteden, Pitsch, Rosenberger, & Meyer, 2018). In the current manuscript the following fixed threshold value was used: ESI was defined when the value was > 0.

Statistical analysis

Statistical analyses were conducted using Statistica 8 (StatSoft, Hamburg, Germany) and the R statistical programming language (R Core Development Team, 2016). Overall performance data were normally distributed (Kolmogorow-Smirnow-Test), thus, data is presented as means and standard deviation (SD). Because ESI within individual subjects was not normally distributed descriptive data are presented as medians with 25th and 75th percentiles.

Changes in ESI were analysed using a linear mixed model with fixed effects for distance (2 levels: 800-m and 1500-m), time point of competition (13 levels: year of competition), round (2 levels: heat and final) and finishing position (51 levels: overall finishing position) and a random effect for a swimmer's identity. The 51 levels for overall finishing position refer to the maximum number of participants in heats. A separated linear mixed model was performed including only final races, with the additional fixed effect of medal (two level: medallist and non-medallist). An α-error of $p < .05$ was accepted as level of significance.

Results

Overall results

Total times in 800-m and 1500-m in both heat and finale races for men and women are shown in Table II. Total time in finals was significantly faster in both distances compared to heats ($P < .001$). In the 800-m, finals were on average 15.53 s faster than heats ($P < .001$); in the 1500-m performance improved by 24.87 s from heat to final ($P < .001$). With regard to pacing pattern, swimmers adopted a parabolic shaped pattern in both distances, racing the first split significantly faster than all others ($P < .001$) and showing a higher split velocity in the last 50-m compared to all others ($P < .001$).

Table II. Number of races and swim times for all subjects ($n = 528$; n in table reflects number of races included)

	Heat total time (min)		Final total time (min)
		Men ($n = 780$)	
800-m ($n = 283$)	08:08,64 ± 21,68		7:48,42 ± 6,84
1500-m ($n = 497$)	15:26,07 ± 34,97		14:55,82 ± 12,29
		Women ($n = 653$)	
800-m ($n = 448$)	08:42,32 ± 18,73		8:26,12 ± 7,56
1500-m ($n = 205$)	16:34,22 ± 35,15		16:04,19 ± 14,31

Data is shown as mean ± standard deviation (SD).

End-spurt

Mean swim velocity of SVMP was 1.57 ± 0.08 m/s during the 800-m races and 1.60 ± 0.08 during the 1500-m, respectively. The mean change in swim velocity between the middle part of the race and the last lap was 0.06 ± 0.02 m/s; 3.68% (1.18 ± 0.19 s) in the 800-m and 0.07 ± 0.02 m/s; 4.20% (1.52 ± 0.23 s) in the 1500-m distance. This was reflected by a mean ESI of 4.24 (Cl: 3.73–4.00) in the 800-m and 4.58 (Cl: 4.30–4.86) in the 1500-m race. A total of 83 swimmers showed a negative ESI of −1.87 ± 0.75 on average, which numerically would indicate the absence of an end-spurt (interquartile range 4.70). Figure 1 shows the median ESI of each individual swimmer as well as their minimum and maximum for the 800-m (A) and 1500-m (B) distance with at least two races. There was no effect ($P > .05$) on ESI for sex, therefore male and female swimmers were analysed together.

No significant effect on ESI was observed for either distance ($P = .64$, $t = -10.0$), time point of competition ($P > .08$) and round ($P = .42$, $t = -0.79$). Between-subject standard deviation was 1.66 (Cl: 1.42–1.97; relative variance component subject ID = 23.2%), while 76.8% of ESI variance remained unexplained. Overall finishing position significantly influenced ESI with better ranked swimmers showing a greater ESI ($P < .001$, $t = 7.28$; Figure 2). Swimmers with a better finishing position in heats or finals showed an ESI of 2.79 (finishing 9th to 50th), whereas in swimmers finishing 1st to 8th ESI was 5.20. When analysing final events only, ESI was significantly higher in medallists (5.99; Cl: 5.32–6.66) compared to non-medallists (4.52; Cl: 4.01–5.02; $P = .001$).

