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Will the Conscious-Subconscious Pacing Quagmire Help Elucidate the Mechanisms of Self-Paced Exercise? New Opportunities in Dual Process Theory and Process Tracing Methods.

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Key Points

The extent to which athletic pacing is under conscious or subconscious control has been a significant point of discussion and disagreement among researchers in this field, yet has failed to produce notable advances in our understanding of pacing mechanisms.

The notion that conscious processes are independent of subconscious, pre-conscious and unconscious influence is conceptually flawed, restricted in theoretical scope and has limited investigative utility.

Key terms of conscious, preconscious, subconscious and unconscious are defined and dual process theory, which distinguishes between intuitive and deliberative action, is offered as an alternative framework for investigating the control of athletic pacing.

Abstract

A prevailing issue is the extent to which athletic pacing decisions are made consciously or subconsciously. In this article we discuss why the one-dimensional conscious-subconscious debate that has reigned in the pacing literature has suppressed our understanding of the multidimensional processes that occur in pacing decisions: how do we make our decisions in real life competitive situations? What information do we use and how do we respond to opponents? These are questions that need to be explored and better understood, using smartly designed experiments. The paper provides clarity about key conscious, pre-conscious, subconscious and unconscious concepts, terms that have previously been used in conflicting and confusing ways. The potential of dual process theory, in articulating multidimensional aspects of intuitive and deliberative decision-making processes, is discussed in the context of athletic pacing along with associated process-tracing research methods. In attempting to refine pacing models and improve training strategies and psychological skills for athletes, the dual-process framework could be used to gain a clearer understanding of i) the situational conditions for which either intuitive or deliberative decisions are optimal, ii) how intuitive and deliberative decisions are biased by things like perception, emotion and experience, and iii) the underlying cognitive mechanisms such as memory, attention allocation, problem-solving and hypothetical thought.

1. Introduction

Athletic pacing has been defined as the way power output, work or energy expenditure is controlled or distributed to complete an event in the fastest possible time, having utilized all available resources [1,2]. One of the most common questions encountered at pacing symposia is whether regulatory mechanisms during self-paced exercise operate at a conscious or subconscious level. Indeed this question has been the focus of much of the pacing literature, including the influential central governor theory [3-8]. Although conscious perceptual processes are a recognised component of this theory [7,8], its main tenet is that a central controller subconsciously regulates the recruitment of motor units during exercise, acting as a protective homeostatic system that responds to afferent feedback about internal physiological disturbances [3-8]. A predominant alternative view is the psychobiological model [9] which contends motor unit recruitment is a consciously regulated process, as evidenced by the negative effects that distracting, loading or fatiguing the conscious mind have on pacing [10,11]. Not surprisingly, perceived exertion plays a central role, and constitutes the main conscious component of these [6,9] and other pacing models [8,12-14]. Hence, the key point of disagreement between the models is not the inclusion of conscious processes, but rather the extent to which such processes are responsible for muscle recruitment and pacing behaviour.

Although perception of effort is a feature of central governor theory [5,15], it is the existence and operation of a subconscious controller in the brain that is regarded to regulate muscle recruitment [5]. Importantly, the theory does not describe the existence of an anatomically distinct central governor structure in the brain, and our interpretation is that central governance refers to a functional property of the central nervous system, which likely involves interactions between various brain structures and neurological networks. In contrast, the psychobiological model argues that pacing behaviour is exclusively under conscious control and so a subconscious controller is not needed [9,10]. Edwards and Polman have proposed an explanation that involves both conscious and subconscious mechanisms [16]. They suggest that, while minor homeostatic pacing modifications operate at a subconscious level, major threats to homeostasis lead to conscious awareness and a deliberate behavioural pacing response [16]. Although this explanation is plausible, it still remains narrowly focused on the issue of consciousness as a determinant of pacing behaviour. We also feel that, at present, there are competing and incongruent perspectives about the relative roles of conscious and subconscious processing in pacing and that simplistic definitions of these concepts are used in the various pacing models.

This conscious-subconscious pacing quagmire is clearly an intellectually engaging debate, yet attempts to resolve it have not furthered our understanding of pacing mechanisms or how exercise intensity is regulated across an exercise bout. This should not imply that the consideration of consciousness and other related philosophical, psychological and psychoanalytical fields in sports science would not be efficacious. In fact, advances in these complex topics constitute some of the most important and exciting developments in contemporary science [17-19]. Our assertion is that the predominant dichotomy wherein either conscious or subconscious mechanisms govern pacing is both conceptually flawed and unlikely to yield significant gains in our understanding of how pace is regulated during exercise. Consequently, the conscious-subconscious question will be reframed into one of dual-processes, which we believe provides greater investigative utility in elucidating pacing mechanisms. We would also like to point out that exploring the conscious-subconscious paradigm is only one facet of the multidimensional process of decision-making in the context of regulating exercise intensity. An overly strong focus on only this leaves other exciting and useful areas of exploring human behaviour in sports context relatively unattended. For example, athlete-environment interactions as described in a recent review [20], are a crucial factor in understanding the regulation of exercise intensity. In this review, a framework is proposed based on ecological psychology and the interdependence of perception and action. This framework allows us to incorporate, understand and explore athletic behaviour in more complex pacing situations, such as how athletes respond to actions of their opponents. With dual-processes theory, we can also provide a broader framework capable of incorporating processes of decision-making, pacing and performance in more complex, real life competitive situations. It is our contention that conceptualizing decision making in pacing as involving intuitive or deliberative process provides a means through which progress can be made on parallel problems without getting ‘stuck’ on the singular issue of conscious versus subconscious control. In addition to the opportunities for exploring the multidimensional character of pacing, such an approach reflects the complex nature of athletic decision-making. We begin by clarifying fundamental conscious, subconscious, preconscious and unconscious concepts.

2. The Conscious, Subconscious, Preconscious and Unconscious

In some of the pacing literature, mechanisms are commonly discussed as being under either conscious or subconscious control [7,9]. For several reasons, this is a false dichotomy. The terms subconscious and unconscious have unfortunately been used synonymously [21-24] but they are distinct, and the distinction has a particular relevance to the issue of pacing.

The *subconscious* relates to mental processes operating outside consciousness, such as habitual or instinctive action. This is clearly an important factor in athletic pacing, but it needs to be differentiated from the *unconscious* by which is meant the dynamic unconscious of psychoanalytic theory. This will be explored below. According to the Freudian topographical model, there is also the *preconscious*, which is the location for those mental representations and processes of which you are unaware in the present but could be aware of if your attention was drawn towards them, either voluntarily or involuntarily [25]. During exercise an athlete might be unaware of certain actions like pedaling or stride length, or physiological functions like respiration unless their attention is shifted towards them at which point conscious awareness would occur.

In contrast to the subconscious and the preconscious, the *unconscious* mind contains phantasies, memories and thoughts that an individual is unaware of and cannot readily access by redirecting their attention. The concept of the unconscious is firmly rooted in traditional psychoanalytic theory [25] and, while it has undergone considerable theoretical evolution [26-29], there are several principles that all perspectives share in common. The first is that the unconscious mind contains all mental representations and processes that, by definition, an individual is not aware of. The second is that the unconscious mind operates in a dynamic way, influencing our conscious experience, feelings, personality and behaviour. As such, rather than being distinct, a transactional relationship exists between the unconscious and conscious mind.

