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BRIEF REVIEW

Competition Between Desired Competitive Result, Tolerable Homeostatic Disturbance, and Psychophysiological Interpretation Determines Pacing Strategy

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Scientific interest in pacing goes back >100 years. Contemporary interest, both as a feature of athletic competition and as a window into understanding fatigue, goes back >30 years. Pacing represents the pattern of energy use designed to produce a competitive result while managing fatigue of different origins. Pacing has been studied both against the clock and during head-to-head competition. Several models have been used to explain pacing, including the teleoanticipation model, the central governor model, the anticipatory-feedback-rating of perceived exertion model, the concept of a learned template, the affordance concept, the integrative governor theory, and as an explanation for "falling behind." Early studies, mostly using time-trial exercise, focused on the need to manage homeostatic disturbance. More recent studies, based on head-to-head competition, have focused on an improved understanding of how psychophysiology, beyond the gestalt concept of rating of perceived exertion, can be understood as a mediator of pacing and as an explanation for falling behind. More recent approaches to pacing have focused on the elements of decision making during sport and have expanded the role of psychophysiological responses including sensory-discriminatory, affective-motivational, and cognitive-evaluative dimensions. These approaches have expanded the understanding of variations in pacing, particularly during head-to-head competition.

***Keywords*:** homeostasis, fatigue, psychophysiology

The concept of pacing, that is, distributing energetic resources over the duration of a task, is not new. Historical examples remind us of the necessity for pacing, including Aesop's fable of the tortoise and the hare; Emil Zatopek asking Jim Peters (1952 Olympic marathon) in midrace if "they were running fast enough"; Vladimir Kuts (1956 Olympic 5- and 10-km) using an interval pacing patten to defeat world-record (WR) holder Gordon Pirie; Kipchoge Keino using a "go out fast" strategy in the altitude of Mexico City to defeat WR holder Jim Ryun (1968 Olympic 1500 m); David Wottle, coming from 20 m behind after the first 200 m to win (1972 Olympic 800 m); and WR holder Steven Jones (European Championships marathon,1986), 2 minutes ahead of the field at 20 miles, who faded and finished 13th place. In all these cases, pacing (good or bad) helped define the competitive result.

Pacing is the process of using the resources available at the start, in an anticipatory manner based on experience,[1] or in response to internal and external stimuli,[2] to achieve the desired result. Often the goal is to finish as quickly as possible, particularly against-the-clock rather than head to head. Pacing represents the balance between energy availability, technique, and fatigue. Energy availability depends on energy producing systems, which depend on physiologic capacity and the duration and mode of the event. Technique depends on neuromuscular performance, which is of modest importance in running, but crucial in other activities (skating, cycling, cross-country skiing, rowing, and swimming), and may deteriorate with fatigue. For example, in cycling and skating, athletes are able to continue to glide or roll toward the finish even after considerable losses of power output; whereas, in running and swimming, there is a rapid deceleration with loss of power output. Fatigue, which has become better understood,[3–6] depends upon the depletion of substrates (adenosine triphosphate, creatine phosphate, glucose, and glycogen), the accumulation of metabolites (inorganic phosphate and hydrogen ions) and heat, and functioning as control processes via afferent nerves, as well as the interpretation of what these changes mean.

Historical Evidence of Interest in Pacing

The concept of pacing is not new. The first report was by Tripplet in 1898.[7] He evaluated why drafting improved performance. While describing performance improvements when following a pacer, he reported distance–velocity relationships which anticipated the critical speed (CS)/critical power (CP) concept.[8] He also developed theories (suction, shelter, encouragement, and hypnotic suggestion) anticipating concepts of reduced wind resistance[9] and the ergogenic effect of a competitor riding just a little faster than an athlete's personal best.[10] Other studies by Kennelly[11] and Hill,[12] performed a century ago, described the distance–velocity relationship (for running, walking,

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cycling, and skating). The classical study of Robinson et al,[13] perhaps the first experimental study of pacing, showed that VO_2, O_2 deficit, and [blood lactate] favored an even pace. Thus, by ~65 years ago we knew that: (1) there was a regular distance–velocity relationship that anticipated the CS/CP concept; (2) there were differences in the absolute dimensions related to the mode of ambulation; (3) drafting was advantageous; and (4) for tasks of longer than ~3 minutes, there was an advantage to even pacing. Today, we are better at explaining the science behind pacing, but early concepts have endured.

The Concept of Pacing Strategy Emerges

The first contemporary studies of pacing emerged from groups in the Netherlands and the United States.[14–19] These studies demonstrated that: (1) there was a range of advantageous pacing strategies in cycling events of 1000 to 4000 m (or even longer); (2) an all-out strategy was better in shorter events; (3) longer events favored a brief high intensity start which was then "dialed back" after ~10 to 15 seconds; and (4) more even, or U shaped, pacing patterns were seen in longer events. These studies, particularly the frequent observation of an end-spurt, also established the concept that high speed at the finish was essentially wasted kinetic energy that might have been better used to go faster earlier and arrive at the finish sooner. Trying to improve performance (particularly in events <4 min) required an athlete to take a "calculated risk" of starting faster than normal, in order to achieve a performance that they had never previously achieved.[20]

Teleoanticipation Model

By the mid-1990s, the first conceptual model of pacing emerged. Ulmer[1] suggested that energy output was governed by central control mechanisms designed to: (1) avoid early fatigue, (2) not waste time with a slow start, (3) use learned behavior as a template for current activity, and (4) anticipate the time required to finish. Thus, the *teleoanticipation model* was conceptualized as a closed-loop, feedback dependent, anticipatory regulation of energetic output. About this same time, evidence emerged of a replicable pattern of pacing strategy and that elite athletes used the same pacing as recreational athletes.[21] Beyond single efforts, there was evidence of pacing in the Grand Tours of cycling, in which general classification competitors would only exert themselves heavily on the days when significant time gains were possible.[22] On other days, teammates would keep them near the front of the peloton. These findings reinforced Ulmer's concept of anticipating stresses across an entire event. Less than a decade later, evidence emerged of a consistent pattern in the pacing of races where the goal was to defeat other competitors head to head.[23,24] It also became evident that pacing displayed a consistent pattern, evolving toward less of the fast–slow–slower–fast pattern observed in early 20th century.[23,24] The concept also emerged that the pacing strategy, in attempts to improve best performance, was consistent over time.[25] Supporting Ulmer's concept, there was evidence that different events had unique pacing patterns, suggesting that the anticipation of muscular power output was very strongly grounded.[26–29]

