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SYSTEMATIC REVIEW

Pacing in Swimming: A Systematic Review

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Abstract

Background Pacing strategy, or how energy is distributed during exercise, can substantially impact athletic performance and is considered crucial for optimal performance in many sports. This is particularly true in swimming given the highly resistive properties of water and low mechanical efficiency of the swimming action.

Objectives The aim of this systematic review was to determine the pacing strategies utilised by competitive swimmers in competition and their reproducibility, and to examine the impact of different pacing strategies on kinematic, metabolic and performance variables. This will provide valuable and practical information to coaches and sports science practitioners.

Data Sources The databases Web of Science, Scopus, SPORTDiscus and PubMed were searched for published articles up to 1 August 2017.

Study Selection A total of 23 studies examining pool-based swimming competitions or experimental trials in English-language and peer-reviewed journals were included in this review.

Results In short- and middle-distance swimming events maintenance of swimming velocity is critical, whereas in long-distance events a low lap-to-lap variability and the ability to produce an end spurt in the final lap(s) are key. The most effective strategy in the individual medley (IM) is to conserve energy during the butterfly leg to optimise performance in subsequent legs. The pacing profiles of senior swimmers remain relatively stable irrespective of opponents, competition stage or type, and performance time.

Conclusion Implementing event-specific pacing strategies should benefit the performance of competitive swimmers. Given differences between swimmers, there is a need for greater individualisation when considering pacing strategy selection across distances and strokes.

Key Points

- The ability to maintain swimming velocity throughout a race is vital for optimising performance across all events.
- Although pacing profiles in competition have been well characterised, it is unclear whether these are optimal, therefore implementing alternative pacing strategies may benefit performance in some swimmers.
- Coaches and sports scientists should consider greater individualisation when determining a swimmers' optimal pacing strategy.

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1 Introduction

The main objective in competitive swimming is to complete the race in the fastest possible time. To achieve this objective, energy use needs to be distributed effectively to utilise all available resources while limiting premature fatigue [1]. This energy distribution during exercise is known as 'pacing' or the 'pacing strategy' and it is widely accepted that pacing can substantially impact athletic performance [2]. The possible negative impact of an inability to pace effectively on race day on performance is disappointing, or sometimes heartbreaking, for the swimmer given the hundreds of hours of physical, technical, tactical and mental preparation. With recent advances in technology and science in professional sport, the margins between winning and losing are narrowing, and as a result pacing is playing an increasingly important role.

The volume of pacing research has grown considerably over the last decade and is dominated by endurance sports such as running, cycling and triathlon. The focus on endurance sports is most likely related to the relative ease of investigating pacing under controlled laboratory or field conditions. Pacing research in swimming, however, is limited given, in part, the inability to externally control swimming pace effectively and difficulty in obtaining physiological measurements in the pool. Despite these challenges, the dearth of research is somewhat surprising as pacing is likely to be more critical in swimming than most sports, given the inherent low mechanical efficiency and highly resistive properties of water. While the mechanical efficiency of swimming varies with stroke, only $\sim$ 6–18% of energy generated is actually converted into mechanical work, which is low in comparison with cycling at 18–24% [3]. These characteristics are unique to swimming and have considerable implications on selection and execution of a pacing strategy. As a result, the research in land-based sports has limited application to swimming and to date a review investigating pacing in swimming has not been conducted. Therefore, the aim of this systematic review was to evaluate the pacing strategies adopted by competitive swimmers in competition, and their reproducibility, and investigate how manipulations of pace affect kinematic, metabolic and performance variables. The purpose is to provide coaches and sports science practitioners with valuable and practical information regarding pacing in swimming.

2 Methods

A systematic search of relevant databases was conducted to identify articles suitable for this review (publications to August 2017): Web of Science, Scopus, SPORTDiscus (via EBSCO) and PubMed. Examination of the reference lists of the selected articles was conducted. The search terms used were 'pacing' and 'swimming'. Studies that included collection and assessment of pacing data of pool-based swimming in peer-reviewed journals are discussed. A total of 23 studies were included in this review and the selection process is illustrated by a flow chart in Fig. 1.

3 Pacing Profile Characterisation

Pacing profiles in swimming are typically characterised by plotting split times or velocity over each lap of the event. Split times from competitions are easily accessible in the public domain via online results permitting calculation of mean lap velocity (m s^{-1}) by dividing lap distance (m) by the split time (s). Alternatively, a widely accepted method is to express velocity in each lap as a percentage of the overall mean race velocity [2]. These data provide a descriptive analysis of pacing strategies typically adopted by swimmers in competition. However, it is unclear whether these profiles are optimal for swimming performance or reflective of a deliberate pre-planned pacing strategy. Although the influence of external factors is relatively limited in swimming, the presence of a competitor in a lane nearby can influence a swimmer's pacing strategy. Swimmers might consciously modify their race plan to gain a tactical advantage over a competitor, or simply change pace to keep up with a competitor who is pulling away. Therefore, elite swimmers must possess the ability to execute a pre-determined race plan and be willing and able to respond appropriately to developing race situations. Another limitation is that only a handful of studies to date have measured split times every 5–10% of the race distance to gain the high resolution necessary to determine accurate pacing information [4].