Autonomic physiological processes like the cardiac cycle or perspiration operate at a subconscious level, as do perhaps elements of what have previous been described as pacing templates or schemas [30]. They are unconscious in that they are outside awareness but more usefully described as subconscious, so as to differentiate them from the psychoanalytic dynamic unconscious. By this is meant aspects of lived experience that individuals find traumatic, overly conflicted or otherwise difficult to cope with. Freud referred to repression as the mechanism by which these were placed in and kept in the unconscious rather than reaching our awareness [25]. For an athlete, this could include difficult experiences or perceptions that they experience during a race. It could also include unconscious conflicts about succeeding or failing, or other emotional conflicts that are impeding the optimum capacity to function at this particular moment or indeed driving one further to win. In this sense, repression is a defence mechanism that protects the conscious self from experiencing disturbing or threatening thoughts. While it could be argued that repression potentially benefits performance by regulating negative thoughts, feelings and anxieties, it might also limit performance by inhibiting and interfering with conscious drives and motivations. Whether debilitative or facilitative, psychoanalytic theory predicts that it is the dynamic relationship between unconscious and conscious mind that influences all behavior including athletic pacing.

It is important to point out that the term unconscious in this context is not referring to a sleeping state although sometimes, through dreaming, elements of the unconscious mind can move into conscious awareness. In this model the experience of not being able to remember a dream occurs because the meaning of the dream moves back into the unconscious mind. Psychoanalysts and psychodynamic psychotherapists often use methods like free association to bring aspects of the unconscious mind to conscious awareness. Hypnosis, which Freud experimented with but then later abandoned, is another technique for gaining access to the unconscious. Interestingly, it has been found that changes to perceived exertion, cardiovascular activity and cerebral blood flow during cycling can be elicited using hypnotic manipulation [31-33] suggesting an unconscious influence on how individuals consciously experience exercise and further indicating that conscious experiences are only a relatively small part of what governs our decisions and reactions.

The *conscious* mind contains those thoughts that a person is aware of in the present. In the context of exercise this would include perceived exertion, perceived fatigue, pain and other sensory-perceptual experiences. The consciousness of perception remains a highly debated issue [34] although in the context of regulation of pace it has been suggested that a continuum of conscious control exists from not aware to fully aware [16]. It would also include affective feeling states such as moods and emotions. A range of complex higher-order cognitive skills relevant to athletic pacing also proceed through conscious thought such as problem-solving, mental rehearsal, mental simulation, logical reasoning and language-dependent strategies such as self-talk [35].

The conscious, preconscious and unconscious are not independent of each other and this has implications for the conscious-subconscious pacing debate. The conscious is a subset of the preconscious that is, in turn, a subset of the unconscious. Thus every thought, perception and decision an athlete feels they have experienced or made consciously, has unconscious origins [28,29]. The question of whether pace is under conscious or subconscious control is therefore flawed because it implies one is distinct or separate from the other (see Figure 1a), rather than the conscious being a subset of the unconscious (see Figure 1b). Furthermore, during a race athletes are known to shift their attention between external and internal sensations [36,37] as well as between associative and dissociative thoughts [35,38]. Redirecting attention during an event in this way is indicative of the dynamic interrelationship between the unconscious, preconscious and conscious mind. The predictable, trait-like pacing behaviours that have recently been demonstrated [39] perhaps have their roots in the unconscious origins of personality [40].

Even if it would be possible to definitively establish which aspects of pace regulation an athlete was consciously aware of, which aspects shifted between preconscious and conscious, and which aspects an athlete was not aware of (unconscious), it is unlikely that such knowledge would advance our understanding of underlying mechanisms. For instance, establishing that a decision to increase speed was made consciously would reveal nothing about the information processing and cognitive processes that led to that outcome. Similarly, showing that some changes in speed are made without the athlete being consciously aware of them, also tells us very little about the processes behind regulation of pace and how athletes select pace. In this sense the prevailing issue of whether pacing control is conscious or subconscious, which may have developed from earlier peripheral versus central control discussions [3,15], is rather one-dimensional and therefore of limited investigative utility.

3. Dual-Processes: An Effective Alternative

We propose the traditional debate about pacing in terms of either conscious or subconscious regulation should be reframed in terms of intuitive or deliberative control mechanisms. Although there is some overlap with conscious-subconscious, examining intuitive and deliberative processes introduces new questions regarding the potential influence of dual cognitive processes of pacing behavior likely to enhance our understanding of the phenomenon.

The origins of dual processes in judgment and decision-making arose from several academic fields of study including economic decision theory [41-48], social judgment theory [49,50] and cognitive psychology [51-57]. The fundamental principle that underpins dual process theory is that, contrary to previous beliefs, individuals are not always fully rational when making decisions. Furthermore, decisions are often subject to a variety of influences including emotional state, previous experience, perception and social context. This perspective is consistent with findings from two recent reviews of pacing [20,21] in which the complexities of making pacing decisions were highlighted, particularly in regard to processing a wide array of situational cues and sensory-perceptual information. The present manuscript adopts a contemporary psychological perspective of decision-making in pacing, which is very accommodating of athlete-environment interactions.

The interdisciplinary literature on dual process control has revealed several consistent distinctions between intuitive and deliberative thought. Intuition is automatic and does not use working memory resources [57]. Consequently it involves very little cognitive effort, is quick, powerful and facilitates parallel functions [58,59]. Intuition is also associative and practical, meaning that complex tasks, problems and uncertain situations can be tackled by drawing on previous experience and beliefs [56,60]. Intuition is not associated with general intelligence [61]. In contrast, deliberation involves conscious language-related reflection [62] that draws heavily on working memory resources [63,64] and is linked with general intelligence [61,65]. It is slow, sequential and requires much cognitive effort [66-68]. Deliberative thinking does however permit abstract and hypothetical thinking.

4. Heuristics and Biases

Dual process theory also provides a framework around which research studies can be designed to gain a better understanding of the cognitive mechanisms of pacing and in this regard heuristics and biases are two useful concepts. A heuristic is a cognitive shortcut that enables people to make decisions, often quickly, in situations where there are large amounts of complex, confusing and competing sources of information that would be impossible to process. In other words, people reduce complex scenarios into simpler decision-making propositions by ignoring some of the information available to them, and this can proceed either through intuitive or deliberative means [45]. Until the mid 1970s it was assumed that people are rational decision-makers but in work that eventually earned them the 2002 Nobel Prize for Economic Science, Tversky and Kahneman showed that most decision-making errors can be attributed to heuristic influences that have an irrational basis [45]. In dual process theory, decision-making errors that are highly predictable are referred to as biases.

In the context of pacing, it would be impossible for an athlete to consider all of the possible factors and potential outcomes of taking certain actions therefore we propose that heuristic principles enable athletes to make pacing decisions in uncertain conditions. This is particularly relevant to early pacing decisions that are made during endurance activity at a point where a great deal of uncertainty exists about how external factors might change or how the athlete's physical condition will develop. The concept of heuristics is also far less deterministic than previous models [6,8,9,12-14] that have suggested the universal driver of pacing behavior is perceived exertion. Dual process theory is less rigid, accommodating the possibility that perceived exertion might be just one of many other heuristic influences that athletes could utilize in making pacing decisions. This is consistent with a view put forward by Gigerenzer and colleagues [69] that heuristics are used in an adaptive way with individuals selecting heuristics according to the perceived demands of a situation or problem. Evidence also suggests that athletes are similarly adaptive in how they make decisions. For example, it has been shown that conditioned beliefs about performance strongly influence early pacing behavior despite unsustainably high levels of perceived exertion [70] suggesting that in some circumstances the self-belief heuristic might have a stronger influence on decisions than the perceived exertion heuristic. In a number of other studies, the actions of a competitor have been strongly associated with pace change [71-73] perhaps indicating that, in some situations, it might be strategically advantageous to act in ways that would otherwise be contraindicated by the corresponding perceived exertion trajectory.

