

Pacing and Decision Making in Sport and Exercise: The Roles of Perception and Action in the Regulation of Exercise Intensity

Benjamin L. M. Smits · Gert-Jan Pepping ·
Florentina J. Hettinga

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Abstract In pursuit of optimal performance, athletes and physical exercisers alike have to make decisions about how and when to invest their energy. The process of pacing has been associated with the goal-directed regulation of exercise intensity across an exercise bout. The current review explores divergent views on understanding underlying mechanisms of decision making in pacing. Current pacing literature provides a wide range of aspects that might be involved in the determination of an athlete's pacing strategy, but lacks in explaining how perception and action are coupled in establishing behaviour. In contrast, decision-making literature rooted in the understanding that perception and action are coupled provides refreshing perspectives on explaining the mechanisms that underlie natural interactive behaviour. Contrary to the assumption of behaviour that is managed by a higher-order governor that passively constructs internal representations of the world, an ecological approach is considered. According to this approach, knowledge is rooted in the direct experience of meaningful environmental objects and events in individual environmental processes. To assist a neuropsychological explanation of decision making in

exercise regulation, the relevance of the affordance competition hypothesis is explored. By considering pacing as a behavioural expression of continuous decision making, new insights on underlying mechanisms in pacing and optimal performance can be developed.

1 Introduction

In pursuit of optimal performance, athletes and physical exercisers alike have to make decisions about how and when to invest their energy. In sport and exercise science this phenomenon is also known as pacing. In the performance-oriented sports context, pacing has been associated with the regulation of exercise intensity throughout an exercise bout based on circumstantial factors, in order to maintain internal homeostasis [1, 2] and/or to avoid early exhaustion [3, 4]. The circumstantial factors are a combination of interoceptive (i.e. physiological, psychological and/or biomechanical) and exteroceptive (i.e. environmental) factors [5]. Additionally, the pacing strategy athletes adopt throughout the exercise bout is related to personal goals and knowledge of the likely demands of the bout [6]. Many studies have shown how performance and pacing are related [7–10], how self-paced performances involve predetermined exercise templates [10–14], and how pacing strategies can be predicted based on theoretical modelling [10, 15–17]. It has been found that athletes tend to self-select strategies closely related to their natural disposition for exercise [18] and that forced adoption of an externally paced intensity is more physically demanding than self pacing [14]. To identify underlying mechanisms that are relevant in the regulation of an athlete's exercise intensity, the current review considered both pacing and decision-making literature in the context of the potential roles of perception and action in the regulation of exercise intensity.

B. L. M. Smits · G.-J. Pepping · F. J. Hettinga
Center for Human Movement Sciences, University Medical
Center Groningen, University of Groningen, Groningen,
The Netherlands

G.-J. Pepping
School of Exercise Sciences, Australian Catholic University,
Melbourne, VIC, Australia
e-mail: gert-jan.pepping@acu.edu.au

F. J. Hettinga (✉)
Centre of Sport and Exercise Sciences, School of Biological
Sciences, University of Essex, Wivenhoe Park,
Colchester CO4 3SQ, UK
e-mail: fjhett@essex.ac.uk; fhettinga@hotmail.com

Decision making has been defined as the capability of individuals to select functional actions to achieve a specific task goal from a number of action possibilities [19]. Action selection is an important component in the process of decision making. Certainty about exercise duration, knowledge of the end point, and the physical sensations of effort and fatigue have all been associated with adequate pacing, and their integration seems to guide appropriate action selection [20]. We first provide an overview of how perception and action are treated in the current literature on exercise regulation and pacing. Next, we review the literature on decision making and note important similarities between certain approaches to decision making and pacing. Based on these similarities and their associated shortcomings in integrating a coupling between perception and action in the regulation of exercise intensity, we introduce and explore an ecological approach to understanding pacing and decision making in the regulation of exercise intensity. To contribute to the neuropsychology of decision making in exercise regulation, we end with introducing a novel hypothesis inspired by an ecological approach on the neural integration of information in the context of pacing and decision making.

2 Perception and Action in Pacing

In pacing literature perception is usually investigated by focusing on processes generally accepted to be affiliated to perception, such as sensations accompanying prolonged exercise, and internal proxies for perception, such as afferent signals. In particular, the sensations of effort, whole-body exertion and fatigue are phenomena that are much studied in relation to pacing.