For example, this approach would require measurement every 10–20 m in a 200 m race and every 20–40 m in a 400 m race. This level of resolution has been achieved in swimming research [5, 6] and enables effective identification of velocity changes in free swimming and in the non-swimming components of each lap. The non-swimming components include the dive start, turns and the finish, while the remainder of the race is categorised as free or mid-pool swimming. This type of detailed information is useful for coaches when identifying swimmer's strengths

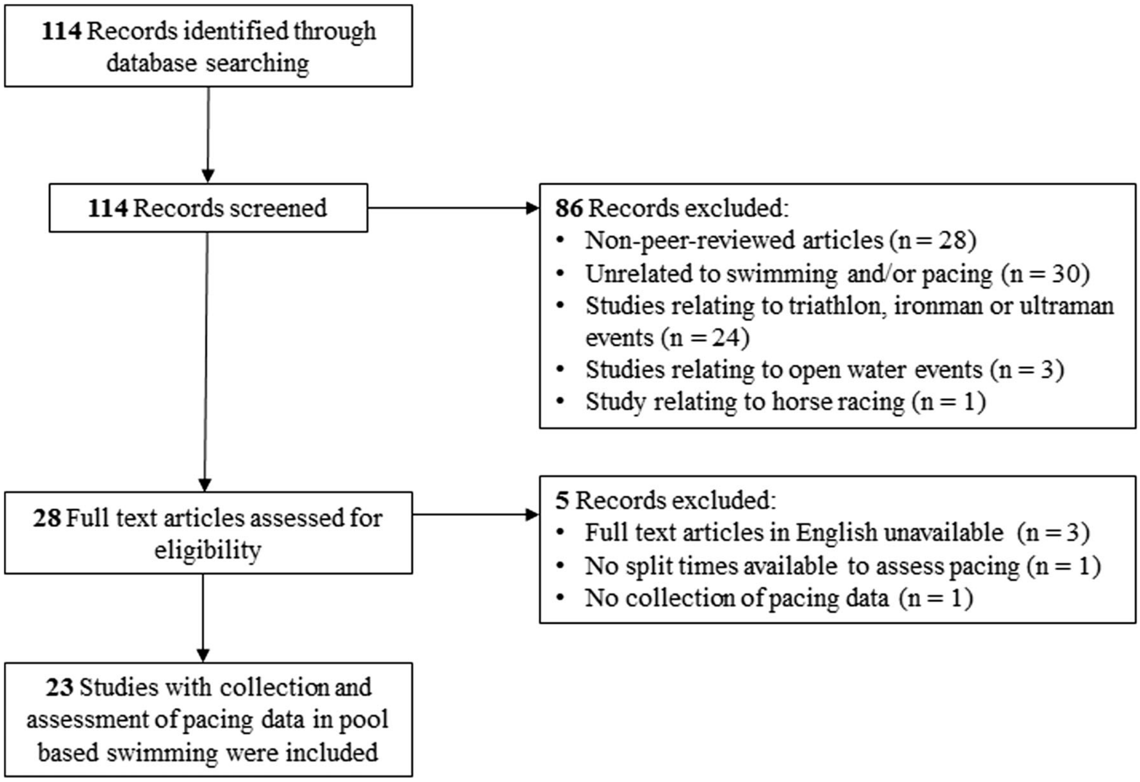

Fig. 1 Flow chart summary of the study selection process

and weaknesses to program training and design individualised race plans [7].

Swimming velocity is the product of stroke rate and stroke length [8] and typically there is a negative relationship between them whereby as one measure increases the other decreases. Stroke rate can be defined as the number of strokes per minute or the time required to complete one stroke cycle, whereas stroke length, often referred to as distance per stroke, is the distance in metres that a swimmer travels during each stroke cycle. The optimal combination of stroke rate and stroke length for a given event seems to be highly individual [9]. Finalists at the U.S. Olympic Swimming Trials in 1984 achieved higher swimming velocities compared to non-finalists due to increased distance per stroke in the majority of events [10]. Similarly, Olympic female swimmers typically display greater stroke lengths and higher stroke rates compared to National level swimmers [11]. However, stroke length decreases as fatigue develops, therefore successful swimmers are either able to sustain stroke length or compensate for a loss of stroke length by increasing stroke rate [9–11].

In swimming, the pacing profile adopted in a particular event is dependent on both race distance and stroke. A wide range of pacing profiles have been observed in swimming competitions including negative, all-out, positive, even, parabolic, and J-shaped pacing (as depicted in Fig. 2) [7, 12–15]. Across all events the rapid acceleration obtained from the dive start results in a fast first lap relative to subsequent laps. A faster first lap occurs to a lesser extent in backstroke as swimmers start in the water and therefore flight time is reduced compared with a block start [14, 16–18]. In freestyle and backstroke events, the split time for the first lap also includes the time taken to complete a tumble turn, whereas in breaststroke and butterfly events the time taken to complete the touch turn is included in the second lap split. This methodological convention means that the drop off in time between the first and second laps is typically 1–2 s longer in butterfly and breaststroke events [18]. However, for the purpose of this review, we evaluated the pacing profile characterisation research by event distance rather than by stroke. Given the unique nature of the individual medley (IM) event which comprises four different swimming strokes it will be considered separately.

3.1 Sprint Events (50–100 m)

There are surprisingly few studies detailing the pacing strategies in sprint swimming, especially in 50-m events. In short-duration sporting events lasting less than 30 s an all-out pacing strategy is typically employed [2]. Despite a