We are not suggesting that perceived exertion is not an important heuristic in pacing but rather, as part of an adaptive system, athletes have other heuristic principles that they might draw on in making pacing decisions. The affect heuristic [45], whereby a person's present emotional state influences their decisions, is one of the most common and powerful heuristics known and, as some research has indicated has a relevance to pacing [74]. As previously noted, perceived exertion shares many characteristics of an emotion [15] and in this regard may act similarly to the affect heuristic in the determination of pace as many of the models predict [6,8,9,12-14]. However, sometimes perceived exertion models of pacing are unable to account for failures in performance resulting from poor pacing which, for example in the central governor model should be prevented through homeostatic control [3-6], or in perceived exertion trajectory models [8, 12-14] would result in preventative pacing adjustments. It is through the availability of other heuristics, and athletes' ability to use them in adaptive ways, that it becomes conceptually possible to account for both successful and unsuccessful pacing outcomes on both an intra-individual and inter-individual basis. Specifically, the availability of other heuristics means that pacing successes and pacing errors can be explained in terms of the situational appropriateness of heuristic selection and utilization, or attributed to cognitive biases or dysfunctional cognitive shortcuts that have driven the decision. Dual process theory can also account for the interesting suggestion that different individuals adopt different decision-making strategies, according to the particular heuristics they prefer. In summary, dual process theory is much more flexible and accommodating of varied pacing behavior than previous perceived exertion centric models.

5. Pacing as a multidimensional process

Returning to the conscious-subconscious discussion, a further point we would like to make is that pacing is a multidimensional process. If we limit ourselves to only one facet of this multidimensional process, the conscious versus subconscious control issue, other exciting and useful areas of exploring human behaviour in sports context will remain relatively unattended. Therefore, as proposed in several recent reviews [20,21], we argue for a broader focus aimed at exploring how decisions are made in real life competitive situations and what information is used to inform such decisions. It has been demonstrated that opponents in 'real world' athletic competitions appear to influence athletic decision-making and tactics [75,76], supporting the interdependence of perception and action as advocated by the ecological perspective [20]. Action possibilities are afforded by the environment, and the perception of these action possibilities will be affected by the action capacity of the exerciser. This allows us to explain and further investigate human-environment interactions, such as racing against opponents, as well as analysing in-competition behaviour exploring new facets of pacing not possible with existing models. In addition, it is important to explore what other factors influence pacing and decision-making. There are indications that cognitive performance and potentially decision-making ability are compromised when individuals become physically fatigued [77], or as a consequence of low self-efficacy [78] or high anxiety [79]. The effects of physical fatigue on decision-making are clearly very relevant for occupations such as the military and emergency services where physical capacity and decision-making ability are crucial for optimal performance. An overly strong focus on the conscious-subconscious paradigm neglects the multiplicity of factors relevant to athletic decision-making that might be accommodated better with dual process theory.

6. Implications for Pacing Research

Dual process theory and the distinctions between intuitive and deliberative cognitive processes outlined above provide several new directions and questions for pacing research, and an opportunity to more effectively explore the multidimensional characteristics of pacing. Conceptually it can accommodate the idea that pacing behavior and associated muscle recruitment can arise out of both intuitive and deliberative cognitive processes. This is useful because research can focus on understanding how particular tasks, situations and triggers create the conditions under which intuitive and deliberative processes are more likely, when certain heuristics are selected in preference to others, and how they influence or bias pacing decisions. For example, it might be hypothesized that pre-planned pacing strategies that are consciously formulated by athlete and coach well in advance of the race are deliberative, and follow a systematic control strategy based on the execution of pre-planned algorithms. Equally it could be hypothesized that intuitive decision-making processes are better in situations during the race, where there are complex, incomplete or conflicting cues and a high degree of outcome uncertainty. Intuitive processes may also provide an important means by which athletes can make rapid pacing decisions perhaps in response to sudden and unexpected competitor behavior.

Future research could focus on identifying and understanding the heuristic principles that athletes rely on to make intuitive pacing decisions in complex situations that are otherwise difficult to resolve through deliberation. But we also need to develop a better understanding of how heuristic decision-making can in some circumstances lead to outstanding performance yet failure in other instances. Overall, greater insight about how heuristics and biases affect pacing and performance could help develop methods to improve intuitive decision-making skills in athletes to help them effectively adapt and respond to novel or difficult situations.

While in some situations intuitive decision-making capacity is useful, other circumstances lend themselves to deliberative processes. To illustrate this point, Kahneman & Tversky analogized, "…making decisions is like speaking prose – people do it all the time, knowingly or unknowingly." (p.341) [45]. In pacing research we must gain a clearer understanding of i) the situational conditions for which deliberative processes are most advantageous and ii) the hidden pre-decisional cognitive processes through which deliberation proceeds. The first point is important because it will help break the impasse in pacing research associated with the issue of conscious versus subconscious control. The second point is important because what should emerge from such understanding is the development of conscious attention, perceptual and problem-solving strategies that athletes can use to improve pacing decisions. In the pacing literature a great deal of emphasis is placed on the importance of anticipation [3,5-8] yet very little has been done to understand the cognitive processes involved in anticipating the demands of a future task, or how such appraisals influence subsequent pacing decisions. The ability to anticipate involves hypothetical thinking [80] and prospective mental simulation [81]. For prospective thought to accurately predict events two essential conditions must be met: i) the context we are in or imagine we are in during simulation does not vastly deviate from the actual future context that transpires and ii) the memories used to simulate are sufficiently vivid and realistic representations of the future event [81]. In the context of athletic pacing, especially during the early stages of an endurance event, the likelihood of inaccurate mental simulation is high owing to the potential for internal or external conditions to change that could result in pacing errors and negative effects on overall performance. A further complication is the influence that opponents in ‘real world’ athletic competitions might have on athletic decision-making and tactics [75,76] for which circumstance, intuition and hypothetical thinking may play a crucial role. A fuller understanding of deliberative cognitive processes will help develop conscious decision-making skills for athletes.

There are many practical issues that need to be considered to operationalize dual-process athletic pacing research. The first is to recognize the limitations of time series measurements of speed and power which, although useful indicators of post-decisional pacing behaviour, reveal very little about pre-decisional cognitive processes whether intuitive or deliberative. The issue is further complicated by the fact that many of the predecisional cognitive processes are hidden and not directly observable so a special category of research techniques known as process-tracing is needed. These and other operational research issues are discussed more comprehensively in the Electronic Supplementary Material Appendix S1, along with an introduction to process tracing methods and their application to dual-process athletic pacing research.

7. Conclusions

The one-dimensional conscious-subconscious debate that has reigned in the pacing literature has suppressed our understanding of the multidimensional processes that occur in pacing decisions. If we limit ourselves to only one facet of the multidimensional process of pacing, the conscious-subconscious debate, other exciting and useful areas of exploring human behaviour in a sports context will remain relatively unattended. We need to explore how and based on which information athletes make their decisions using smartly designed experiments that incorporate eg athlete-environment interactions. It is our contention that conceptualizing decision making in pacing as involving intuitive or deliberative process provides a means by which further research progress can be made on parallel problems without being constrained by the singular issue of conscious versus subconscious control. In addition to the opportunities for exploring the multidimensional character of pacing, such an approach reflects the complex nature of athletic decision-making.