2.1 Perception in Pacing: Fatigue and its Quantification

Fatigue is an important aspect of pacing and performance, and has been associated with both an increase in the

perceived effort necessary to exert a desired exercise intensity (also called sensation of fatigue or discomfort) and the eventual inability to produce that exercise intensity [21]. Adequate management of sensations of fatigue leads to optimal performance. Starting a race too fast risks early exhaustion, whereas starting too slow could conflict with performance goals [2]. In the case of developing physical exhaustion, sensations of fatigue are related to the interpretation of the effect of the current level of activity on future exercise capacity [22], while the regulation of a pace is associated with tolerating discomfort and knowledge of the likely task demands [6]. Fatigue and accompanying perceptual processes might thus be important components for decision making in pacing.

A popular way of measuring perceptions of fatigue and affiliated sensations, such as whole-body exertion, is by means of the rating of perceived exertion (RPE) scale. This evaluation tool is mostly used in experimental settings [23–27]. RPE has been described as being related to the circumstantial factors (see Table 1) that provide afferent input for a mechanism that allows an athlete to complete an exercise task within certain metabolic and/or mechanical limits [25]. A number of studies have suggested the existence of a system in which the integration of sensory systems and previous experience takes place [28, 29]. According to Lambert and colleagues [28], for instance, the identification of significant changes in negative feedback controllers, the so-called homeostats, suggests an active neural process aimed at prevention of exhaustion. It has been concluded that effort perception involves an integration of multiple afferent signals. Depending on the circumstances, a particular physiological signal may be markedly altered and become the dominant mediator of the overall RPE [25]. In contrast to the classic interpretation that RPE is a measure exclusively of exercise intensity [23], it is suggested that RPE is related to the duration of exercise that has been completed or that still remains [30].

Table 1 Summary of research investigating factors that are related to the rating of perceived exertion, divided into the four pacing factor-related categories

Physiological	Psychological	Biomechanical	Environmental
Heart rate [31–35]	Perception of time [36]	Body posture [10]	Terrain [37]
Ventilation/respiratory rate [38, 39]	Motivational/emotional state [40, 41]	Movement coordination [42]	Course elevation [43]
pH changes associated with lactic acid production [44–46]	The relative amount of a competition to be completed [47, 48]	Gross efficiency [10, 49]	Climate [50]
Sensations of strain and discomfort in exercising limbs [51, 52]	Knowledge and certainty about the endpoint and the duration of exercise that remains [47]		
Fluid and fuel store changes [53–57]	Presence of competitors [58] and, as a result, the breaking down of psychological inhibitions or barriers [59–62]		

2.2 From Perception to Action

Ulmer [2] proposed that exercise may be regulated by central calculations and efferent commands that attempt to couple metabolic and biomechanical limits of the body to the task demands in a process described as teleoanticipation. It is argued that a central programmer would function as an input/output black box to coordinate afferent and efferent pathways such that exercise intensity does not exceed exercise limits. However, no consensus on what constitutes these limiting factors of exercise exists [25].

In the 1920s, Hill and colleagues [63] proposed that human exercise was limited by a maximal cardiac output, which was reflected in lactic acid accumulation and/or myocardial ischaemia. In the late 1990s, the Hill model was under debate because it allowed no role for the brain in the regulation of exercise performance and protection of homeostasis [5, 64]. Noakes [5] proposed that homeostasis is protected under all conditions through behaviour modification, and changes of speed stand in proportional relation to changes in the extent of skeletal muscle recruitment (e.g. allowing an end spurt) [65]. Accordingly, the Central Governor model (CG-model) was introduced, in which the brain occupies a dominant control position [64]. The CG-model proposed that the development of physiological exhaustion is a relative rather than an absolute event, and sensations of fatigue are a symptom and not a physical state. Based on the integration of internal sensory signals and information from the environment, a subconscious governor brain region sets and regulates the exercise intensity by determining the mass of skeletal muscle that is recruited throughout the bout [66] and projects the symptom of fatigue to the conscious brain [27]. This symptom acts as an additional conscious limiter of the exercise intensity. Finally, anticipatory pacing as proposed by Ulmer [2] was rediscovered [67, 68] and incorporated in the CG-model [5]. For decision making in pacing, this means that sensations of fatigue are important, as well as teleoanticipatory planning of the race based on knowledge of the likely demands of the remaining exercise bout.