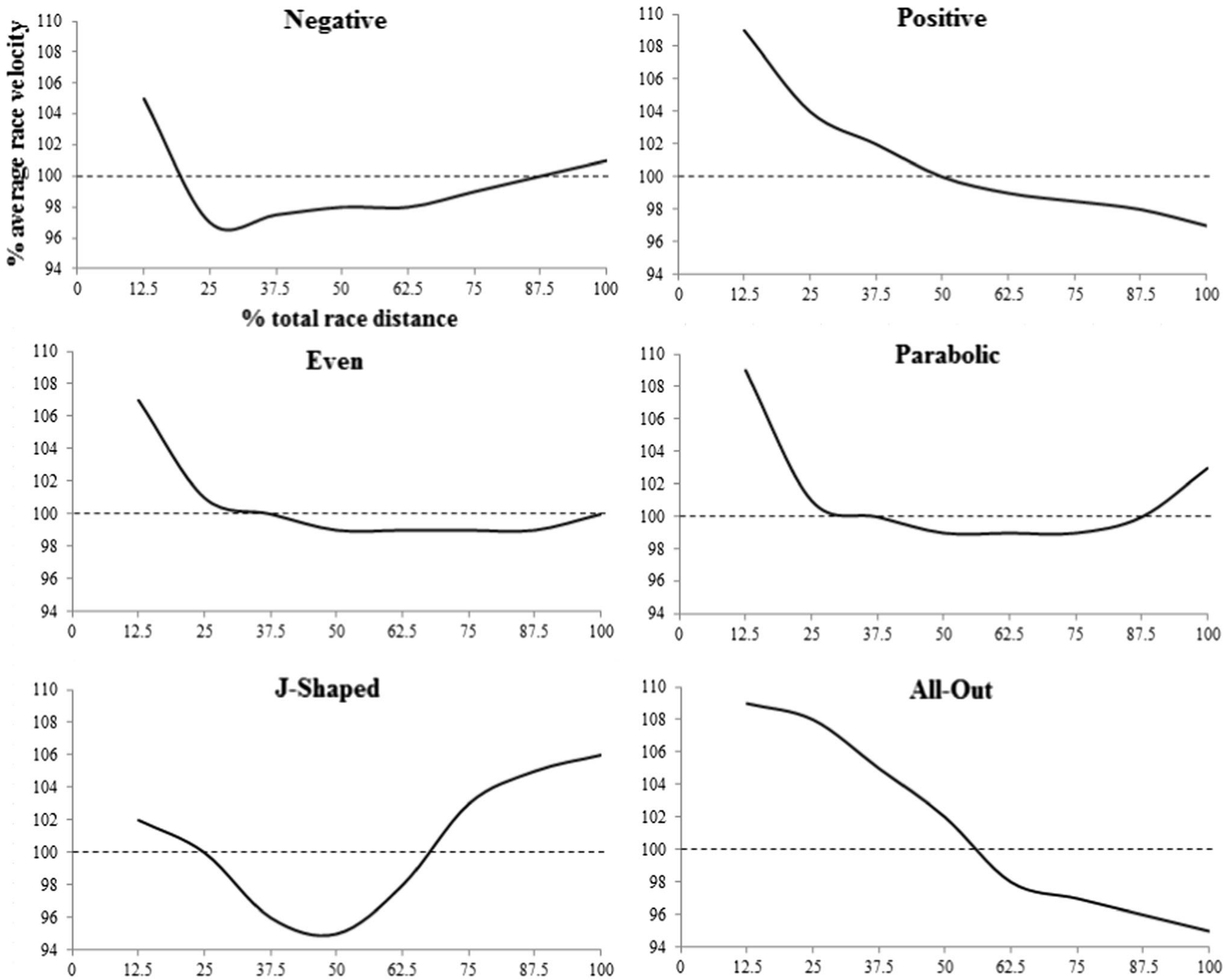

Fig. 2 Schematic diagram illustrating examples of various pacing profiles commonly observed in swimming across the range of competitive events

lack of evidence, observations from competitions indicate a rapid acceleration at the start as a result of the dive followed by a gradual decline in swimming velocity throughout the race as fatigue develops, indicating an all-out or near all-out pacing strategy in 50-m events resulting in a positive profile [6]. In such a short event swimmers should perform with the optimal stroke rate and stroke length combination to provide maximum velocity and then try to maintain this for the entire race distance [18].

The 100-m event is also classed as a sprint event and there is some evidence characterising pacing profiles in these events, predominantly in freestyle swimming. Athletes competing in the 100-m freestyle at the FINA World Masters Championships in 2014 typically adopted a positive pacing strategy whereby the mean 50-m lap time increased by 12% from the first to the second lap [15]. All swimmers entered in this event across all age groups were included in this analysis (690 females, 912 males). This positive pacing strategy was also employed by sub-elite adolescent swimmers in the same event at an international schools swimming competition in a short course pool [16]. The same was also true for finalists and semi-finalists competing at long-course international competitions where a similar pattern of lap times was evident irrespective of finish position or gender [14]. These results suggest that pacing profile is not affected by skill level, but rather by the event distance and stroke, and elite swimmers are simply faster in each lap. A faster first lap underpinned by the dive start means that the second lap is slower leading to a positive pacing profile. The increase in lap time from the first to the second lap can be greater in females than in males [15]. A positive pacing profile is also typically displayed in 100-m backstroke, butterfly and breaststroke events with only small differences in the magnitude of the drop off in velocity between the two laps [7, 18].

The importance of remaining competitive early on in such a short race should not be underestimated, implying that swimmers should get out relatively fast at the start and expect a slight drop off in the second half of the race. Performance in the second lap of a 100-m race is highly correlated (r = 0.65–0.85) with final time across all strokes in elite male and female swimmers [14]. Analysis from nine international competitions, including Olympic Games, World and European Championships and Commonwealth Games, shows that the most successful 100-m swimmers swam faster times in each lap as well as maintained their speed more efficiently in the final lap leading to a smaller drop off [14]. Winners of the 100-m freestyle event at major international competitions swam a faster second lap in comparison to their competitors [14]. It is unknown whether these faster lap times produced by winners in the freestyle event are a result of higher free-swimming velocity, a superior push-off from the wall, faster finish times, or a combination of all of these elements. On the other hand, the most successful 100-m breaststroke swimmers typically achieve quicker free swimming velocities as well as faster times for all skill components, although most of the variance in performance time in this event was explained by mid-pool swimming velocity [7]. The correlation between finish time (the final 5 m of the race) and overall performance time in the 100-m breaststroke was very large in males and females (r = 0.76–0.82), highlighting the importance of this skill in sprint events [7].