Pacing Versus Fatigue (Central Governor Model)

Early concepts of fatigue were based on observations of the progressive reduction in force/power output (to near zero values) in isolated skeletal muscle despite supramaximal stimulation.[30] It was thought that muscle failure was related to factors including level of stimulation, blood flow, availability of O_2, and the ability to buffer changes in pH. Observations by Noakes[31] that humans rarely exercise to the point of total muscular failure suggested that fatigue was not solely related to absolute levels of muscular substrates or metabolites. While there is evidence that homeostatic disturbances are profound during severe exercise, and that exercise end points occurred at similar levels of homeostatic disturbance regardless of the task,[32–35] complete muscle, cardiac, or organ system failure rarely occurred. This evolved to the understanding that fatigue acts to prevent cellular damage related to severe homeostatic disturbance.[36] Even demanding tasks such as the Wingate test (30 s in duration) can be extended to as long as 3 minutes, with the power output only falling as low as the CP.[37] These data suggested the presence of bidirectional signaling between the efferent neural output and afferent signals from peripheral receptors, rather than unidirectional unresponsiveness by the muscle. Noakes et al[38–40] called this bidirectional signaling the *central governor model*. This concept was expanded by St Clair Gibson and Foster[41] suggesting that pacing involved competition between the psychological drive to perform a task and managing homeostatic disturbances. Thus, although catastrophic collapses of ambulatory ability are possible, they are comparatively rare.[42] Studies of exercise in the presence of afferent blockade[43] supported the role of afferent signaling as an obligatory feature in pacing. Evidence in support of bidirectional signaling was provided by studies where warm-up was manipulated to induce fatigue before a time trial.[44] The lesson from the central governor model was that pacing, far from being an epiphenomenon of athletic competition, was a window into how fatigue was experienced and managed.

Patterns of Pacing Strategy

Much of the early pacing research was dominated by observations during athletic competitions. Abbiss and Laursen[45] identified basic pacing strategy variants. Subsequent work from a number of laboratories,[14–19,21,22,27–29,45–72] identified physiological responses during variations in pacing strategy. These studies demonstrated that pacing could be understood in terms of the power balance model of van Ingen Schenau et al,[18,19] with power production depending on the summation of aerobic and anaerobic energy provision and power losses related to summated resistive forces. The first clear evidence that pacing was related to homeostatic disturbances, primarily related to substrate (creatine phosphate[32–34] and glycogen[46–48] depletion, and/or metabolite accumulation[32–35] and hyperthermia),[49–51] appeared during this time period.

Pacing strategy follows general rules related to the distance/time taken to complete a task and displays differences related to the nature of the task, particularly the retarding medium.[52] There is evidence of "reserve" built into pacing strategy[53,54] that can be disrupted by deception regarding distance feedback and influenced by another competitor (or avatar) that is slightly faster than an athletes previous performances,[60–65] but hindered if the other competitor is too much faster.[65–69] These findings suggest that the reserve during exercise tasks can be manipulated, either by time/distance deception or the meaningfulness of the competition (club race vs Olympic final). Furthermore, the most predictable strategy to improve performance is a faster than normal start. However, only about 50% to 80% of fast start experiences will lead to improved performance.[65–69,73,73,74] Head-to-head racing against a much superior opponent can lead to both an inappropriately rapid increase in rating of perceived

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exertion (RPE), and a negative affect and loss of self-efficacy during the race, leading to reductions in speed/power output (ie, letting go of the leading competitors).[73,75,76]

The structure of the pacing pattern (Figure 1), at least against-the-clock has been conceptualized as a "landscape" where the interaction of race distance and percentage of the race completed define momentary power output, regardless of whether power output is attributable to aerobic or anaerobic energetic sources.[77,78]

Rating of Perceived Exertion

Several studies have shown that RPE grows in a systematic manner in relation to the percentage of a task completed.[25,28,29,79–89] This suggests a scaling of RPE to the overall level of homeostatic disturbance, regardless of the precise nature of the disturbance. The rate of RPE growth during an event appears to be tightly regulated, as blinded changes in inspired (O_2) cause a rapid change in muscular power output while the rate of RPE growth barely changes.[80,89–91] Similarly, while changes in preexercise muscle glycogen exert a consequential influence on power output, the growth of RPE normalized to endurance time hardly changes.[92]

The overriding importance of RPE as a way to express the sensation of both intensity and progressive fatigue is so powerful that the third major conceptual model of pacing, the *anticipatory-feedback-RPE* model[93,94] proposes that power output is regulated based on prior experience, anticipated completion time, and rate of growth of RPE. If the rate of growth of RPE is discordant with that anticipated, then power output is either upregulated or downregulated to return RPE to the anticipated growth curve (Figure 2). This concept has been supported in studies where power output was increased by mid-race tactical decisions[81,91] or deception regarding the distance remaining.[60,64]

The growth of RPE relative to the percentage of an event remaining has been combined into a derived variable called the