In attempting to refine pacing models and improve training strategies and psychological skills for athletes, the dual-process framework could be used to gain a clearer understanding of i) the situational conditions for which either intuitive or deliberative decisions are optimal, ii) how intuitive and deliberative decisions are biased by perception, emotion and experience, and iii) the underlying cognitive mechanisms such as memory, attention allocation, problem-solving and hypothetical thought.

Compliance with Ethical Standards

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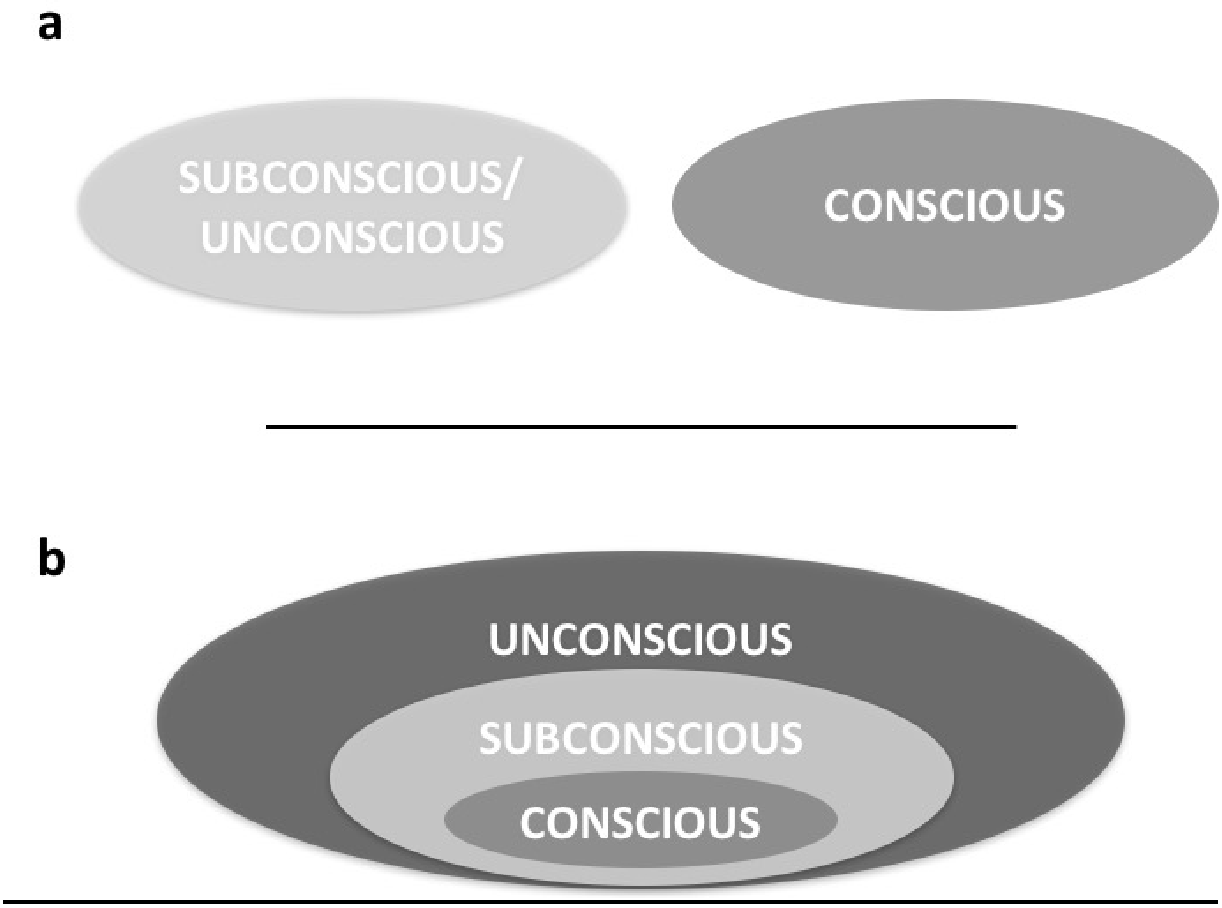

Legends

Figure 1. In previous pacing models the conscious and subconscious mind are conceptualised as distinct (conscious $\not\subset$ subconscious) with no adequate definition or distinction of subconscious or unconscious being made (Figure 1a). In contrast the topographical model emphasises a psychodynamic relationship whereby conscious $\subset$ subconscious $\subset$ unconscious (Figure 1b). Thus all thoughts, perceptions and decisions that are experienced in conscious awareness have unconscious foundations. By redirecting attentional focus an individual can become aware of subconscious content [25].

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'Electronic Supplementary Material Appendix S1

Operational Research Issues in Dual Process Pacing Research.

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1. Introduction

In the linked main article, philosophical considerations of how dual process theory might contribute to a developing understanding of pacing mechanisms are discussed. What is missing, and what will be the focus of this Electronic Supplementary Material, is important practical issues that we hope will help operationalize this kind of research. We propose that pacing research can be categorized according to three dimensions that broadly represent its descriptive, prescriptive and explanatory objectives, acknowledging that some studies span the dimensions. The constraints of existing methods in pacing research will be discussed in the context of dual-process decision-making and then an overview of particular approaches and methodologies will be given. This Electronic Supplementary Material is not intended to give detailed guidance on each method but rather provide a rudimentary introduction to a variety of process-tracing techniques that have particular utility in investigating dual-processes during self-paced exercise. Readers interested in using certain techniques are encouraged to refer to the corresponding key literature for more detailed methodological guidance which we have included under each section.

2. Dimensions of Pacing Research

Pacing research can be broadly categorized as being *descriptive, prescriptive or explanatory*. Descriptive pacing research, aims to measure changes in speed or power output during athletic tasks that vary in type, duration or distance. Descriptive pacing research involves the observation and measurement of pacing outcomes and there is no manipulation of variables. It was the evidence amassed from descriptive research, whereby particular patterns of changing speed or power where found to correspond with events of certain durations, from which the taxonomy of pacing strategies has emerged. This research is reviewed elsewhere [1] but summarily it has been found all-out and positive pacing strategies are mostly used that short duration events, whereas even, negative or U-shaped pacing strategies are used in longer duration events. An extension of this type of research has been to describe the biomechanical, physiological, psychological and overall performance consequences of various pacing strategies, again also reviewed more comprehensively elsewhere [1,2].

The purpose of prescriptive pacing research is to identify pacing strategies that are optimal for, i) events of a certain type, duration or objective, ii) particular environmental or situational conditions and, iii) athletes of a particular group, category, standard or level of fitness. Prescriptive pacing research goes beyond observing and describing pacing patterns by attempting to investigate which pacing strategy produces the most favourable performance with respect to either completion time or finishing position. Prescriptive pacing research is usually driven by a desire to identify optimal pacing strategies, often with coaching practice or other forms applied athlete support in mind. There are three main approaches to prescriptive pacing research. The first, which we recognize overlaps with the descriptive dimension, involves observing and describing the pacing strategies of elite or expert performers, the findings of which are then used to approximate optimal pacing strategy. While good examples of this kind of research exist [3-6], it should not be assumed that the strategies adopted by elite performers are generalizable to all groups of athletes or all situations. A second, between-subjects approach, has been to compare the pacing strategies of different groups of athletes, for instance by gender [7-9], successfulness [9-11] or experience [12,13]. The third approach to prescriptive pacing research uses a within-subjects approach whereby the impact of different pacing strategies is tested by repeating a performance with either all or part of the pacing strategy manipulated [14,15].