3.2 Middle-Distance Events (200–400 m)

Middle-distance events include 200- and 400-m distances that take just under 2 min and up to 4.5 min to complete depending on stroke and gender. Similar to sprinters, the most successful middle-distance swimmers swim at higher velocities in each lap and maintain velocity throughout the race [6, 14]. Free-swimming velocity typically decreases by approximately 6–8% from the first to the last lap of 200-m events [6], although this reduction is often greater in breaststroke events due to the importance of leg propulsion in this stroke [14]. Mathematical modelling indicates that an almost even pace is optimal for 200-m swimming performance across all strokes [19]. Even pacing seems to be a sensible option given that water resistance increases disproportionately with increases in swimming velocity, thereby elevating energy expenditure substantially [3]. This effect is a consequence of the cubic relationship between force and velocity in water [20], in contrast to the linear relationship in cycling [21]. Across all 200-m events, the third lap displayed the strongest correlations to final time indicating the importance of this lap on overall performance [14]. The most commonly used pacing strategies in middle-distance backstroke and freestyle swimming across a range of competitive levels are parabolic; a fast start followed by an evenly paced mid-section and a fast end-spurt [12, 22], or fast-start even; a fast start followed by a relatively even pace [14, 16, 23]. Conversely, positive pacing is often observed in 200-m breaststroke and butterfly events likely due to greater fluctuations in velocity during each stroke cycle as well as lower mechanical efficiency than freestyle and backstroke [14, 18]. In breaststroke, positive pacing leads to deterioration in kinematic variables such as turn speed and stroke length as the race progresses [7, 24]. Conversely, a fast-start even pacing profile was observed across all 200-m events at the 2013 World Swimming Championships with overall lap velocity remaining relatively stable in the final lap [6]. This stability was achieved despite a decrease in free swimming velocity from the first to the last lap as swimmers were able to maintain underwater velocity off the turns. Therefore, although overall lap velocity remained even throughout the middle laps, the pacing profile for the free swimming component was positive in nature [6]. Swimmers maintained underwater distances in the backstroke and butterfly events given that underwater velocity in these strokes is typically faster than free-swimming velocity. However, given that FINA regulations limit underwater kicks in breaststroke, and freestyle surface velocity is faster than underwater velocity, underwater distances were decreased in these events in the last turn. Despite this, reductions in turn velocity throughout 200-m breaststroke and butterfly events have been reported [7, 25], which is likely related to the decrease in free swimming velocity.

Similar to the 200-m freestyle, pacing profiles in the 400-m freestyle are typically either fast-start even or parabolic in nature [12, 26]. An example of when parabolic pacing has proved successful in 400-m freestyle swimming was Mack Horton's gold medal winning performance at the 2016 Olympic Games where the 100-m split times were 54.06, 57.13, 56.82 and 53.54 s. Some swimmers in this event adopt alternative pacing strategies including positive, negative, even and variable profiles, although these are much less common [12, 13]. It appears that no single pacing strategy yielded a significant competitive advantage on 400-m freestyle performance at major international competitions, although swimmers were on average 1.7 s faster with fast-start even and parabolic pacing compared to positive pacing [12]. Differences of this magnitude have a practically meaningful impact on performance given the small margins between winning and losing in swimming. However, these margins could be affected by the fastest swimmers selecting these profiles or by seeking a tactical advantage in a particular race.

In contrast, a substantial impact of pacing strategy selection on 400-m freestyle performance is evident when comparing swimmers with minimal physical (S10 classification) or visual (S13 classification) impairment to able-bodied swimmers [13]. Even and negative pacing profiles were most commonly adopted across all swimmers and the fastest performance times were achieved with a negative profile, except for S13 female swimmers who swam fastest with even pacing [13]. Other pacing profiles adopted included fast start by able-bodied swimmers only, parabolic by able-bodied and female S10 swimmers, and parabolic fast start by impaired swimmers only [13]. The latter two strategies produced the slowest performance times, although the reason for this is unclear. The degree of impairment in these athletes was considered minimal and may explain why the majority of these swimmers; able-bodied, physically or visually impaired, displayed an even or negative pacing profile. Despite these similarities, impaired swimmers displayed greater lap-to-lap variability and performance times inferior to their able-bodied counterparts who subsequently maintained a more consistent pace, which would be advantageous in minimising energy expenditure and drag. Therefore, it appears that successful pacing strategies in one cohort may not necessarily be as effective in another with the possibility that an optimal pacing strategy might vary between individuals. Coaches and sports science practitioners should tailor and individualise pacing strategies by taking into account each swimmers' physiological, biomechanical and psychological characteristics.

Given that the majority of 400-m freestyle swimmers adopt a similar pacing profile, it is important to identify what factors differentiate medallists and non-medallists in this event. It appears the most important factor is the ability to increase swimming velocity in the final 100-m lap to produce a substantial end spurt [22]. Medallists in the 400-m freestyle start more conservatively, by swimming below their mean race velocity for the first half of the race, compared with non-medallists who swam above their mean race velocity. These findings support the work of both Taylor et al. [13] and Mauger et al. [12], who reported faster 400-m freestyle performances with a negative pacing profile. It would appear that faster swimmers are able to adopt a relatively controlled start, which permits them to conserve energy early in the race, such that they can then increase their swimming velocity substantially in the final lap. In contrast, the non-medallists expend too much energy early on and as a result are unable to sustain this pace during the latter stages of the race. The middle two 100-m laps of a 400-m freestyle race are most highly related to overall race performance [14]. This relationship seems logical given the impact that the pace in these middle laps will have on the ability to produce an end spurt in the final lap.

3.3 Long-Distance Events (800 m or Above)

Similar to middle-distance freestyle events, parabolic pacing is typically utilised in freestyle events of 800 m or above whereby swimming velocity is greatest at the start and end of the race [27–29]. The most successful female 800-m freestyle swimmers at the 2008 Olympic Games maintained swimming velocity at an even pace through the middle of the race and then increased velocity substantially in the final 100 m [27]. These swimmers typically swam the second half of the race either faster or at the same pace as the first half [27], and it appears that faster 800-m swimmers increase stroke rate in the second half of the race [10]. Analysis of international and national competitions between 2000 and 2014 indicated that a similar pacing profile is utilised by elite male 1500-m freestyle swimmers where the first and last 100 m are fastest with a gradual slowing of pace in the middle laps [29]. Improvements in 1500-m freestyle performance time are characterised by the first two laps being swum relatively slower while the last two laps are swum relatively faster. The fastest swimmers also demonstrated reduced lap-to-lap variability [29] and typically display longer stroke lengths [10]. Other research in both middle and long-distance events shows the need to conserve energy at the start, swim at a consistent pace in the middle sections and then increase velocity in the latter stages [14, 22, 27]. A parabolic pacing profile has also been observed in a 25-km pool-based time trial where participants started conservatively and then gradually decreased their velocity during the trial until the last 500 m when they markedly increased their velocity [30].