Discussion

This study was designed to analyse end-spurt behaviour in elite 800-m and 1500-m freestyle swimming. An end-spurt indicator has been applied and evaluated to investigate the influence of potential determinants such as distance, time point of competition, round and finishing position. Firstly, ESI among medallists is greater compared to non-medallists which illustrates its construct validity. Secondly, the retrospective analysis of elite competitions during the last 18 years revealed that swimmers seem to consistently execute an end-spurt of a similar magnitude in both the 800-m and 1500-m races. However, there was no significant effect of time point of competition or round. To the authors' knowledge, this is the first attempt to quantify an end-spurt statistically according to the individual responses paradigm and to estimate potential influencing factors. The current results expand on previous research which mainly assessed mean differences within the velocity pattern (Lipinska et al., 2016; Lipińska et al., 2016) by developing an indicator that considers different variance components as well as within-subject variability during the middle part of the race.

The presence of an end-spurt in the 800-m and 1500-m is in accordance with previous research (Lipinska et al., 2016; Lipińska et al., 2016) and expectations. In a recent review, McGibbon et al. summarised that similar to middle-distance pool events, parabolic pacing is typically observed in freestyle pool events of 800-m or above with the highest swimming velocity at the start and the end of the race (McGibbon et al., 2018). Lipinska et al. reported a 3.6% and 5.8% faster last lap compared to the middle part in 800- and 1500-m competitions over a period of 13 years (Lipińska et al., 2016). Whilst the change in pace in the 800-m is similar to our analysis, the last lap in the 1500-m was only 4.2% faster. This discrepancy in the 1500-m could be related to the fact that Lipinska et al. only included the fastest race at a competition into their analysis, leaving out performances in heats or slower races (Lipińska et al., 2016).

Based on the random between-subject and random within-subject variability the ESI seems fairly consistent between and within competitions. This supports its use because stable pacing profiles between and within swimmers are in accordance with recently published findings in simulated and real competitions (McGibbon et al., 2018; Skorski