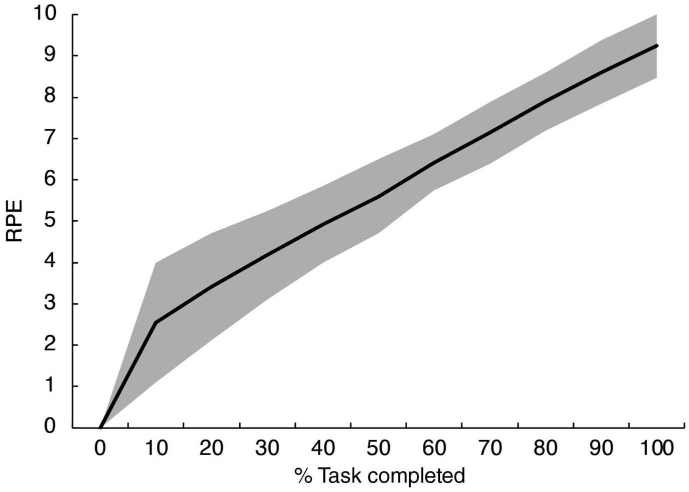

Figure 2 — Schematic of the growth of rating of perceived exertion (RPE) in relation to the percentage of a task completed. Data included are for ambulatory tasks such as walking, running, and cycling, as well as for lifting weights to failure with different levels of resistance.[21,25,28,51,53,54,64,72,80,88,93–96]

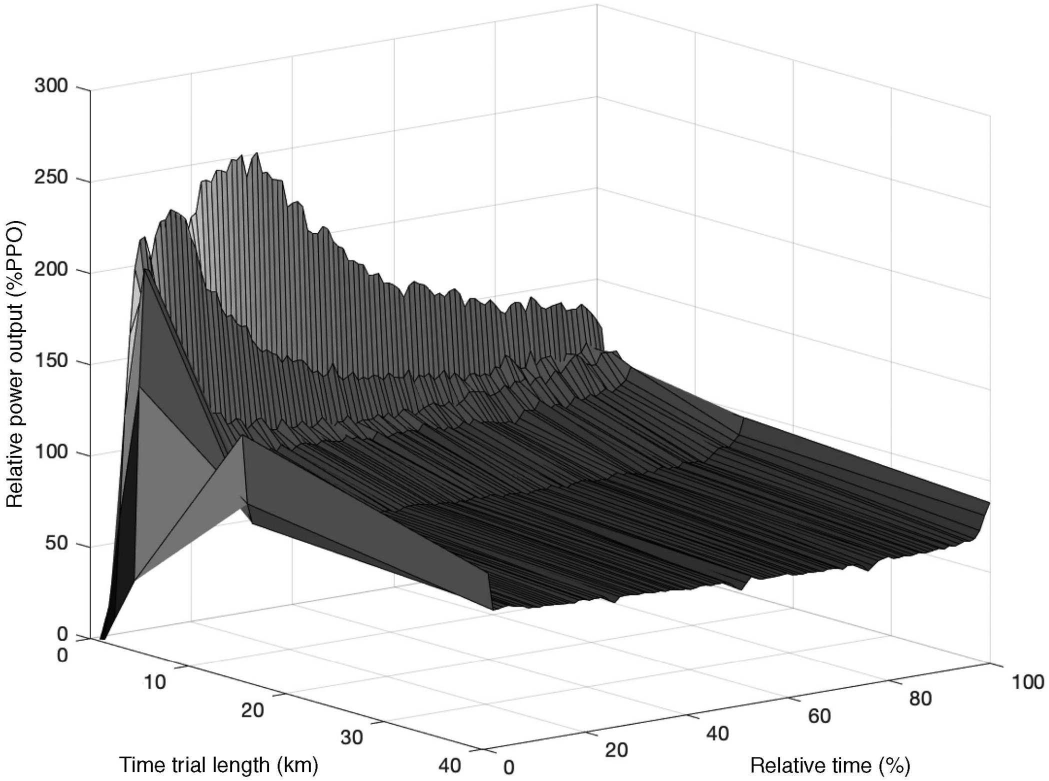

Figure 1 — Schematic of relative power output versus total distance and relative percentage of a time trial completed. The graph resembles a "landscape" and shows that in almost all distances there is an initial peak in power output at the start and a terminal end spurt in all but the shortest distances.[29,77,78]

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Hazard score (momentary RPE × fractional distance remaining), which seems to be able to inform athletes when to change power output during an event.[82,84,95,96] An extension of this technique, the summated Hazard score, has been shown to allow appreciation of how taxing an event feels.[96]

For as important as the RPE has been to understanding pacing, it has been recognized that RPE is a gestalt of a number of sensory inputs that reflect how a given power output, progress through an event and homeostatic disturbance is interpreted. As such, RPE has been criticized as being a less than ideal psychophysiological marker, with other measures being regarded as potentially more discriminatory. Do Carmo et al[66] and Renfree et al[97,98] have demonstrated that another psychophysiological construct, the affect (or valence) toward a task (degree to which momentary effort is viewed as pleasant or unpleasant) is more explanatory of when an athlete is having a good or bad performance, despite identical RPE growth. Thus, affect appears superior to RPE in the heuristic type of decision-making processes which athletes often use. Given the importance of head-to-head competition in augmenting performance,[68,97–100] the ability of athletes to solve the performance challenges raised by their own physiology, the capacity, and tactics of their opponents and challenges presented by the course and environment requires a more granular psychophysiological tool than RPE.

Venhorst et al[73,75,76] have shown that affect (valence) and RPE grow differently during head to head competition and reflect of the degree to which an athlete is "winning" or "losing" a competition. In particular, changes in affect (valence) reflect the point in a competition when athletes first begin to fall behind and then "disengage" from their competitors (action crisis).[73,75,76] They suggest that psychophysiological regulation of exercise behavior can be viewed in 3 dimensions. The first, is perceived physical and mental strain, reflecting sensory-discriminatory processes akin to homeostatic disturbances. The second, is affect and arousal reflecting the interpretation of effort as pleasant–unpleasant and the momentary level of arousal. This can be viewed as interpreting whether the increasing level of discomfort is worth continued effort. The third is cognitive-evaluative process, what they term as an "action crisis" or "letting go" of their opponent in mid race. Their model accounts for traditional homeostatic challenges provided by a task, how pleasant or unpleasant the task is, and how willing they are to continue to compete.