Explanatory pacing research is more concerned with understanding underlying mechanisms, either intrinsic or extrinsic, that lead to particular pacing behaviours. Developing a better understanding of pacing mechanisms should provide a basis for new prescriptive pacing studies designed to further our knowledge of what constitutes optimal pacing. The approach typically adopted with this type of research is to examine the effect that manipulating certain variables has upon pacing strategy and performance, thus using inductive methods to isolate, observe and make conclusions about the causes of pacing. Investigations of this kind have revealed a plethora of variables that influence pacing strategy that can be categorized as physiological [83], neurophysiological [16], psychological [17-19] and environmental [20,21]. Deception methods have been particularly prevalent in researching the role of performance feedback on pacing behavior [22,23], especially given the prominence some theories have placed on awareness of the endpoint [24-32]. Decision-making has been recently highlighted as an important mechanism of pacing behavior [33,34] and this relatively new perspective on pacing clearly falls under the explanatory dimension of pacing research. Understanding how pacing decisions are made will require new and sophisticated approaches to pacing research.

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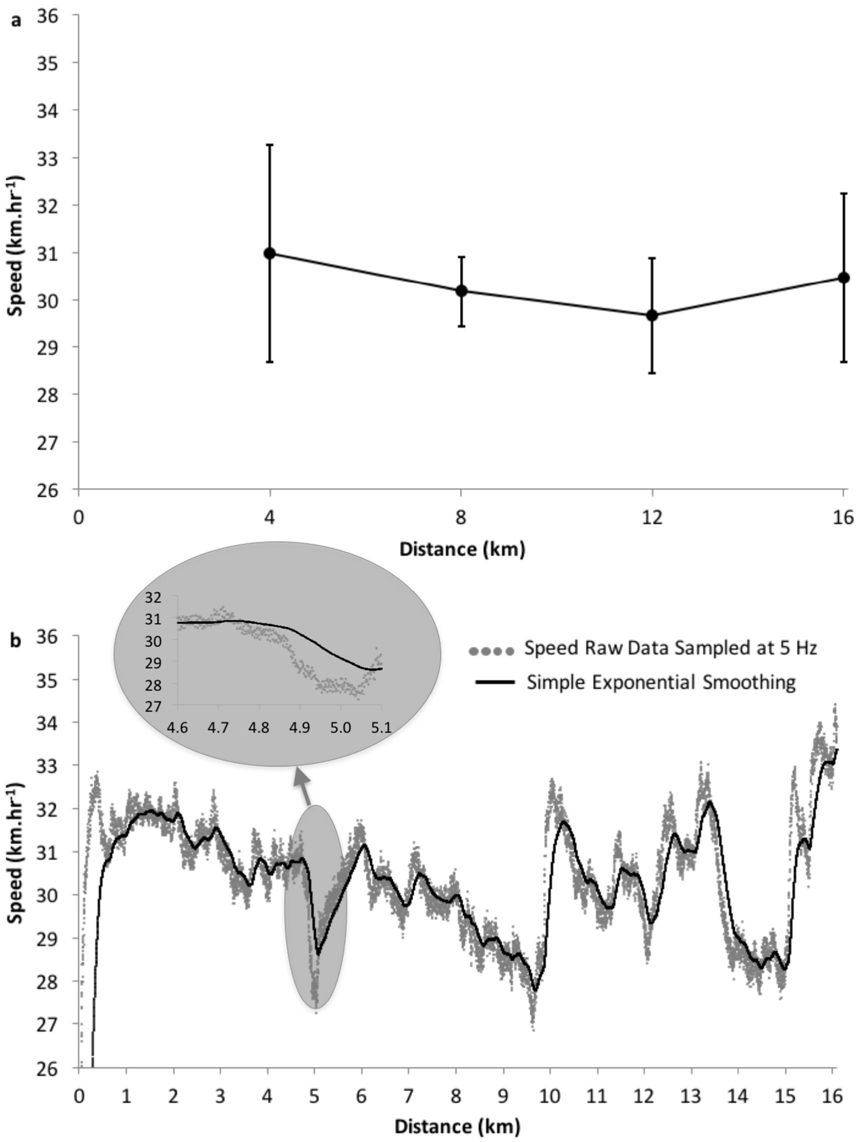
3. Limitations and Opportunities of Current Approaches to Pacing Research

Before overviewing particular methodologies, it is first necessary to discuss ways in which existing approaches to measuring pace limit the inferences that can be made about associated judgment and decision-making processes. The example pacing traces given in Electronic Supplementary Material Figure S1 represent changes in speed measured during a 10 mile (16.1 km) cycling time trial by a novice time-trial cyclist. In Electronic Supplementary Material Figure S1a, speed has been averaged across 25% (4 km) segments from which a parabolic reverse J-shaped pacing pattern is evident. Segmenting pacing data in this way is commonplace in the pacing literature and can vary from as much as 5% segment averaging [19] to as little as 25% averaging [12]. Segment averaging is a helpful way of presenting and analyzing pace because it provides a way to identify pacing patterns from otherwise noisy and confusing data. Nevertheless, there are some explanatory limitations associated with segment averaging since it fails to adequately represent and potentially misrepresents momentary pacing behavior and underlying decision-making processes that have led to that behavior. For instance, in Electronic Supplementary Material Figure S1a it could be concluded that the cyclists chose a fast start during the first 25% of the time-trial, adopted a negative (falling) pace during the middle sections and then increased pace during the last 25% of the event. However Electronic Supplementary Material Figure S1b, which presents the raw data for the same trial sampled at 5 hz, reveals much more stochastic and complex changes in pace. With such frequent and sometimes erratic changes in pace it seems obvious that segmentation is unlikely to reveal anything useful about moment-to-moment decision-making processes, especially since it is unlikely that athletes' strategic deliberations correspond with the particular segment sizes specified by the researcher. Put another way, researcher-defined segments do not necessarily correspond with the cognitive representations of time or distance that athletes actually use in making pacing decisions.



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Electronic Supplementary Material Figure S1. Example pacing pattern of a 10 mile (16.1 km) cycling time trial with 4 km segment averaging (a) and continuous data with simple exponential smoothing (b).

It would be useful to develop a way of analyzing raw pacing data such that particular moments can be identified where pace has changed and corresponding decisions have been made. This is an important but difficult problem because: i) it is difficult to define what constitutes a strategically meaningful change and to differentiate between those changes that are a consequence of mechanical fluctuations rather than intuitive or deliberative decisions; ii) it is difficult to precisely identify when such a change in pace has occurred which is important to investigate decision processes that precede it either immediately or after a short delay; and iii) decisions not to change pace are effectively invisible in a pacing trace and can only be revealed by triangulating continuous pacing data with other information. These problems are best exemplified by considering the grey area highlighted in Electronic Supplementary Material Figure S1b which shows an apparent drop in speed which occurs somewhere between 4.6 to 5 km and then an increase in speed between 5 km onwards. Closer inspection of the exploded section (inset) highlights the difficulty of pinpointing the exact moment the drop in pace was initiated because the numerous data points that occur in the proximity of the peak. While a variety of smoothing methods like moving averages or more sophisticated exponential smoothing (as displayed in Electronic Supplementary Material Figure S1b) can be applied, all such methods produce lag between the raw and smoothed data (see inset section of Electronic Supplementary Material Figure S1b) and therefore are not helpful in determining precise moments of change. Furthermore, it seems impossible to determine from raw data whether changes in pace were intuitive or deliberate, if there was any delay (latency) between when a decision was made and implemented, and whether the magnitude of change in speed was strategically meaningful. In this sense, even continuous measurements of pace similar to that presented in Electronic Supplementary Material Figure S1b, have limited utility when presented alone in understanding decision-making processes. It is crucial that pacing data, whether presented as speed, power or some other measurement, is treated and interpreted as a behavioural outcome of pacing decisions and not as a surrogate measure of the decision-making processes themselves. While the pacing trace can provide useful information about the implementation of pacing decisions, it does not reveal anything about the hidden dual processes of judgment and decision-making for which additional measurements are needed and are discussed in section 4.