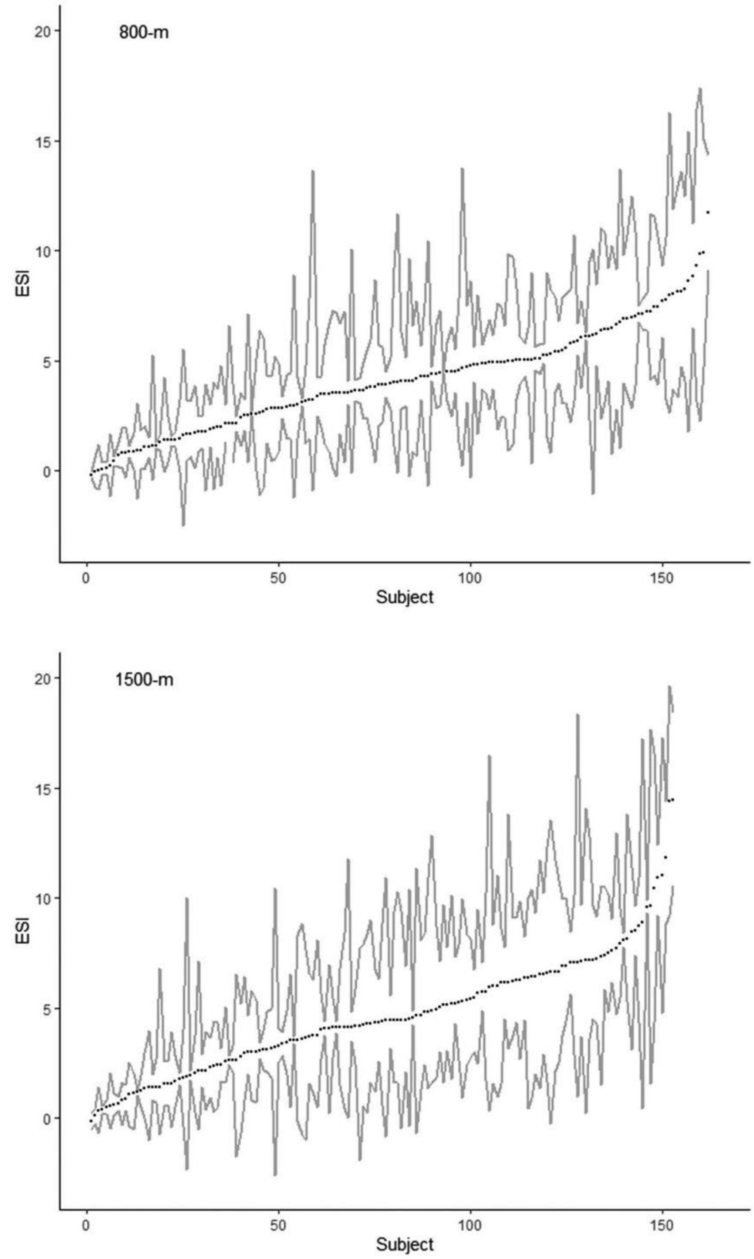

Figure 1. Individual End-Spurt Indicator (ESI; black dots) for the 800-m (A) and 1500-m (B) distance. The grey lines display the minimum (lower line) and maximum (upper line) ESI observed in each individual. Swimmers are sorted according to their ESI from small to large (swimmer number does not relate to subject ID). Because ESI within individual subjects was not normally distributed, descriptive data are presented as medians with 25th and 75th percentiles.

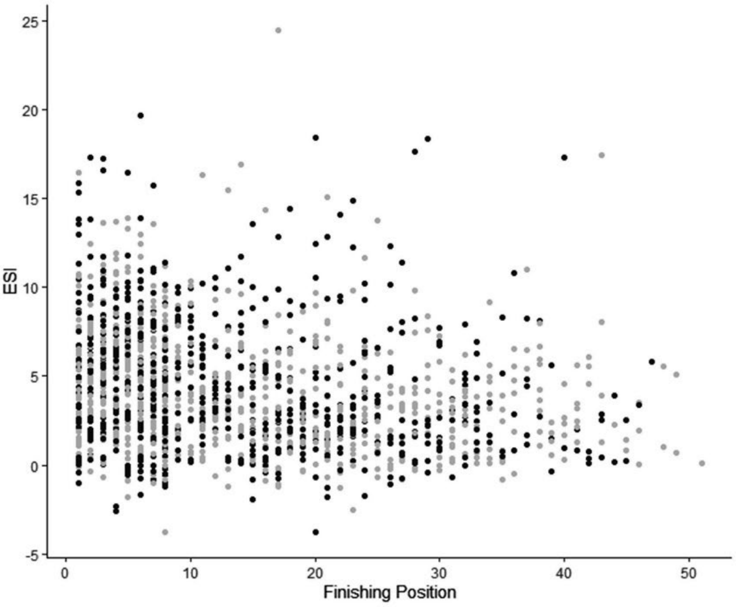

Figure 2. Scatterplot displaying the individual End-Spurt Indicator (ESI) in relation to final finishing position for the 800-m (grey dots) and 1500-m (black dots).

et al., 2014; Skorski, Faude, Rausch, & Meyer, 2013). It indicates that world-class swimmers do not seem to modify their end-spurt due to varying race tactics or different types of competition. The random within-subject variability of ESI was higher than the random between-subject variability indicating that the variation in ESI comes from the variability of the swimmers themselves rather than from different general race tactics. Nonetheless, further complexities such as the position of a competitor within the race during different time points may alter the ESI which should be subject of future research. It should further be considered that the current analysis only included World Championships and Olympic Games. As these are the major events in a swimmer's career it can be assumed that the athletes tried to produce a best time during these competitions. Future research should evaluate if the end-spurt changes throughout a season and/or an athlete's career and if such a potential change is associated with the general performance development.