Several scientists have questioned the existence of a subconscious (dominant) control region in the brain regulating whole-body homeostasis and pacing, and alternative mechanisms have been proposed. Since physiological catastrophes can and do occur [1] and a variety of peripheral factors can impair muscle performance [69], it is suggested that the proposed dominant governor could at least be overridden. MacIntosh and Shahi [70] proposed a peripheral governor, working at the cellular level, which can reduce the muscle contraction by attenuating activation to avoid metabolic catastrophe. Marcora [71] suggested that deciding when to terminate exercise is done by the conscious brain without the need to include an additional

subconscious entity. Task disengagement occurs when the effort required by the prolonged constant-power exercise is equal to the maximum effort the athlete is willing to exert, or when the athlete believes they have exerted a true maximal effort. Edwards and Polman [6, 72] regard a single control region in the subconscious brain as unlikely and subsequently proposed to consider the brain as a complex system of neural communications, regulated by consciousness. In a nutshell, they assumed that (1) the conscious brain is the central governor; (2) subconsciousness can be considered as a state of subawareness within a conscious state; and (3) low levels of physical effort are regulated by the conscious brain, but possibly at a level of automated sub-awareness. The bombarding of sensory negative cues, as a consequence of high-intensity exercise, triggers the conscious awareness to control the performance [6, 72].

All of these proposals suppose that in some way sensations of fatigue, and a willingness to tolerate discomfort (in anticipation of future rewards [73]), are important in the process of action regulation. However, whereas the body of knowledge of pacing is associated with the proposal that a subconscious governor brain region sets and regulates the exercise intensity, the importance and dominance of (specific regions in) the brain in regulating actions is increasingly challenged.

2.3 The Selection of an Appropriate Pacing Strategy

Four important aspects of pacing in the context of perception and action regulation can be extracted: (1) the goal of pacing is to complete the exercise bout without the development of exhaustion/disturbed homeostasis [74]; (2) the development of exhaustion is a relative event and sensations of fatigue are a symptom that acts as an additional conscious restrainer or modulator of the exercise intensity [27]; (3) RPE is the overall conscious perception of integrated physiological activity [27]; and (4) recognising significant changes in both homeostats [28] and fatigue [66] are part of an active neural process, the function of which is to prevent the development of exhaustion. In short, the regulation of an athlete's pace (action) seems to be associated with processes at the neural level, which are influenced by afferent signals (which influence perception). However, the literature does not address how perception and action merge [3, 72, 75] and which underlying action regulation processes occur. A serial linking between perception and action is advocated, requiring the need for an additional mechanism that can bridge an apparent void between the two, a perception/action gap. A black box control system is suggested that secures homeostasis during exercise [2, 64]. However, the location of and processes occurring associated with this controller are not understood yet. Different mechanisms are suggested at muscular level [70] as well as within the brain [64].

Recently, Roelands and colleagues [76] made a first attempt to determine underlying neurophysiological mechanisms involved in the complex skill of pacing. They linked fatigue with pacing and concluded that a complex interplay between different neurotransmitter systems potentially influences pacing during exercise. In pursuit of a broad-perspective understanding of the complex skill of pacing, the current review now continues the exploration of pacing from a more behavioural perspective, and considers the viewpoint that there is a more intimate link between perception and action than the serial links proposed so far. From this perspective, pacing is approached as a continuous process of decision making. Before we set out this approach to pacing and decision making, however, we provide a brief overview of the literature on decision making in intermittent sports and show some important similarities between the dominant approach in research in pacing and in research on decision making, and discuss the shortcomings in failing to consider the coupling of perception and action that follow from them.

3 Decision-Making in Sport and Exercise

During exercise, athletes are continuously required to make decisions. While most pacing literature focuses on endurance sports, research in the decision-making domain is mainly conducted in intermittent sports (e.g. team ball sports and racket sports [77–79]). Whereas in endurance sports decision making in response to interoception is relatively more dominant, in intermittent sports decision making is commonly related to exteroceptive influences in a continuously changing environment [80].