3.4 Individual Medley (IM) Events (200 and 400 m)

The IM is unique as it incorporates all four strokes into one event typically with substantial variation between swimmers given individual strengths and weaknesses across strokes. Although two swimmers may produce similar performances times, their strategy to achieve this time could be markedly different. A 12-year analysis of pacing strategies in the 200- and 400-m IM at international competitions indicated that the butterfly leg was the fastest irrespective of final placing or gender [31]. This outcome is not surprising given the effect of the dive start on the first leg of the IM. Males tend to adopt a positive pacing strategy in an IM, swimming relatively faster in the first half of the race, whereas females start more conservatively adopting a negative pacing strategy and swimming relatively slower in the first half of the race. When comparing medallists to semi-finalists the most successful IM swimmers spend a higher percentage of race time on the butterfly leg (400 m: + 0.29% or 0.79 s; 200 m: + 0.23% or 0.30 s) and a lower percentage on the backstroke (400 m:

− 0.13% or 0.35 s; 200 m: − 0.20% or 0.26 s) and breaststroke legs (400 m: − 0.15% or 0.41 s; 200 m: − 0.16% or 0.21 s) [31]. A more conservative start may be beneficial to conserve energy for the two middle laps. In support of this contention, the backstroke leg displayed the highest correlations with performance time in male medallists in both the 200-m ($r = 0.82$) and 400-m ($r = 0.81$) IM events [31]. Similarly, in female medallists the backstroke leg displayed the highest correlation with performance time in the 200-m IM ($r = 0.78$); however, in the 400-m IM the freestyle leg was most highly correlated ($r = 0.78$) with the backstroke leg following closely behind ($r = 0.76$) [31]. Clearly individualisation of a swimmer's pacing strategy is a priority and has practical implications for coaches when programming training IM swimmers. For example, female 400-m IM swimmers may need to focus on having a strong freestyle leg, whereas 200-m specialists might concentrate on the backstroke leg.

3.5 Summary

Pacing profiles in swimming vary by event distance as well as by stroke (as depicted in Fig. 3). In both sprint and middle-distance events the ability to maintain swimming velocity throughout the race is a major factor determining a swimmer's success irrespective of gender. Typically, greater losses in velocity are evident in breaststroke and butterfly events given their relative inefficiency and higher energetic cost. In 400-, 800- and 1500-m freestyle events the ability to swim at an even pace in the mid-sections followed by an end spurt in the final lap(s) is critical for a successful outcome. Although pacing in IM events is somewhat dependent upon each swimmer's strengths and weaknesses across the four strokes, it appears that conserving energy during the butterfly leg is a prudent strategy to promote performance in subsequent legs. The outcomes of studies characterising pacing profiles in swimming are summarised in Table 1.

4 Pacing Profile Reproducibility

As well as characterising pacing profiles in competition, researchers have examined the reproducibility of these profiles between and within individuals and competitions. Unlike many cycling or running events, swimmers race in their own lanes meaning they don't need to compete for positions. Swimmers are somewhat isolated from their opponents and subject to minimal interference from external factors. As a result, within-subject reliability is greater in swimming than in track running when comparing events of similar durations [32] with a typical race-to-race variability in performance of ~ 1% [33]. In theory this should allow swimmers to implement a pre-determined race plan irrespective of opponents or competition, although some may swim to gain a tactical advantage. For example, swimmers may attempt to upset the race plan of their competitors by taking the race out faster or slower than expected, which can cause a competitor to abandon their original or usual race strategy. Some swimmers may also position themselves in such a way as to avoid swimming through turbulence created by their competitors as this increases energy expenditure. However, variability in pacing is more likely to originate from the swimmer themselves rather than from differences between competitors [26]. Highly experienced swimmers produce stable and consistent pacing profiles between and within competitions, although the variability appears to be higher in junior swimmers [17, 26]. This outcome is not unexpected given that athletes develop their individual performance template(s) through repeated practice and competition experience over several years [4, 34].

Another important factor is the variability of pacing between laps of a swimming event. Competitive junior swimmers showed consistent pacing profiles during the first three quarters of simulated 200-, 400- and 800-m freestyle races with a coefficient of variation (CV) < 2%, but the variability increased above 2% in the final quarter of each race distance [17]. The pacing variability of finalists at senior European and World Championships between 2007 and 2011 also increased slightly with each lap in 400-m freestyle event, although the CV remained under 2% at all time points [32]. Greater variability in pacing both in mid-pool swimming and non-swimming components during the latter stages of a race in both senior and junior swimmers could be attributed to accumulation of fatigue causing deterioration in mechanical efficiency and increased drag [32]. However, it is possible that swimmers of lower-expertise may be more easily influenced by the actions of their opponents leading to deviation from their planned pacing strategy resulting in a greater variability in velocity. The stroke can also influence pacing; for example, there is increased variability during breaststroke swimming probably related to the relatively higher intra-cycle velocity fluctuations and lower mechanical efficiency that elevates energy expenditure [26, 35]. There is also some evidence indicating that higher-expertise swimmers are able to maintain a more consistent turn performance, particularly in the latter stages of a race [25, 36]. However, the majority of elite swimmers tend to adopt similar pacing profiles in any given event irrespective of gender or final placing [14, 28]. This is not surprising given that coaches and athletes often select a pacing strategy based on observation of world class athletes in the same event [4]. Although many of the most successful distance freestylers utilise parabolic pacing, it is