The Pacing Template (Self-Regulation Model)

One striking element of pacing is how difficult it is to disrupt freely chosen patterns. Monetary incentives to improve performance by going out faster have little effect.[101] Conscious prerace decisions to select different strategies have small effects on the actual pacing pattern used, at least in against-the-clock events.[81,91] Pairing with a faster opponent can improve performance, but only when the opponent/avatar is seen as a realistic "rival" and "within reach" of the best current performance.[68–72] Otherwise, the riders "let the superior rider go." This corresponds to the action crisis described by Venhorst et al.[73,75,76] Apparently, the magnitude of "reserve" within pacing strategy can be revised by changing the focus from anticipatory-internal monitoring (against the clock) to relative positional–external monitoring (head to head) so long as homeostatic changes are not ignored.

Within race experimental manipulations, such as exposing participant to sudden onset episodes of hypoxia and hyperoxia, can rapidly change the pattern of power output.[28,80,89,90,102] However, blinded exposure to simulated altitude in the minutes immediately before the start of an event does little to change the early pattern of power output.[89,90] Even exposure to simulated altitude during the warm-up period, sufficient to result in increases in heart rate, blood [lactate], and RPE, does little to influence power output during the opening segment of time trials (Figure 3). Beyond this initial phase, with opportunity for afferent feedback to express itself, there is a large negative effect consistent with that expected in hypoxia.[102] There is a large negative effect of prerace glycogen depletion in events ranging from 1500 (~2 min) to 4000 m (~5 min)[102] (Figure 3) to 1 hour.[48] Power output in the early stages of a time trial is only modestly affected by glycogen depletion (Figure 4). During warm-up, there is an increased heart rate, decreased blood [lactate], and increased RPE, expected with glycogen depletion. Similarly, strategies designed to increase muscle glycogen content, resulting in improved performance, do not exert an effect until later within an event.[46,47] Evidence supports the presence of a preexercise template, which is a learned behavior, specific to competitive circumstances.[103] Learning may take several trials and typically evolves as a faster early pace (eg, less "reserve"). In time trial events, this learned strategy seems very hard to override, despite conditions in the warm-up that might be expected to reset the template.[104] In head-to-head competitions, it is possible to reset the template. This supports data regarding the development of pacing strategies in youth athletes of the need for experience to develop self-regulating strategies.[105,106]

In fit people, with minimal time trial experience, there is evidence of modifications in the template with repeated time trials,[103] that may take ≥6 trials. In athletes attempting to improve their best performance, the pacing pattern is more or less similar, with the exception that the opening segment is slightly faster, suggesting that improved performance is more attributable to improved physiologic capacity than to pacing.[25] Empirical evidence suggests that competitive performance may improve when novel pacing strategies are employed during practice or less important competitions, in order to reset the template.[16]

Specific attempts to influence the pacing strategy, such as by mid-race "break away" efforts,[81,91] support the concept of a template, in that upward speed departures from a normal template in 10- to 20-km time trials are marked by a subsequent reduction of power output until homeostatic disturbances (heart rate, blood [lactate], RPE, and muscle O_2 saturation) return toward normal, at which time the template is resumed (Figure 5). Similarly, attempts to force starting ~5% faster or slower over the first 30% of a time trial show a rapid return to the "best race" template as soon as the experimental constraints are removed.[96]

Pacing Strategy Versus Racing Strategy

Early research on pacing was mostly conducted on events where performance was against the clock, the competitive pattern in pursuit cycling, 1-hour cycling, metric-style speed skating, and swimming. Many events where pacing might be important are decided based on relative placing rather than absolute time, leading to a more stochastic pacing pattern.[67,104,107–111] These events demonstrate evidence of variations in starting strategy and of an end-spurt. In addition, they display evidence of intentional variations in speed or power output. Within a single elite athlete, WR or best performances are often characterized by small variations in momentary speed (eg, low coefficient of variation). Championship races are often characterized by frequent, potentially preplanned,

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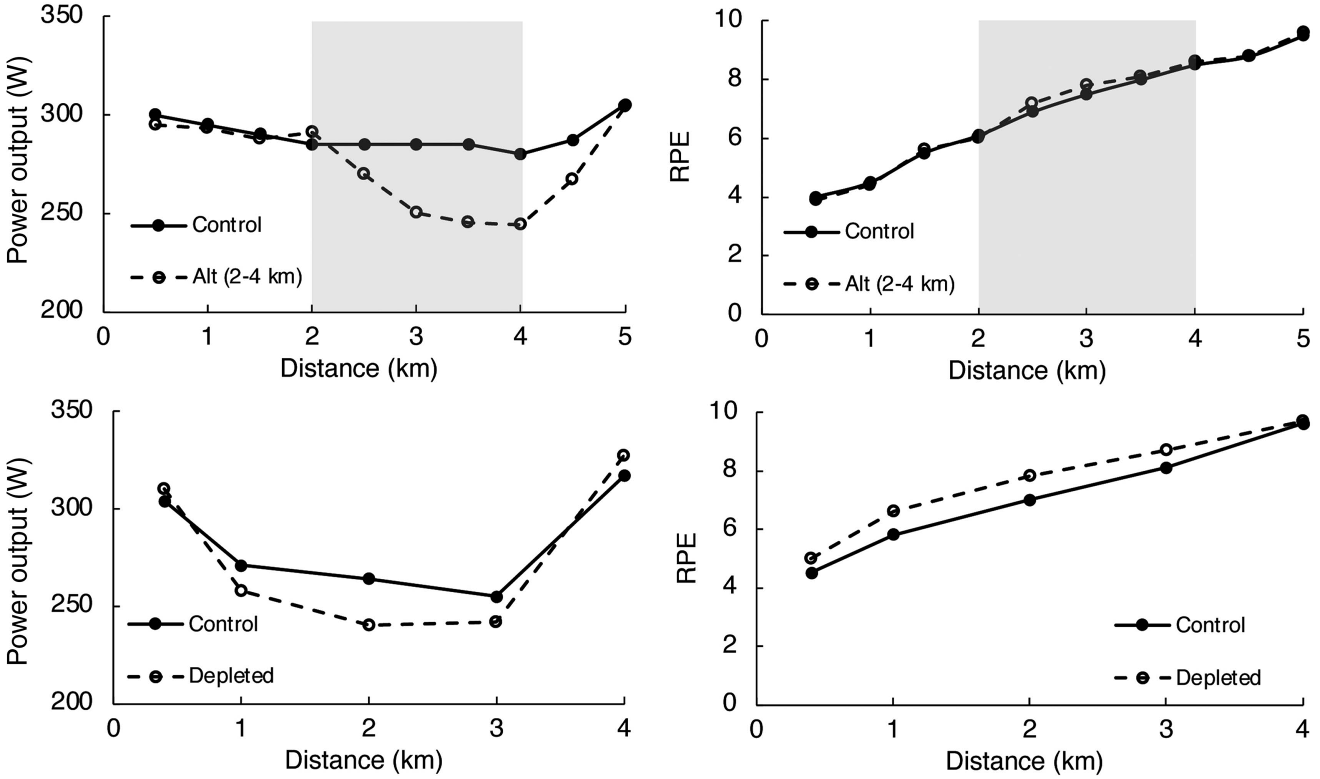