4. Methodological Approaches to Dual Processes and Decision Making in Athletic Pacing Research

At this point it is helpful to make a hypothetical distinction between two ways through which pacing decisions might proceed. The first is where an athlete continually monitors and interprets important cues while performing a task and makes a decision to maintain, increase or decrease their pace that they might implement across varying timescales. The second is where an athlete might make and implement an instantaneous pacing decision perhaps as a reaction to an expected or unexpected event such as a sudden change in terrain, environmental conditions, competitor behavior or their own physiological condition. In both such situations the decision-making process typically involve a number of common processes including the acquisition of information, the integration and interpretation of information, and decision implementation. The adequacy of the pacing trace in measuring the implementation of pacing decisions has already been discussed in section 3. The remainder of this section will outline methods that can be used to investigate information acquisition, integration and interpretation. Because these research techniques are concerned with investigating cognitive processes, either intuitive or deliberative, they are sometimes collectively referred to as process tracing methods. Process tracing methods are intended to reveal pre-decision behaviours and cognitive processes that lead to a decision [35] whereas, as previously discussed, measurements of speed and power represent post-decision pacing behaviour.

4.1 Information Acquisition Research Methods

In trying to establish which type of information is most important to athletes, a typical approach has been to manipulate selected information using blinding or deception methods [22,23]. The purpose of such studies is to evaluate the dependency upon, and importance of, certain types of information in the regulation of pace. The rationale is that, if, after altering or removing a particular source of information pacing or performance changes, it can be inferred that, that information source has an important contributory role. It is evidence from these studies that have led to pacing models where awareness of progress towards the endpoint, either by distance or time, have come to be so dominant [24-32]. These experiments have provided a useful way of investigating the influence of certain information on pacing behavior but such methods are not without their limitations. One is that, in designing these experiments, it is necessary to make prior assumptions about which informational variables to manipulate. While this has application in testing theories where the importance of certain information such as the endpoint is specified, it is less useful in constructing pacing theory and discovering which information athletes actually seek out and use during self-paced exercise. It also assumes that all individuals commonly use the same information cues to make pacing decisions, therefore missing opportunities to understand individual adaptive variations in information preference, acquisition and interpretation. Active information search and eye fixation measurements are process-tracing methods provide an alternative to deception and blinding studies to investigate information acquisition processes.

4.1.1 Active Information Search

A question of great importance to understanding pacing behavior is what information athletes seek to make pacing decisions? One method that can help progress this question is active information search (AIS) yet, for a variety of reasons and to our knowledge, it has never been used in pacing research. During the performance of a task, AIS can be used to identify what information participants use, what information they ignore, and the sequence of information they refer to while solving problems [36]. There are several phases to the AIS procedure. During the first phase, participants are presented with information about a scenario that requires a decision and several choices. During the next phase participants are permitted to ask questions to which they receive a standardized pre-prepared answer usually given through an answer card or computer display. Participants are permitted to ask as many questions as they feel necessary, and may repeat questions if they like before entering the final phase of AIS which involves making a choice. A more comprehensive review of the AIS method and its variations is available elsewhere [37].

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The advantage of AIS is that it allows researchers not only to measure what information participants think they need in order to make a decision about a given problem, but also the sequence in which they refer to, or go back to, information. It must be emphasized that it does not reveal anything about whether such information was actually used in making the decision, which is why we have introduced it as an information acquisition research method. The AIS method has investigative potential in understanding deliberative decision-making processes but there are challenges to overcome for its use in athletic pacing research. One challenge relates to using AIS during exercise. Traditionally, participants carry out an AIS task in a laboratory in non-exercising conditions where they have time to read a scenario and then request more information before making a decision. The timing and sequence to information requests is either logged automatically using software such as WebDip [38] or recorded manually. The conventional AIS method is therefore difficult to carry out while participants are exercising and therefore would need modifying for pacing studies.

One adaptation might be to develop exercise related AIS scenarios that, although athletes would complete during non-exercising conditions, would still require them to make a decision about whether to increase, decrease or maintain pace. In order to achieve this, it would be necessary to pre-prepare responses to likely questions that the athlete participant might ask and the procedure for doing this is described in more detail elsewhere [37]. In this version of AIS participants would not be completing a self-paced task but we would nevertheless argue that such methods are still helpful in understanding the information acquisition processes athletes undergo before arriving at a pacing decision. The ecological validity of AIS could perhaps be improved by asking participants to complete the task in various states of exertion or fatigue.

The second is to develop self-paced exercise scenarios where all the usual feedback information is withheld from participants and only made available to them upon an explicit request. At the most basic level this could involve hiding performance information such as time or speed which participants could reveal by operating a control of some kind. In more complex scenarios participants might have the opportunity to ask for more information about the environment, weather, competitors, probabilities and other factors.

While there are challenges associated with the AIS method in pacing research, it does have potential in developing a better understanding of what information athletes think they need to make key pacing decisions. In being able to measure the order in which certain information is requested, the AIS method can reveal more about deliberative decision making-processes and the corresponding information needs of athletes.

4.1.2 Eye Fixations

Of all the senses, vision is the superordinate means through which individuals acquire information about their immediate environment. As such measuring what athletes look at during the performance of certain tasks has huge potential in revealing information acquisition patterns, unconstrained by the previously discussed assumptions and biases of information-manipulation studies. Measuring eye-movements is relatively easy and a variety of methods are available which are comprehensively reviewed elsewhere [39]. Eye-tracking technology has improved significantly during the past decade, particularly mobile eye-tracking devices which are clearly very useful for both laboratory and field-based pacing studies. There are a variety of ways in which eye-trackers work, the most common of which involves monitoring and recording corneal reflection. An eye-tracker typically consists of a forward-looking scene camera and a second camera that records the eye. Modern eye-trackers have the capability to make high-definition recordings and have advanced from having monocular to binocular tracking functions that provide enhanced sensitivity and better resolution of eye movement measurements. All eye-trackers require calibrating for each individual participant. For some individuals the devices can be difficult or impossible to calibrate meaning that some participants are excluded from the sample. Another practical issue of using eye-trackers during exercise is the added likelihood that sudden head movements or perspiration droplets obscuring the eye camera can knock-out the calibration during a capture period. While these issues can be minimized, using eye-trackers during exercise requires skill and patience to ensure that reliable, high-quality data is collected and this should be accommodated during the pilot phase of any study.

Eye-tracking involves measuring saccadic eye movements. Saccades are a particular category of eye movements that involve quick jumps from fixating on one object to another. Saccadic eye movements can be easily observed without any equipment by looking at the eyes of another person while they are reading. Saccades while scanning a scene typically involve about 6° movements and can be a fast as $700°.s^{-1}$ [40]. The ability to measure eye fixations and saccadic eye movements is a very reliable way of directly determining information acquisition processes which, during self-paced exercise studies, has the potential to reveal what environmental or informational cues participants consider to be important.