Research on the influence of physiological factors on decision making during exercise has mainly been performed by looking at the effects of physical activity on cognitive decision-making performance measures. For instance, Tomporowski [81] reviewed the effects of acute bouts of exercise on adults' cognitive performance and concluded that submaximal aerobic exercise performed for periods of up to 60 min facilitated certain aspects of cognitive performance, whilst extended exercise leads to performance decrements. More recently, using meta-analytical approaches, McMorris and colleagues [82] investigated the effects of acute- and intermediate-intensity exercise on the speed and accuracy of performance of working memory tasks. Exercise was found to demonstrate a small yet significant effect on cognition [83], in particular during moderate-intensity exercise. In particular, a common finding was that the speed of decision making was improved whilst the accuracy of decisions was left unaffected by exercise. Fatigue has also been related to cognitive performance. In general, higher intensity levels of a primary

task require a stronger supraspinal drive to compensate for the more enhanced peripheral fatigue [84]. This negatively affects cognitive performance in a second cognitive dual task, which becomes more pronounced with fatigue.

In defining self efficacy—an athlete's belief in the ability to perform a certain task—Bandura [85] included physiological states as a principal source of information. According to Bandura, people read their visceral arousal in stressful and taxing situations. In activities involving strength and stamina, sensations of fatigue and aches are indicators of physical inefficacy [85]. Processing visceral information is closely related to emotional and motivational aspects of behaviour. Baron and colleagues [4] suggested that affective load (AL) may contribute to the regulation of exercise intensity. The AL scale indicates how positive and negative affective responses are relative to each other during exercise. The more positive the affective responses are, the greater the desire to maintain or to increase the exercise intensity will be and vice versa. Thus, AL might play a role in decision making in pacing.

Whereas in pacing literature it is emphasised that the integration of knowledge of the likely demands of the remaining exercise bout [6] and the physical sensations of effort and fatigue act as a guide in determining response characteristics [20], descriptions of steps made during action regulation/response initiation in (intermittent) sports do not address the state of the body. For example, according to Tenenbaum [80], motor behaviour in competitive situations consists of encoding relevant environmental cues, processing the information through interactions between working and long-term memory, making an action-related decision, and executing the action while leaving room for refinements and modifications.

In the context of the current review on decision making in pacing, the usefulness of such a model of response initiation in intermittent sports is questionable. For instance, it is important to consider the current physiological state, the consequences of possible actions on the future physiological state, and the likely demands of the remaining exercise bout. Athletes may not always be able to refine their actions while perceiving significant discomfort [86].

4 Decision Making in the Regulation of Exercise Intensity

4.1 Current Perspectives

At every instant during exercise, the circumstances present athletes many opportunities and demands for action, which faces them with the problem of which action to select. The literature presented in this review thus far suggests that external information about objects in the world in

combination with internal information about the current physiological state are used to select an appropriate action. Further, the literature suggests that athletes fit the actions they perform in anticipation to the behavioural needs (e.g. exhaustion avoidance or goal achievement). This involves specification of action parameters, which requires information about the spatial relationships among objects and surfaces in the world, represented in a coordinate frame relative to the orientation, configuration and state of the athlete's body [87]. Athletes continuously decide 'what to do' (action selection) and 'how to do it' (action specification) [88]. In order to accomplish this, the literature presented so far advocates a view of the brain as an information processing system. In this view, by the time motor processing begins (action specification), cognitive processes have decided what to do (action selection), and a single motor programme is prepared before movement execution [89, 90]. This traditional information processing approach fits with the concept of a central control system that is responsible for decision making in pacing. The input (perception) and output (action) of the control system are known, but no clarity exists about how perception and action are related to one another. The main explanations for how perception and action might be linked refer to an indecipherable entity (i.e. input/output black box), which is not further specified.

From an information processing approach, three processes can be seen to serially follow each other before movements are executed, namely (1) perception: the construction of internal representations of the world that are used as the input to cognitive systems; (2) cognition: bringing salient context-dependent information together in a temporary working memory buffer, manipulating representations to build complex knowledge, store and retrieve information from long-term memory, perform deductive reasoning, and make decisions; and (3) action: the motor systems are tools that implement action plans chosen by cognitive processes [88]. The information processing approach was originally proposed as an explanation for complex human abilities of abstract problem solving [91, 92]. Information about the world must be obtained, and a great deal of computation must take place, before taking any external actions. Nowadays, scientists studying sensorimotor control also tend to analyse behaviour in terms of transforming input representations to output representations through a series of intermediate processing stages [88], as also found in the literature on pacing [27]. Attempts to interpret neural data from the information processing approach encounter several anomalies that have still not been invalidated [88]. Moreover, the information processing approach does not explain how perception and action come together in the ongoing regulation of exercise intensity.