Figure 3 — Schematic responses of the degree to which changes in power output (PO) are used to regulate the growth of rating of perceived exertion (RPE) during heavy exercise. In one trial (upper panels), the subjects completed a 5-km cycle time trial, either breathing room air throughout or breathing a hypoxic mixture between 2 and 4 km.[28] During hypoxia, the PO is rapidly reduced and then returns to normal when normoxia is restored. However, the growth of RPE across the duration of the time trial is barely affected. In another trial (lower panels), the subjects competed a 4-km time trial in either a control condition or following an exercise/diet manipulation calculated to cause muscle glycogen depletion. In the depleted condition, there were profound decreases in PO after the opening 400-m segment but only modest increases in RPE.[92]

variations in momentary speed, and high speed during the end-spurt, high coefficient of variation. Variations in pacing seem designed to drop weaker competitors from the leading group and reduce the number of competitors in contention before the end-spurt occurs.[67,104,107–111]

Hettinga et al[68] discussed the role of opponents in pacing, using ecological principles and the affordance hypothesis. They explored mechanisms of interactive behavior, proposing a pacing framework to understand head-to-head competition in which both internal (eg, fatigue) and external (eg, opponent) factors interact. Support for this model was obtained through a series of laboratory and field studies[67,68] pacing behaviors of other exercisers[69] and different competitive circumstances. In addition to a preplanned template, interactions with competitors and other environmental aspects play roles that have been described as the *affordance concept*, wherein the actions of the opponents afford the athlete with a range of possibilities to modify preplanned strategies.[67–69,74]

St Clair Gibson et al[112] proposed the *Integrative Governor Theory* proposing a continuous oscillation between psychological drives (eg, competitive goals) and homeostatic disturbances that serves to regulate momentary power output. Both concepts highlight the complexity of the processes regulating momentary power output and highlights the meaningfulness of competition and actions of opponents are drivers of competitive strategy. In addition, since slower starting strategies reduce feelings of effort during competition,[96] there is a tendency in head-to-head competition to start slower than the best performance strategy, insert competitive “surges,” and recovery sections, and rely on the end-spurt to win the race. This is true unless the athlete perceives that their own end-spurt might be inadequate to match other competitors, whereupon higher intensity segments might be inserted to neutralize the end-spurt of other athletes, or to force them to drop off mid-race. This is an example of the *concept of affordances.* Head-to-head races use best performance strategy, until the actions or perceived capabilities of opponents afford the opportunity to use stochastic pacing. This is particularly true in aerodynamic (cycling, speed skating) or hydrodynamic (rowing, swimming) events where the cost of locomotion can be influenced by pacing or where the pacing of teammates (cycling, pack style skating, or team pursuit skating) or adversaries (Grand Tours, open water swimming) can influence energy cost. It is even possible that an athlete may go to the front, with the intention of slowing the pace, if they perceive that they cannot effectively complete the pace their opponents have adopted. In other words, starting with the best performance strategy as a default, pacing in head-to-head competitive events can be modified almost infinitely depending on the real or potential behavior of competitors. However, the overriding need to limit the magnitude of homeostatic disturbances remains, causing competitors to change from the externally monitored competitive strategy back to the internally monitored best performance (eg, survival) strategy. Opponents have thus been called social placebo’s/nocebos, influencing expectations regarding successful/unsuccessful pacing and performance.[113]

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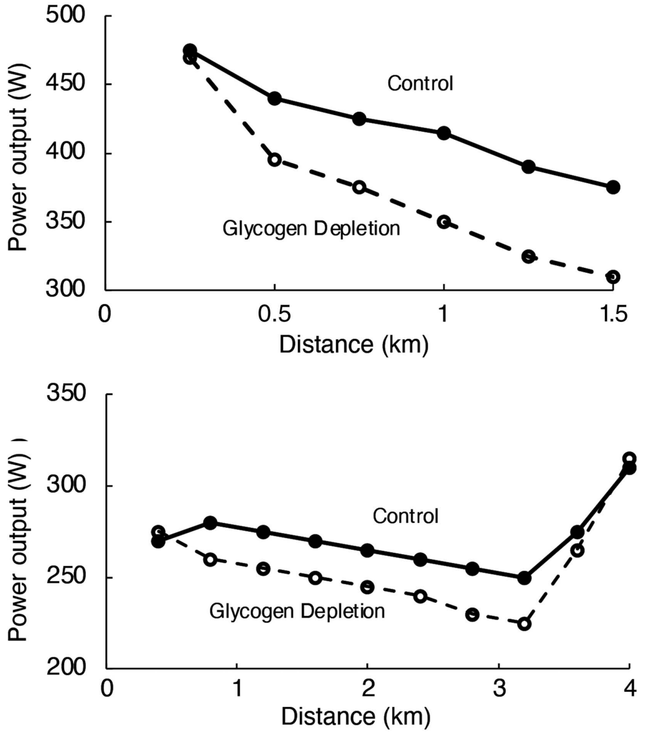