The cues that participants look at are commonly referred to as objects of regard. Two particular measurements can be used to indicate the relative importance placed upon particular objects which are fixation time [41] and fixation frequency [42]. Fixation times can be calculated in several ways. Total accumulated time that an object of regard is looked at is considered to be a measure of importance [41]. Average fixation time is considered to represent cognitive processing effort and has been used to differentiate between intuitive (fast) and deliberative (slow) thinking [43]. In a recent study, at this time published as a conference abstract, average fixation time was used to show that expert cyclists primarily looked at speed during a 10 mile time-trial whereas novices primarily looked at elapsed distance [44]. Eye fixation sequences, or the order in which participants look at or switch between objects of regard, are also a useful measure of information acquisition. During self-paced exercise this could be useful in understanding how athletes find or select important cues during complex or novel situations. It could also be useful in revealing what information athletes use when faced with a situation that requires them to make a choice between a number of alternative possibilities. For example, whether to pursue an attacking competitor or hold back.

4.2 Information Integration and Interpretation Methods

While eye tracking can measure information acquisition, it is nevertheless limited in that it does not reveal anything about what participants think. For example, in one eye-tracking study expert time-trial cyclists where found to look at speed for longer [44] and it would be tempting to conclude that they value feedback about speed more than distance. However, it may just be that the processing of distance information is quick and required less cognitive effort whereas, in regulating their performance, they required more continual monitoring of speed and more in depth processing of this type of feedback. In order to understand how athletes are using the information they attend to, other process tracing methods are needed which can either be used in isolation or in conjunction with other methods such as eye-tracking. This section will focus on verbal protocols and response times.

4.2.1 Concurrent Verbal Protocols

Concurrent verbal protocol is a process-tracing method that involves participants verbalizing their thoughts aloud while they are carrying out a task [45]. Thoughts that are spoken aloud contemporaneously with a task have been put forward as a reliable way of understanding actual thinking [46] because it reflects short term memory processing and internal deliberation [47,48]. Acknowledging the complex relationship between language and thought [49], thinking aloud can provide important subjective data about deliberative decision-making processes during self-paced exercise. While a reasonable body of literature exists regarding the closely related subject of self-talk during physical activity [50-54], it is important to recognize that self-talk is not a process-tracing technique but rather a psychological skill that athletes sometime used to overcome anxiety, negative thoughts or other mental stressors.

Concurrent verbal protocols can take many different forms but our focus will be on the version put forward by Ericsson and Simon [47] which is considered to be the gold standard. Their standard comprises four important phases involving participant instructions, participant familiarization, data recording and data analysis. Participants are first given written instructions to read, which should ask them to say their thoughts aloud during a task. The instructions should emphasize the importance of saying everything they are thinking and to talk continuously throughout the task without pause. Participants should be then familiarized with thinking aloud by allowing them to practice while completing a simple problem, perhaps involving basic arithmetic or choosing which painting they prefer from two alternatives. During the familiarization phase participants may have to be reminded to simply verbalize what they are thinking rather than to explain their thoughts. Only once a participant develops competence in thinking aloud should an attempt to collect experimental data proper commence. During the data collection phase both the participant's verbalizations and their actions relating to the task should be recorded. The researcher should aim for minimum interference and interaction, but should remind a participant to keep talking should they stop doing so for more than 5 seconds. Analyzing the data usually involves segmenting the transcribed verbal recordings into blocks and coding the content which is then used to identify either component processes of decisions, sequences of processes or complete models [55]. The approach to analyzing verbal protocol data varies considerably [56] although a helpful framework for identifying decision-making processes from verbal data does exist [57].

Think aloud data does have great potential in determining whether intuitive or deliberative thought processes produce better pacing decisions. This is possible by comparing the effectiveness of a solution to a problem a participant first mentions (intuition) against the effectiveness of the eventual solution that they carry out (deliberation), an approach which has be used to investigate decision-making during chess [58]. However, while it is easy to quantify the strength of a chess move, it is more difficult to quantify the strength of a pacing decision and if such approaches are to be adopted then protocols will need to be developed where pacing decisions can pin-pointed in time, measured and evaluated for effectiveness.

Concurrent verbal protocols do have their limitations, in particular the significant threats to their reliability and validity. Two particular forms of invalidity have been associated with concurrent verbal protocols [59] which are reactivity, where a participant's attention to verbalizing their thoughts interferes with their decision-making processes, and non-veridicality, where participants either omit some of the decision-making processes or misrepresent such processes. The issue of reactivity can be addressed by including a control condition in which participants are not required to think aloud, nevertheless in pacing research participants' ability to verbalize will be significantly hampered by the high-intensity nature of most studies. It is possible to collect concurrent verbal data during high-intensity exercise but the technique will require practice and researchers should also carefully consider whether the potential effects verbalization itself has on energetics and performance is a compromise worth making. Non-veridicality can be minimized by ensuring participants clearly understand the instructions and have sufficient opportunity to become competent in thinking aloud during the familiarization phase. Ericsson and Simon further argued that think aloud data must satisfy several conditions including being relevant to the task in hand rather than some unrelated issue, and to be logically consistent with the immediately preceding verbalization.

4.2.2 Retrospective Verbal Protocols

An advantage that retrospective verbal protocols have over concurrent verbal protocols is that reactivity threats can be eliminated, providing participants are not made aware that they will be asked about their decisions retrospectively. However, different threats to validity are introduced the most notable of which is associated with errors in memory recall such as distortion, omission and construction effects [59]. One of the known problems of asking participants after an event why they made a decision is the tendency to infer a reason rather than trying to remember their actual thought processes [60]. This is a significant threat to the validity of post-decision surveys and interviews, although this can be minimized by carefully briefing participants beforehand.

There are two main methods for gathering retrospective verbal reports. The first involves a traditional interview which can vary from being unstructured to fully structured during which participants are asked to explain, describe or rate decision-making processes. The second, known as a cued retrospective verbal reporting, involves simulated recall in which participants are asked to discuss their decision-making processes while watching replayed video footage of themselves performing a problem or task [61].

Retrospective verbal reports are advantageous in pacing research because they avoid reactivity, particularly the likelihood that concurrent verbalization will interfere with the performance of the exercise task and vice-versa. However, unlike concurrent reports, retrospective reporting lacks spontaneity and therefore has a diminished ability to differentiate between intuitive and deliberative pacing decisions. Both concurrent and retrospective verbal protocols are, by their nature, also limited to conscious processes except when pre-conscious, subconscious or unconscious processes temporarily move into consciousness. Verbal protocol methods represent a powerful way of gathering and analyzing subjective decision-making data in dual process pacing research providing such studies are carefully designed and deployed with rigour.

4.2.3 Response Times and Systems Factorial Technology Methods

According to dual process theory, intuitive decision-making is quick and depends mostly on parallel processing of information whereas deliberative decision-making is slower owing to the serial processing of information. Another dimension of cognitive processing relevant to decision-making is whether all possible cues are considered before a decision is made (exhaustive processing), or whether processing stops once an acceptable decision is arrived at (self-terminating processing). In simple decision-making tasks, where participants are to make a choice based upon two input cues, response time between the presentation of the cues and the decision can potentially differentiate serial from parallel processing. Athletic pacing decisions, however, are usually made in complex environments with many cues. This creates a problem because parallel processing slows down as a function of the number of cues and thus response time has a diminished capability to discriminate serial from parallel processes, an effect known as the model mimicking dilemma [62].