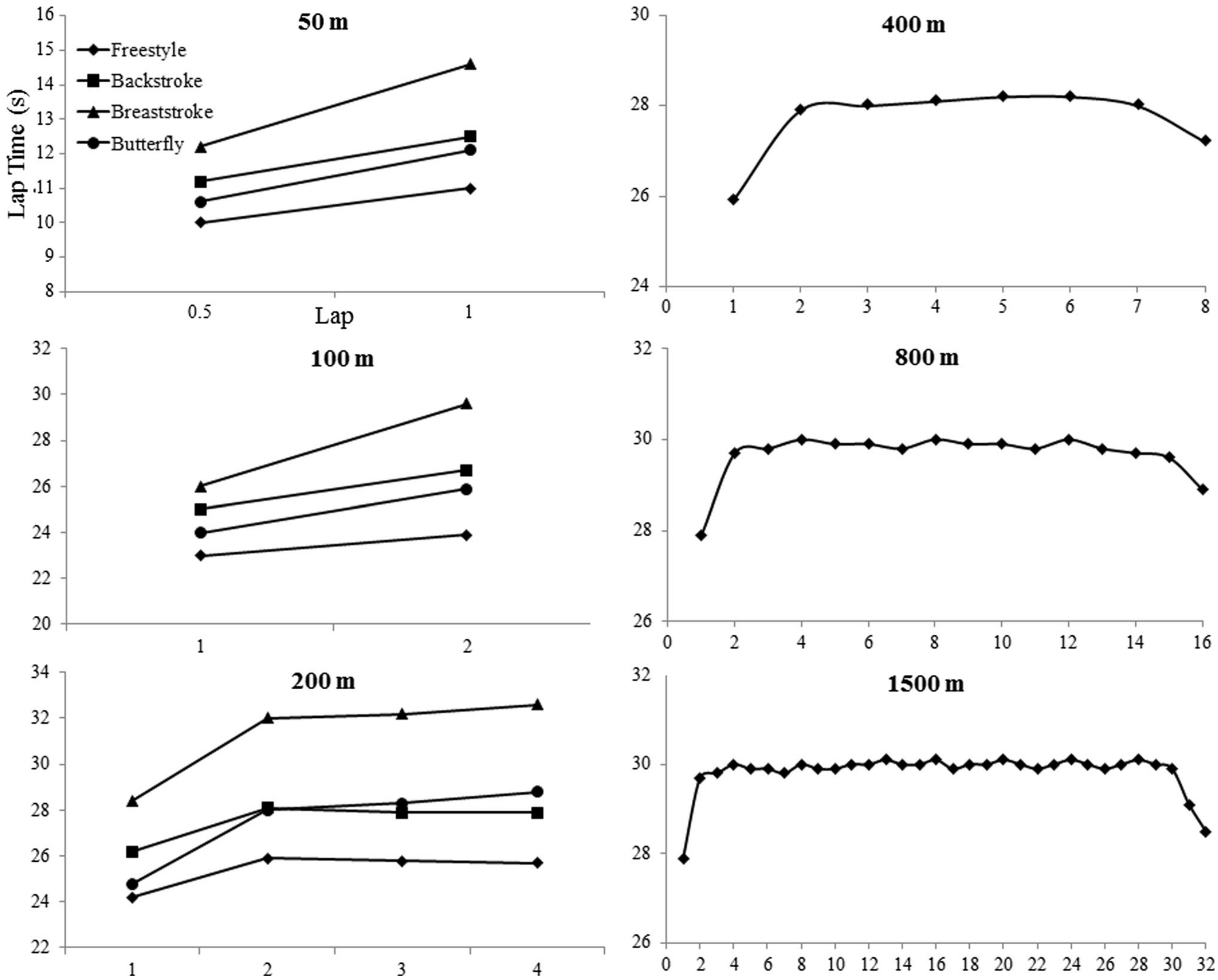

Fig. 3 Pacing profiles across different swimming events Reproduced with permission from Thompson et al. [40]

unknown whether this strategy is in fact optimal for all swimmers. It is possible that this may be highly individual and dependent on a variety of factors unique to each swimmer [13]. However, further research is needed to determine the impact of alternative pacing strategies on swimming performance.

When examining reproducibility within the same competition, pacing patterns display low variability from heats to finals in elite senior swimmers despite substantial differences in overall performance times [26]. Mean improvements in overall performance times from heats to finals within the same competition range between 1.1–1.3%, whereas between competitions the improvements range between 0.2–1.0%, relative to the number of weeks between the competitions [33]. Despite these variations in overall performance times, an individual's pacing pattern in a particular event remains relatively stable within the same competition as well as between competitions [17, 26]. There are few differences in pacing profiles between simulated and real competitions, although there is often a subtle rise in velocity in real competitions [17]. Therefore, it appears swimmers select their pacing strategy based on prior experience independent of competition or race type. Race simulations in training can provide a useful tool to practice pacing strategies, providing more opportunities for younger inexperienced swimmers to develop their performance template(s). However, simulations may not accurately replicate the physiological and psychological demands of real competitions, such as the presence of spectators and media coverage. To ensure swimmers are able to execute their pacing strategy under potentially stressful competition conditions, they should be given sufficient opportunities to practice pacing strategies in minor competitions before a major competition.

In summary, pacing profiles remain relatively stable irrespective of opponents, competition stage or type, and