Figure 4 — Schematic of the effect of glycogen depletion during time trials of 1.5 and 4.0 km. In concert with the effect of a preexercise template, there is no effect on power output at the beginning of the time trial, but there is a rapid and progressive decrease in power output throughout the course of the glycogen-depleted time trial.[87]

CS and Pacing

CS or CP is the speed /power associated with highest sustainable metabolic rate.[8] This is derived from the asymptote for the hyperbolic speed–time or power–time relationship, recognized for nearly 60 years,[7,8] and anticipated before the turn of the 20th century.[11] Although not exactly the same, CS/CP approximates the physiological intensity of the maximal lactate steady state, the second ventilatory threshold, or the second lactate threshold.[8,114] CS/CP is at least as explanatory of endurance performance as maximal oxygen consumption and ventilatory threshold. If the CS/CP explains the upper limit of sustainable aerobic power, the concept of D′ (or W′) representing the curvature constant of the speed–time or power–time relationship accounts for additional nonoxidative energetic capacity during exercise above CS/CP. The momentary balance of W′/D′ can explain the likelihood of needing to decrease power output during severe exercise or the ability to increase power output in service of competitive goals.[115,116] This “anaerobic” energy can be used as needed to sustain metabolic rates in excess of CS/CP in shorter events (<15 min), to make mid-race surges, or during the end-spurt. Using direct measurement of anaerobically attributable energy supply, there is evidence[78,117,118] that, within an individual, the magnitude of anaerobically attributable energy (eg, D′), after adjustment for changes in gross efficiency, may be more or less constant.[80] There is evidence supporting the concept that the D′/W′ may be reconstituted if, during the middle of an event, the speed/power output decreases below CS/CP.[115,116] Examining the pacing of elite runners during 10-km competitions, it is evident that WR performances are performed close to CS, whereas important races (Olympic finals) are

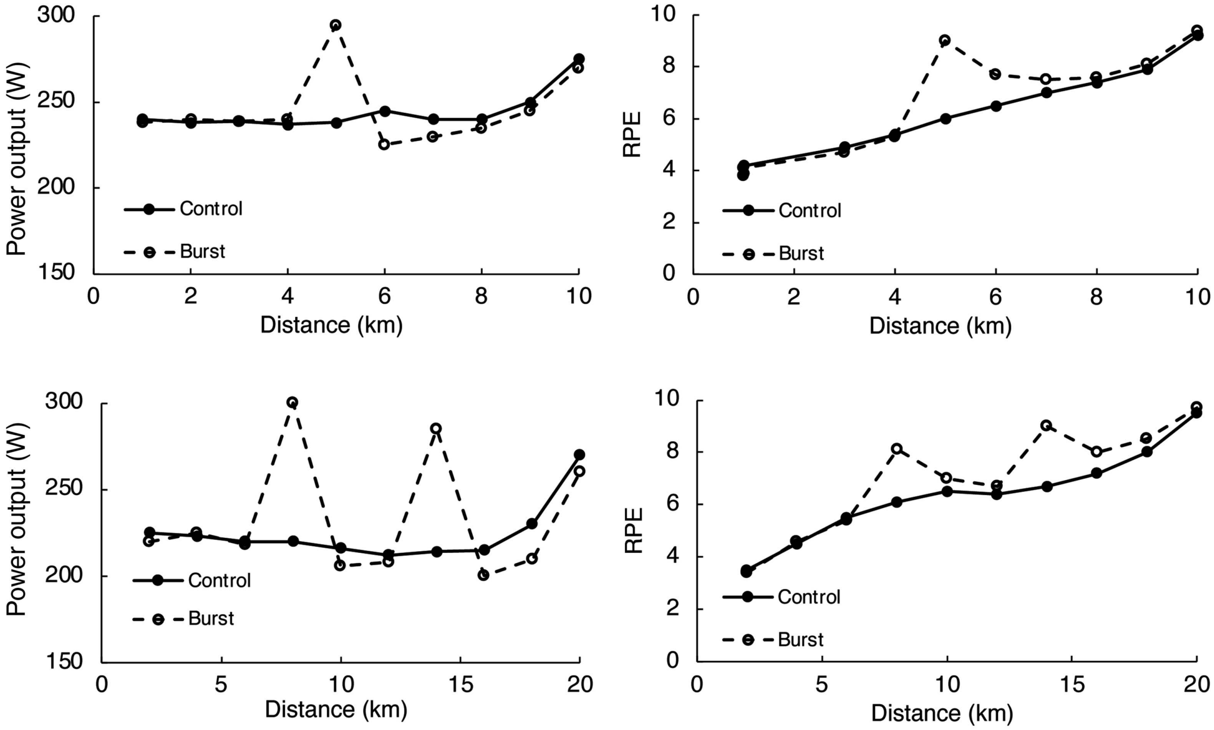

Figure 5 — Schematic responses of 10- (upper panels)[79] and 20-km (lower panels)[88] cycle time trials where one or more bursts, as if the rider were trying to “break away from the peloton,” were inserted. In both cases, during the burst the rating of perceived exertion (RPE) grew at a higher rate than in the control (self-paced) trial and slowly recovered after the burst, consequent to a reduction in power output. The data demonstrate that the rate of growth of RPE is tightly controlled and that power output is adjusted to maintain the expected rate of growth of RPE.