The finding that medal placing had a significant effect on ESI is in agreement with previous research. For example, Mytton et al. observed that medallists showed a greater increase in speed at the end of a 400-m freestyle race compared to non-medallists (Mytton et al., 2015), which seemed to be the main factor differentiating medallists and non-medallists in their analysis. Further, it was described that medallists swam below their mean race velocity for the first half of the race and non-medallist above their mean race velocity, whereas the opposite was seen in the final 100-m of the race. Therefore, it was concluded that medallists start more conservatively compared to non-medallists in the 400-m freestyle (Mytton et al., 2015). Alternatively, it is possible that some non-medallists have not produced an end-spurt because of too little prospect of winning. Although the similarity/comparability of pool and open-water swimming is questionable, a faster end-spurt was highly correlated with a better overall finishing position in 5 and 25-km events with better positioned swimmers showing a significantly faster last lap compared to lower ranked athletes (Baldassarre et al., 2019; Rodriguez & Veiga, 2018). Indeed, when analysing finishing position, we also observed a significantly greater ESI in swimmers with a higher finishing position compared to swimmers with a lower finishing position. It is suggested that better athletes are able to keep a reserve capacity for the end-spurt, whereas swimmers with a lower fitness level already have to perform at their individual "limit" to keep up with the faster swimmers (i.e. medallists) during the middle part of the race. A potential explanation might be that medallists experience less physiological disturbance during the start and middle part of the race, taking longer to reach their VO_2max than non-medallists and therefore retain a greater reserve for the end spurt (Mytton et al., 2015).

Several studies have attempted to describe pacing behaviour during long-distance swimming in the pool (Lipinska et al., 2016; Lipińska et al., 2016; Mytton et al., 2015) and in open-water races (Baldassarre et al., 2019; Rodriguez & Veiga, 2018; Veiga et al., 2019). However, the majority of these studies investigated changes in swim velocity throughout the race, without a specific focus on the end-spurt. In head-to-head competitions the capability to outperform an opponent in the last meters of a race is especially important for the single athlete. Therefore, a better understanding of individual end-spurt behaviour could help athletes and coaches in their individual race preparation. As mentioned earlier the majority of pacing literature defines an end-spurt as a significant increase in speed in the last lap of a race or the effect size of it (Lipińska et al., 2016; Mytton et al., 2015). However, an evaluation of group means is of little value with respect to the individual athlete. Thus, it seems beneficial to consider the intra-individual variability during the middle part of the individual race. Similarly to approaches to evaluate individual responses in performance changes (Atkinson & Batterham, 2015; Hecksteden et al., 2015), it seems important to understand sources of variation that may contribute to overall gross variability. Therefore, the current ESI includes the standard deviation of the mean swim velocity in the middle part of the race as an indicator of within-subject variation. According to the literature this might help to determine the true individual difference in speed throughout the race and at the end (Atkinson & Batterham, 2015), which can lead to a better understanding of individual end-spurt behaviour in swimming. Although this definition and mathematical model is based on statistical principles, it needs further verification. Nonetheless, this analysis presents a first attempt for an objective measure to quantify an end-spurt in relation to the individual swim speed variability.

The current investigation was purely observational and retrospective. Influencing factors such as motivation, shaving, different swimming suits or diets could not be controlled for. Even though Skorski et al. (2013) observed similar pacing profiles in simulated and real competitions the internal validity of our approach might have been lower than in lab-based experiments. Since analysed data were taken from real competitions in high-level swimmers, however, a high external validity is ensured and results are applicable to the highest performance level. Furthermore, Mauger et al. (2012) recently described that pacing patterns seem independent of swimsuit design.