Table 1 Summary of pacing profile characterisation studies

Reference	Participants		Data collection							Pacing profile results
	Number	Level	Type	Level	Date range	Swims	No. of comps	Pool	Event(s)	
De Koning et al. [19]	n/a	n/a	Mathematical modelling		n/a	n/a	n/a	LC	200-m FS	Even profile optimal
Dormehl and Osborough [16]	56 M, 56 F, 112 T	Sub-elite	C	International Schools	n/a	?	1	SC	100-m FS 200-m FS	Positive Fast-start even
Invernizzi et al. [30]	8 M	Competitive	TT		n/a	n/a		SC	25,000-m FS	Reverse J-shaped
Lipińska [27]	8 F	Elite	C	International	2008		1	LC	800-m FS	J-shaped
Lipińska et al. [28]	20 F	Elite	C	National and International	1998–2014	192 swims	50	LC	800-m FS	Parabolic
Lipińska et al. [29]	24 M	Elite	C	National and International	2000–2014	330 swims	173	LC	1500-m FS	Parabolic
Mauger et al. [12]	147 M, 117 F, 264 T	Elite	C	National and International	2003–2010	264 swims	?		400-m FS	Fast-start even and parabolic
Mytton et al. [22]	?	Elite	C	International	2004–2012	48 swims	6	LC	400-m FS	Parabolic
Nikolaidis and Knechtle [15]	?	Masters	C	International	2014	4481 swims (2221 F, 2260 M)	1	LC	100-m FS 200, 400, 800-m FS	Positive Parabolic
Robertson et al. [14]	?	Elite	C	International	7 year period	3057 swims (1530 M, 1527 F)	9	LC	100-m FS, BK, BR, BF 200-m FS and BK 200-m BR and BF 400-m FS	Positive Fast-start even Positive Parabolic
Saavedra et al. [31]	?	Elite	C	International	2000–2011	1643 swims	26	LC	200-m IM 400-m IM	Positive (M), Negative (F)
Skorski et al. [17]	9 M, 7 F, 16 T	Junior	Simulated Competition		n/a	6 swims	Test and re-test	LC	200-m FS 400-m FS 800-m FS	Fast-start even Parabolic Parabolic
Skorski et al. [26]	158 M	Elite	C	National and International	2010	362 swims	22	LC	200-m FS, BK and BF 200-m BR 400-m FS	Fast-start even Positive Parabolic
Taylor et al. [13]	?	Elite (AB and PARA)	C	International	2006–2012	1176 swims (801 AB, 375 PARA)	14	LC	400-m FS	Parabolic
Thompson et al. [7]	159 M, 158 F per event	National to Elite	C	National and International	1992–1997	634 swims	12	LC	100-m BR 200-m BR	Positive Positive

Table 1 continued

Reference	Participants		Data collection							Pacing profile results
	Number	Level	Type	Level	Date range	Swims	No. of comps	Pool	Event(s)	
Veiga and Roig [6]	64 M, 64 F	Elite	C	International	2013	128 swims	1	LC	200-m FS 200-m BK 200-m BR 200-m BF	Fast-start even

AB able-bodied, *BF* butterfly, *BK* backstroke, *BR* breaststroke, *C* competition, *F* female, *FR* freestyle, *IM* individual medley, *LC* long course, *M* male, *PARA* athletes with a disability, *SC* short course, *T* total, *TT* time trial, *?* unknown

performance time. Swimmers develop their pacing strategy over several years and as a result pacing profiles of junior or inexperienced swimmers will likely be more variable than their experienced, senior counterparts.

5 Pace Manipulation

The research surrounding the effects of different pacing strategies on physiological, biomechanical and performance variables is sparse. To date there are only four studies manipulating swimming pace and these are limited to breaststroke and freestyle swimming only. Commonly used methods to manipulate pace in swimming include a small device positioned just behind the swimmer's ear emitting audible beeps at set intervals, and underwater flashing light systems installed at the bottom of the pool.

A recent study manipulated pace during the first quarter of a simulated 400-m freestyle competition using a flashing light system or by audible signals every 25 m. Swimming pace in the first 100 m was set to either 3% faster or 3% slower than in a self-paced trial. Swimmers were 0.6% faster in the self-paced trial, although from a total of 15 swimmers, three of them swam faster in the fast-start trial and four were faster in the slow-start trial [37]. This pattern indicates that some swimmers failed to select an optimal pacing strategy in the self-paced trial. In cycling, a fast-start pacing strategy can accelerate $\dot{V}O_2$ kinetics, which is associated with improved high-intensity cycling performance [38]. Whether the same would be true for swimming is unclear given differences between modes of exercise and laboratory and aquatic environments. It is possible that a fast-start pacing strategy in swimming may increase energy expenditure and fatigue which collectively is likely to have a negative impact on performance. If this were the case greater metabolic disturbances might be expected with a fast-start but few differences in metabolic variables including blood lactate concentration and heart rate were evident between self-paced, fast-start or slow-start trials [37]. This evidence may help explain the lack of differences in the magnitude of the end spurt despite the expectation of a greater increase in velocity in the slow-start trial due to conservation of energy resources early in the trial. However, perhaps this effect was outweighed by the energetic cost associated with increasing swimming velocity following a slower first quarter of the race. A major limitation of this study was that in the self-paced condition swimmers raced against each other, whereas in both manipulated conditions they swam alone. A competitive element in self-paced trials is likely to impact motivation, performance and pacing, therefore making comparisons with the manipulated trials problematic.

Further pace manipulation research has been conducted in breaststroke swimming using an Aquapacer^{TM} device to emit audible beeps. This device has been shown to be an accurate and repeatable method to control pacing up to 98% of maximal 200-m breaststroke pace [39, 40]. However, in trials where participants were required to swim at maximal and supramaximal speeds, the magnitude of pacing error rose substantially during the latter stages of the trial, which is not surprising given the detrimental effects of fatigue on swimming technique and efficiency. During a trial at 102% of maximal 200-m breaststroke pace, swimmers attempted to maintain swimming velocity and compensate for a reduction in stroke length as fatigue developed by increasing stroke rate and stroke count. Markedly higher blood lactate concentrations were observed in the 102% trial (11.3 ± 1.2 vs. 9.6 ± 1.8 mmol l^{-1} in the 100% trial) indicating an increased anaerobic energy contribution, possibly due to an elevated stroke rate and count which increased swimmers' recruitment and/or activation of fast glycolytic muscle fibres [40]. Therefore, swimmers were able to pace accurately, during high-speed breaststroke swimming, using the

Aquapacer^{TM} until fatigue became a limiting factor. When comparing even, positive and negative pacing profiles in breaststroke swimming it appears that changing pace during a race increases the likelihood of a pacing error occurring [39]. Compared to even pacing, positive pacing in breaststroke swimming increased peak blood lactate concentration, rating of perceived exertion (RPE) and stroke rate [24, 40]. Although turn times were substantially faster with positive pacing compared with even and negative (by 0.4 and 1.4 s, respectively) pacing during the first half of the trial, these turn times deteriorated by over 5% in the second half. Swimmers started each of these trials in the water and so the influence of a dive start is not apparent. These results indicate that positive pacing was perceived to be more physically strenuous and resulted in a higher anaerobic energy contribution than even and negative pacing. In addition, larger reductions in stroke technique and turning proficiency with positive pacing indicate that these factors may contribute to earlier onset of fatigue.