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contested with an average speed $<$ CS, but with tactical bursts above CS (Figure 6).[104,118] Pacing in groups of runners (first 3, middle 3, and last 3) in an Olympic final shows that better runners run much of the early part of the event $<$ CS, preserving D′ for the end-spurt, whereas less good runners run the early part of the event $>$ CS in order to stay with the early pace, thus limiting energetic reserve (D′) to contest the last laps (Figure 7). This concept has been called the D′ balance.[116] On this basis, it would be expected that the D′ balance would fall to very low values near the end of a race. Recent evidence from WR 1-mile races (entirely $>$ CS) and high-level 800-m swimming races[117,118] supports this expectation (Figure 8). Additional evidence from the 2008 Olympic men's 10-km race indicates that the CS/D′ balance could predict how high-level races unfolded, including evidence that the 80% of athletes falling out of contention before the end-spurt do so, often by mid race, when D′ reaches critically low levels and that D′ often increases during the remainder of the race as they are running $<$ CS (eg, survival mode). However, in the 20% remaining in contention until the last 400 m, the magnitude of D′ falls to very low values only at the end of the race (Figure 8).[118] Recent evidence suggests that the magnitude the end-spurt was related to how well runners were able to preserve D′ until the last 400 m and that superior athletes might win or lose competitions based on good or poor management of D′.[108]

The CS/CP and D′/W′ seem to be as definitional of performance level and pacing strategy as were prior candidates such as maximal oxygen consumption, lactate threshold/ventilatory threshold, and the O_2 cost of running.[8,119,120] While these metrics are still powerful predictors of the ability to move at a certain pace, the concept of an anaerobic capacity,[121] and how it is deployed during the course of an event, represented by the concept of D′ is useful for analysis of performance, for explaining why some athletes drop off the leading group during mid-race, and why some athletes have particularly effective end-spurts.[108]

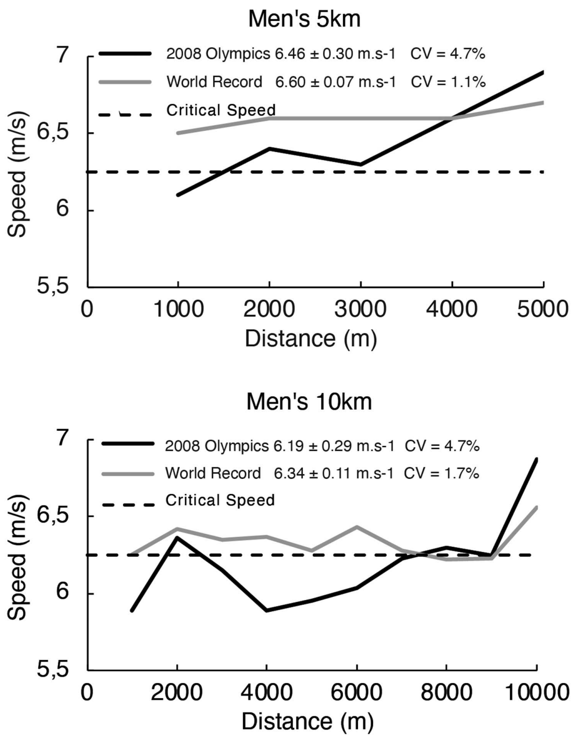

Figure 6 — Speed profiles of Kenesa Bekele (Ethiopia) during world-record 5- and 10-km races and during Olympic gold-medal races in the 2007–2008 time period. Note that the variation in pace during the championship events is much larger (coefficient of variation ~3 × greater). For reference, the critical speed (dashed line), calculated from public-record performances, approximates the velocity of the 10-km world record.

The CS/CP may also explain, at least in part, athletes' predisposition to use a fast start strategy during shorter, high-intensity events. There is evidence that such an approach speeds VO_2 kinetics, leading to a greater aerobic contribution in the early phase of exercise, thereby sparing D′/W′. This effect of a fast start strategy on VO_2 kinetics also increases CP compared with that established using constant work rate protocols. The pattern of D′/W′ use during short-duration exhaustive exercise, where W′ starts at 100% and finishes near 0%, will also be altered by a U shaped (relatively fast start and finish) compared with more even pacing. The regularly adopted U-shaped pacing strategy may be a behavioral evolution not only because is it likely to be performance enhancing but also because it would result in a higher W′/D′ over a large fraction of the mid-race, potentially making the exercise feel more tolerable.

Neuromuscular Factors

Since the paper by Paavolainen et al,[122] it is well accepted that "muscle power factors" contribute to performance. The contribution of neuromuscular factors to pacing in endurance events has

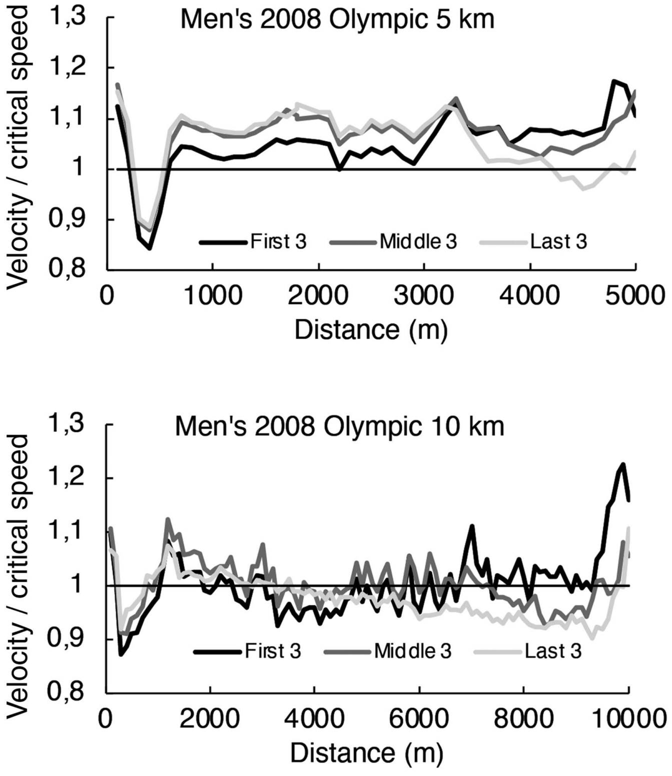

Figure 7 — Speed profiles of the first 3, middle 3, and last 3 runners in the men's 5- and 10-km Olympic finals (Beijing 2008). The data are normalized to the individual values for critical speed, which emphasizes that the first 3 runners are running at a physiologically easier pace during the early part of the race. This may serve to preserve D′ and allow them to run at a relatively higher percentage of their already higher critical speed during the closing stages of the race. A better preserved D′ also increases the likelihood of producing a more effective end spurt.[112]