Practical implications

This study provides an insight into the pacing pattern of elite swimmers in the final stages of 800-m and 1500-m freestyle races. Coaches and sport scientists should take into account that an increase in velocity is used by the majority of the swimmers, particularly by medallists, even though any fluctuations in velocity could create higher relative energy costs (Foster et al., 1994). Therefore, swimmers might benefit from using pacing training sessions to accommodate yield from an end-spurt. However, it is important to note that this study only contains a retrospective analysis of the end-spurt adopted by elite freestyle swimmers. Due to the fact that no experimental data was collected, the underlying physiological and/or psychological mechanisms can only be speculated upon. Based on previous laboratory-based studies, it might be suggested that improved O_2 kinetics (Bishop, Bonetti, & Dawson, 2002; Jones, Wilkerson, Vanhatalo, & Burnley, 2008), the distribution of anaerobic capacity (Jones et al., 2008) and reduction in oxygen deficit (Bishop et al., 2002) in combination with several biomechanical factors could be the cause for a certain pacing pattern including the end-spurt.

Conclusion

It was shown and quantified that elite swimmers execute an end-spurt in freestyle long-distance pool swimming races over 800-m and 1500-m. The extent of the end-spurt is not associated with competition, round, or distance, but is associated with finishing position. In particular, medallists have a more pronounced end-spurt compared to non-medallists. The current analysis proposes a new indicator to evaluate end-spurt behaviour in elite swimmers, which considers within-subject variability of swim speed and might be useful for future research in this area.

Acknowledgements

The authors would like to thank swimranking.net for granting access and permission to use their race report data. The results of the current study do not constitute endorsement of the product by the authors or the journal.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

JOSHUA E. NEULOH http://orcid.org/0000-0001-8914-7460

References

Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Medicine*, *38*(3), 239–252. doi:10.2165/00007256-200838030-00004

Atkinson, G., & Batterham, A. M. (2015). True and false interindividual differences in the physiological response to an intervention. *Experimental Physiology*, *100*(6), 577–588. doi:10.1113/EP085070

Atkinson, G., & Nevill, A. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, *26*, 217–238.

Baldassarre, R., Bonifazi, M., & Piacentini, M. F. (2019). Pacing profile in the main international open-water swimming competitions. *European Journal of Sport Science*, *19*(4), 422–431. doi:10.1080/17461391.2018.1527946

Barbosa, T. M., Bragada, J. A., Reis, V. M., Marinho, D. A., Carvalho, C., & Silva, A. J. (2010). Energetics and biomechanics as determining factors of swimming performance: Updating the state of the art. *Journal of Science and Medicine in Sport*, *13*(2), 262–269. doi:10.1016/j.jsams.2009.01.003

Bishop, D., Bonetti, D., & Dawson, B. (2002). The influence of pacing strategy on VO2 and supramaximal kayak performance. *Medicine & Science in Sports & Exercise*, *34*(6), 1041–1047.

Foster, C., Schrager, M., Snyder, A. C., & Thompson, N. N. (1994). Pacing strategy and athletic performance. *Sports Medicine*, *17*(2), 77–85. doi:10.2165/00007256-199417020-00001

Foster, C., Snyder, A. C., Thompson, N. N., Green, M. A., Foley, M., & Schrager, M. (1993). Effect of pacing strategy on cycle time trial performance. *Medicine & Science in Sports & Exercise*, *25*(3), 383–388.

Hecksteden, A., Kraushaar, J., Scharhag-Rosenberger, F., Theisen, D., Senn, S., & Meyer, T. (2015). Individual response to exercise training – A statistical perspective. *Journal of Applied Physiology*, *118*(12), 1450–1459. doi:10.1152/japplphysiol.00714.2014

Hecksteden, A., Pitsch, W., Rosenberger, F., & Meyer, T. (2018). Repeated testing for the assessment of individual response to exercise training. *Journal of Applied Physiology*, *124*(6), 1567–1579. doi:10.1152/japplphysiol.00896.2017

Jones, A. M., Wilkerson, D. P., Vanhatalo, A., & Burnley, M. (2008). Influence of pacing strategy on O2 uptake and exercise tolerance. *Scandinavian Journal of Medicine & Science in Sports*, *18*(5), 615–626. doi:10.1111/j.1600-0838.2007.00725.x