It appears that the performance of junior 400-m freestyle swimmers may benefit from adopting alternative pacing strategies, although the impact on kinematic variables remains unclear. Furthermore, even pacing in 200-m breaststroke swimming could be advantageous given the reduced metabolic and kinematic disturbances associated with these strategies.

5.1 Methods of Pace Manipulation

The Aquapacer^{TM} has been used by many national team swimming coaches and offers a timing resolution of 1/100th second as well as the ability to control stroke rate [41]. Although this technology is no longer manufactured, a new device the Tempo Trainer Pro^{TM}, has the same functionality. These types of audio devices are a useful tool for coaches to control and manipulate pacing in training and are widely used within the high performance swimming community. The Aquapacer^{TM} is an accurate and reliable method to control swimming pace and swimmers of varying performance levels are able to habituate rapidly to these devices despite no prior experience [24, 37, 39, 40].

An alternative method is an underwater lighting system where instead of following audio signals, swimmers follow pre-programmed visual signals displayed on the bottom of the pool. This technology has been used in studies investigating the reliability of a pool-based testing protocol whereby swimmers of varying experience levels were able to accurately and reliably follow the light signals [42–44]. However, these light-based systems are not easily accessible to many swimming clubs and require skilled personnel to set-up the system prior to a training session.

With both of these methods, swimmers can exhibit difficulties keeping in time with the signals when pushing off at the start or when coming off the wall after a turn. For example, at the start of an effort swimmers may glide underwater faster than the pace the lights are set to, requiring them to then slow down appreciably for the lights to catch up before continuing on. Swimmers may also struggle to get back on pace with the lights following a turn which can impact the rest of the effort. Therefore, the ability to program adjustments for push offs and turns would be useful to ensure the swimmer can easily maintain pace with the lights. Additionally, during competition, swimming velocity often changes within a lap [12], hence the capacity to set the pace of the lights across smaller segments in each lap would be valuable. Clearly, swimmers should familiarise themselves thoroughly with these methods before being able to use them effectively in training and testing.

5.2 Future Directions

Although pacing is clearly an important aspect of swimming, the research in this area is relatively limited and several questions remain unanswered. Much of the literature to date has used competition data to characterise pacing profiles and their reproducibility within and between competitions. There is a need for future research in this area to gain high resolution pacing data to allow for detailed analysis of velocity changes within laps as well as in free swimming and non-swimming components. Only a handful of studies have manipulated pacing in an experimental setting to examine the effects of different pacing strategies on physiological, biomechanical and performance variables, which is currently limited to freestyle and breaststroke swimming. Studies in which the efficacy of multiple pacing strategies are examined across a range of race distances and strokes are needed to determine the optimal pacing strategy in each event. It would also be interesting to determine whether this type of approach aligns with the profiles currently adopted by elite swimmers in competition. Furthermore, it is unclear whether these pacing profiles change when the event is swum as part of a relay. The importance of tailoring pacing strategies to suit individual characteristics requires further research. These studies should closely replicate competition conditions to provide more practically meaningful information for coaches and sports science practitioners. The Aquapacer^{TM} device and underwater lighting systems could be valuable tools to manipulate pace in swimming. It is also pertinent to examine the effectiveness of these tools to entrain pacing strategies, elicit changes in pacing behaviour, and translate improvements in training into the competition environment.

6 Conclusions

Over the past decade researchers have characterised the pacing profiles of elite swimmers in international competitions, with a large proportion of this analysis focusing on middle and long distance freestyle swimming. In these events the most commonly observed pacing profiles are fast-start even and parabolic, and the same is true in the 200-m backstroke event. Conversely, in middle-distance butterfly and breaststroke events a positive pacing profile is evident, likely due to their unique stroke characteristics. The key to success in 200-m events irrespective of stroke seems to be the capacity to maintain swimming velocity throughout the race, whereas in freestyle events of 400 m and above the ability to conserve energy early on and produce a substantial end spurt in the final stages is vital. Although there is less evidence in short distance events, the most successful sprinters across all strokes are better able to maintain swimming velocity therefore minimising the drop off from the start to the end of the race. On the other hand, the pacing requirements for IM events are unique and swimmers should start conservatively to conserve energy for the backstroke and breaststroke legs. The 400 m IM was the only event where a gender difference was evident whereby the strokes that most strongly determined overall performance time were backstroke or breaststroke in males but freestyle in females, which may be reflective of differing race tactics.

Pacing profiles are consistent and reproducible from heats to finals within the same competition as well as from competition to competition. However, pacing variability can increase in the latter stages of a race due to fatigue accumulation, and in junior swimmers given less competitive experience. In general, swimmers tend to display the same pacing profile in any given race irrespective of performance time, which suggests that the pacing profile per se is not a performance defining factor. However, the velocity of a pacing profile can vary with changes in fitness level or during a taper, which leads to changes in overall performance. There is evidence that some swimmers fail to select an optimal pacing strategy in self-paced trials, as experimental trials show that they can improve performance times in trials where their pacing profile was manipulated. Moreover, although positive pacing is most common in the 200-m breaststroke event, this type of profile is associated with greater metabolic and kinematic disturbances for the same performance times when compared to an even profile. Implementing alternative pacing strategies may benefit performance in some swimmers and highlights the need for greater individualisation when considering pacing strategy selection.

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Compliance with Ethical Standards

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Conflict of interest Katie McGibbon, David Pyne, Megan Shephard and Kevin Thompson declare that they have no conflicts of interest.

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