An elegant way of resolving response time ambiguity between serial and parallel processes is found in a non-parametric statistical technique known as systems factorial technology (SFT) for which more detailed guidance can be found in Harding et al. [63]. The fundamental principle of SFT is that when input cues subject to hidden cognitive processes are selectively manipulated, it is possible from the resultant response time patterns to determine whether those hidden cognitive process are serial exhaustive, serial self-terminating, parallel exhaustive, parallel self-terminating, or co-acting.

To illustrate the principles of SFT in a pacing context, imagine a situation where one cyclist (A) was in head-to-head situation with another competitor cyclist (B) who suddenly accelerates into a sprint. Cyclist A is forced to make a decision whether to follow the breakaway cyclist B and suppose we hypothesize in that making such a decision they need to consider two crucial pieces of information; distance remaining and perceived exertion. While we could measure how long it takes cyclist A to make a decision (the response time between cyclist B accelerating and cyclist A acting), it would be impossible from response time alone to determine whether the information cues of distance and perceived exertion were processed in parallel or serial to arrive at such a decision. If, for whatever reason, an erosion in the quality or availability of one or both information sources (distance or perceived exertion) occurred, it would be reasonable to expect that this would disrupt whatever hidden serial or parallel processes are taking place and that this would cause a change to the overall decision time. It is this principle that SFT takes advantage of systematically manipulating input cues to create four conditions which, in the example provided, would involve: i) distance corrupt, perceived exertion complete; ii) distance complete, perceived exertion corrupt; iii) both distance and perceived exertion corrupt and iv) both distance and perceived exertion complete. Each permutation selectively influences each input cue thus provoking different effects on overall decision time and the basis upon which to differentiate between the five types of hidden cognitive processes.

The example given above is a necessary simplification that we have used for illustration purposes. Nevertheless, SFT is a powerful method of uncovering hidden cognitive processes but several important points of detail need to be understood if it is to be of use in dual-process pacing research. The first is that SFT actually uses the survival function of response times rather than mean response times. Survivor functions can be easily calculated using statistical software and details of the underlying methods are elsewhere for the interested reader [64]. The second is that, when plotted, it is the shape of the survivor function can distinguish between serial self-terminating, serial exhaustive, parallel self-terminating, parallel exhaustive and coating hidden cognitive processes. The final point is that applying SFT to pacing research requires considerable care in experimental design. This means ensuring that adequate selective influence of input cues is achieved such that it is possible to independently influence one cue without affecting the other. It also means that in complex environments where there are multiple cues, complex Latin square designs will be necessary and consideration needs to be given as to whether such studies can be adequately powered. Also that, unlike much of the previous pacing literature, SFT design demands a pacing decision protocol to be developed whereby overall response (decision) time can be accurately measured.

4.3 Other Process Tracing Methods Relevant to Pacing Research

So far the main process-tracing methods for investigating information acquisition and information processing have been discussed. There is another category of process tracing methods concerned with measuring psychophysiological correlates of decision-making that this section will briefly introduce. During the past few decades, methods and techniques to measure or image brain activity have become economically viable and much more accessible to researchers around the world which has provided exciting alternatives to some of the traditional process-tracing methods already discussed. Some of the key physiological and neurological measures include, but are not restricted to, pupil dilation, galvanic skin response (GSR) and imaging techniques of localization such as near infrared spectroscopy (NIRS), electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). These measurements can often indicate psychophysiological changes that correspond with cognitive and information processing. Compared to some of the behavioural process-tracing methods already discussed, they tend to depend less on subjective data like verbal information and very often respond to processes that span all degrees of consciousness. Nevertheless, care must be taken to ensure that such measurements are interpreted in a meaningful and appropriate way because, while they do change concomitantly with cognitive processes, there are also many other non-cognitive factors that can provoke such changes especially during exercise. Isolating the information–processing stimulation of neural or physiological factors clearly presents experimental challenges for athletic pacing research. That is not to dismiss such methods but rather to highlight their investigative boundaries as process-tracing methods.

Galvanic skin response (GSR) can be used to indicate activation of the sympathetic nervous system by measuring changes in electrodermal activity related to eccrine sweating and a fuller review is available elsewhere [65]. Since many factors, especially those related to exercise, can provoke changes in GSR care would be needed to use it for dual-process pacing research. However, GSR is a useful indicator of the emotional dimension of decision-making [66] and therefore has the potential to investigate the role of the affect heuristic in both deliberative and intuitive pacing decisions.

In addition to saccadic eye movements, it is also possible to measure pupil dilation using most eye-tracking devices [67]. Pupil dilation measurement methods, or pupillometry, records changes in eye pupil diameter. In addition to responding to light, pupil dilation changes can be used in light controlled conditions to indicate emotional and cognitive processes [68]. Perhaps of particular relevance to dual process pacing research is the most remarkable recent findings that pupil responses can reveal cognitive processing that occurs below the conscious threshold as indicated in studies involving blindsight patients [69] and amnesic patients [68]. Thus it may be possible, in carefully controlled conditions, to use pupillometry to investigate unconscious, subconscious or preconscious mechanisms involved in intuitive pacing decisions.

The final collection of techniques we wish to introduce are brain localization methods which can be passive, such as NIRS, EEG and fMRI, or active, such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS). With passive methods it is possible to gain a better understanding of the neural basis of decision making and, when integrated with behavioural observations, presents a powerful opportunity to test the neurological plausibility of decision-making models [70]. In the context of dual-process pacing research it may, at a fundamental level, be able to test whether behavioural observations of deliberative decision-making correspond with neural activation of brain regions known to have executive control functions. For example, value-based decisions have been associated with prefrontal cortex activation [71] and the parietal cortex [72]. Emotional influences on decisions have been associated with the anterior insular [73] and amygdala [74]. There are a number of barriers to adopting such approaches in dual-process pacing research such as difficulties of reducing movement artefacts during vigourous exercise and compatibility issues between the strong magnets used with fMRI and exercise equipment.

Another limitation of passive imaging methods is that it is impossible to establish causality between neural states and decisions however this is possible with active brain stimulation methods like TMS and tDCS. With TMS an electromagnetic current of approximately 1.5 to 2 tesla is passed across the scalp and skull using a coil to stimulate cortical brain regions [75], whereas tDCS applies a low direct current via an anode to depolarize and excite neuronal activity or hyperpolarize via a cathode to decrease neuronal excitability [76]. The use of TMS and tDCS to disrupt particular cortical regions of the brain and then measure decision-making behaviour means that it is possible to establish causal relationships [77]. For example, stimulation of the right dorsolateral prefrontal cortex has been found to cause riskier behaviour during a gambling task [78] and it maybe that similar techniques could be applied research to test previously reported effects between risk-taking and athletic pacing [12]. As non-invasive brain stimulation techniques, TMS and tDCS have great potential in understanding dual process thinking in athletic pacing.

5. Conclusions

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In attempting to understand dual process thinking and decision making in athletic pacing, behavioural observations of changes in pace are somewhat limited. A key limitation is that they only inform us about the outcomes of a pacing decision, and even then do not reveal anything about decisions not to change pace which are of course invisible. In order to understand the information processing that results in a decision, special tracing methods are needed that can help uncover these otherwise hidden cognitive mechanisms. Collectively these methods are referred to as process tracing and can be broadly categorized as those designed to understand information acquisition processes, information integration processes and neurological correlates of decision-making. There are significant methodological challenges of deploying process-tracing methods to athletic pacing research owing to validity and reliability threats such as those caused by vigorous movement, interference with pacing behaviour or individual differences. Nevertheless, process tracing methods have great investigative potential and, with careful integration and research design, will help advance our understanding of how pacing decisions are made and executed.

ELECTRONIC SUPPLEMENT

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