Lipińska, P. (2009). Kinematic tactics in the women's 800 m freestyle swimming final at the Beijing 2008 Olympic Games. *Baltic Journal of Health and Physical Activity*, *1*. doi:10.2478/v10131-009-0010-0

Lipińska, P., Allen, S. V., & Hopkins, W. G. (2016). Modeling parameters that characterize pacing of elite female 800-m freestyle swimmers. *European Journal of Sport Science*, *16*(3), 287–292. doi:10.1080/17461391.2015.1013996

Lipinska, P., Allen, S. V., & Hopkins, W. G. (2016). Relationships between pacing parameters and performance of elite male 1500-m swimmers. *International Journal of Sports Physiology and Performance*, *11*(2), 159–163. doi:10.1123/ijspp.2015-0117

Mauger, A. R., Neuloh, J., & Castle, P. C. (2012). Analysis of pacing strategy selection in elite 400-m freestyle swimming. *Medicine & Science in Sports & Exercise*, *44*(11), 2205–2212. doi:10.1249/MSS.0b013e3182604b84

McGibbon, K. E., Pyne, D. B., Shephard, M. E., & Thompson, K. G. (2018). Pacing in swimming: A systematic review. *Sports Medicine*, *48*(7), 1621–1633. doi:10.1007/s40279-018-0901-9

Mytton, G. J., Archer, D. T., Turner, L., Skorski, S., Renfree, A., Thompson, K. G., & St Clair Gibson, A. (2015). Increased variability of lap speeds: Differentiating medalists and nonmedalists in middle-distance running and swimming events. *International Journal of Sports Physiology and Performance*, *10* (3), 369–373. doi:10.1123/ijspp.2014-0207

Rodriguez, L., & Veiga, S. (2018). Effect of the pacing strategies on the open-water 10-km world swimming championships performances. *International Journal of Sports Physiology and Performance*, *13*(6), 694–700. doi:10.1123/ijspp.2017-0274

Senn, S. (2004). Individual response to treatment: Is it a valid assumption? *BMJ*, *329*(7472), 966–968. doi:10.1136/bmj.329.7472.966

Skorski, S., Faude, O., Caviezel, S., & Meyer, T. (2014). Reproducibility of pacing profiles in elite swimmers. *International Journal of Sports Physiology and Performance*, *9*(2), 217–225. doi:10.1123/ijspp.2012-0258

Skorski, S., Faude, O., Rausch, K., & Meyer, T. (2013). Reproducibility of pacing profiles in competitive swimmers. *International Journal of Sports Medicine*, *34*(2), 152–157.

St Clair Gibson, A., & Noakes, T. D. (2004). Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *British Journal of Sports Medicine*, *38*(6), 797–806. doi:10.1136/bjsm.2003.009852

Thompson, K. G., MacLaren, D. P. M., Lees, A., & Atkinson, G. (2004). The effects of changing pace on metabolism and stroke characteristics during high-speed breaststroke swimming. *Journal of Sports Sciences*, *22*(2), 149–157. doi:10.1080/02640410310001641467

Tucker, R., Lambert, M. I., & Noakes, T. D. (2006). An analysis of pacing strategies during men's world-record performances in track athletics. *International Journal of Sports Physiology and Performance*, *1*(3), 233–245.

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: A critical review. *British Journal of Sports Medicine*, *43*(6), e1. doi:10.1136/bjsm.2009.057562

Veiga, S., Rodriguez, L., González-Frutos, P., & Navandar, A. (2019). Race strategies of open water swimmers in the 5-km, 10-km, and 25-km races of the 2017 FINA world swimming championships. *Frontiers in Psychology*, *10*, 654. doi:10.3389/fpsyg.2019.00654

Veiga, S., & Roig, A. (2017). Effect of the starting and turning performances on the subsequent swimming parameters of elite swimmers. *Sports Biomechanics*, *16*(1), 34–44. doi:10.1080/14763141.2016.1179782