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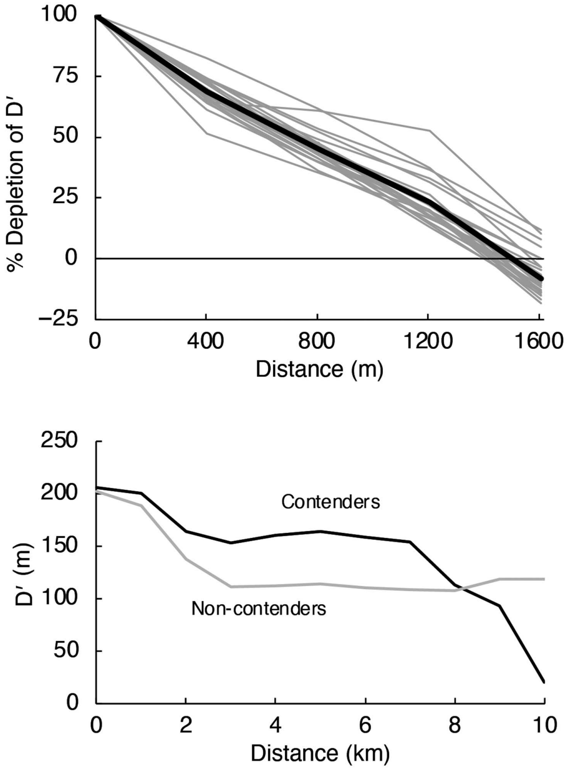

Figure 8 — Top: Progressive depletion of D′, to essentially zero values, during the course of world-record performances in the 1-mile run, based on historical data since ~1920. The critical speed was subtracted from the observed speed during each 402-m lap, and the remaining distance was subtracted from the D′ (both critical speed and D′ were computed based on published historical races for that athlete).[104] Bottom: Progressive depletion of D′ to near zero values in competitors in contact with the leader with 400 m remaining in the men's 10-km final at the 2008 Olympics. In athletes who dropped off the leader prior to 400 m remaining, D′ decreased early but then remained constant or even increased during the remainder of the race.[67]

been scarcely addressed. Damasceno et al[123] documented that improvements in strength influenced the last 2.8 of 10-km races. This finding agrees with cross-sectional studies reporting positive influences of diverse neuromuscular performances on pacing in endurance athletes. Intervention studies have suggested potentiation effects of strength exercises during warming up on the first laps of short time trials in runners,[124–127] cyclists,[128] and rowers,[129] without improving overall performance. Conversely, impaired neuromuscular function after static stretching[130] reduced the starting speed of 3-km running trials without affecting the final time. Therefore, current evidence suggests that neuromuscular function and postactivation performance enhancement would allow optimal pacing behaviors while counteracting the effects of fatigue.[131]

One of the most consistent and striking findings in the pacing literature is the near universal presence of the end-spurt in events of >2- to 3-minute duration, particularly in head-to-head competition. Presumably this evidence of "reserve" in the pattern of energetic expenditure is hard-wired into exercise patterns by virtue of evolutionary history as hunter-gatherers, who needed to preserve reserve until "closing in for the kill."[132] It can be argued that the interaction of muscle fiber type, lactate accumulation, and preservation of anaerobic reserve (D′) can act to define pacing. Athletes with a higher %type II motor units are predisposed to have more top-end power or speed.[133,134] However, since higher %type II motor units have a lower muscle respiratory capacity and lactate threshold (a surrogate of CS[135]), it is likely that the consistent pattern of runners with a higher %type I fibers attempt to "burn off" lesser runners [104] is representative of the need to remove the inherently better sprinters before the competitively critical moment of the race. Certainly, the best evidence is that the athletes winning in the final sprint are those who have best preserved their anaerobic capacity (D′).[108] Thus, the essential pacing decision within an event is whether natural sprinters (high %type II motor units, high D′) can remain in contact with more endurance-oriented athletes (high %type I motor units, high muscle respiratory capacity, high CS).

Practical Applications

Pacing, the way an athlete expends energy during a competition, depends on several factors. Although the term pacing strategy is widely used, the term is probably too broad, as "strategy" encompasses the overall race plan, the tactics used to accomplish the strategy, and the highly responsive pattern of energy expenditure, are all designed to achieve competitive outcome. The first is the competitive result (best performance vs defeating competitors). This will lead to whether the pattern of energetic output is smooth and based on the time–distance characteristics of the event or stochastic, where energetic output is focused on "dropping" competitors or preserving energy for the end-spurt. To accomplish these goals, an athlete needs to have a sense of their own capacity and be able to interpret internal feedback indicating the magnitude of homeostatic disturbances. They also need to have a good sense of their competitor's capabilities and be able to interpret signals from their competitors, in order to vary their tactics. Thus, while pacing strategy is not likely to discriminate between athletes of widely varying ability, it may be critical to achieving a desired competitive result in a tolerable physiological state.

Conclusion

Pacing strategies have been of interest to exercise physiologists for at least the last 30 years. Several models have emerged through the years attempting to predict the optimal pattern to finish an event without excess fatigue or excess remaining energy at the finish. These models have shown that pacing reflects a complex relationship between environmental stressors, physiological feedback, and psychological drive with a default pattern of a relatively "even" pacing strategy with a brief "fast start" to optimize time-centric versus head-to-head competition. These templates are robust even in the face of conditions that predictably would change them (hypoxia, glycogen depletion, etc). Athletes revert to the baseline template unless there is conscious effort to change for tactical reasons. However, templates may have progressive modifications through repeated performances. Once an "ideal" pacing template is achieved, the athlete may use the "concept of affordances" to modify pacing based on events occurring within an event. Although progressive growth of RPE is characteristic of pacing, more subtle psychodynamic factors such as affect (valence) appear to be more discriminatory than RPE on whether an athlete remains with competitors or "lets go" part way through an event.

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