4.2 An Alternative Approach

While considering an information processing approach, the internal processes that are most useful for guiding behaviour (action) are those that first passively construct internal representations of the world (perception) and then reflect upon it with some introspective, intelligent circuits (cognition) [88]. The complex performance environment of athletes, however, requires them to continuously modify ongoing behaviour, evaluating alternative behaviour that may become available, and making trade-offs between choosing to persist in a given behaviour (e.g. current pace) and switching to a different one [88]. In addition, athletes' action capabilities will be affected by fatigue [93]. These complex and dynamic necessities will have to be incorporated in an account of decision making in the regulation of exercise intensity, but have no place in the information processing view as it currently stands.

To accommodate for the complex demands on decision making in the regulation of exercise intensity, in the current paper we put forward an alternative approach to studying decision making in pacing, which is rooted in an ecological approach. In this approach, the coupling of perception and action is seen as a process that mediates sensorimotor interaction in the here and now, on the basis of continuous streams of sensory information as well as prior knowledge and experiences [88, 94]. A central notion within this approach is the concept of affordances, which refer to properties of the environment that can be detected as information to support an action, and which are related to an individual's ability to use it (action capabilities) [94–96]. Instead of taking a Cartesian stance in which a higher-order governor manages the behaviour of the body, it is assumed that internal processes in the mind are reciprocally linked to processes in the body and the environment in which the body acts. Decision making is considered to be a complex and temporally extended process, which does not characterise an individual as having made a decision prior to its behavioural expression [97, 98]. Instead, decision making is considered to be the actualization of affordances, the possibilities for action in the environment that athletes perceive and may act upon [94, 96, 99]. In dynamic situations, where ongoing behaviour has to be continuously modified, action possibilities arise and vanish as a result of changing action capabilities and environmental demands. Because of the dynamic character of situations like these, and the accordingly emergent nature of decisions, this approach has also been referred to as the ecological dynamics approach [98, 100–102].

The use of environmental and bodily information specifying affordances should not be considered in isolation for a given moment, but also in anticipation to factors such as knowledge about the likely task demands, personal

goals, and the rules that make up many competitive sport situations. These sources of information are commonly associated with knowledge structures and memory processes inside the head [103]. From an ecological perspective, however, information is not stored in the head, but granted by or made available in a particular situation; for instance, through a history of similar situations, and over longer periods of time [94, 104–106]. With relevance to regulating exercise intensity, the perception of an affordance of the athlete's bodily state/capacity during a particular exercise event, in particular in anticipation to prior knowledge, is not an isolated moment but an episode in a number of nested long-term events that make up the ongoing dynamics of the athlete's exercise environment [104].

To conclude so far, the ecological approach presented provides a well-grounded alternative way of understanding decision making in the regulation of exercise intensity [98, 107]. Further, if pacing could be approached as a behavioural expression of continuous decision making, new insights in action regulation and performance determinants in sports and exercise can be gained.

4.3 Entering the Neuropsychology of Decision-Making: The Affordance Competition Hypothesis

Traditional cognitive theories propose that in natural behaviour, action selection occurs before action specification. The theory of affordances proposes that during natural interactive behaviour, action selection and specification should be regarded as the same dynamic process [88, 99, 108]. The results of a number of studies in intermittent sports show that athletes are faced with situations where multiple actions are afforded simultaneously [102, 109–111]. To address how people deal with these situations, drawing on ideas from neuroscience and ecological psychology, Cisek and Kalaska proposed the affordance competition hypothesis (AC-hypothesis) [87, 88].

The AC-hypothesis, summarised in Fig. 1 [88], incorporates multiple ideas, such as the proposals that neural processing is continuous and not organised in distinct serial stages, and that several potential actions are prepared in parallel whilst collecting evidence for selection between them [88]. In general terms, the hypothesis is that behaving in a natural environment involves continuous and simultaneous processes of interactions between environmental stimuli and an individual's action capabilities and needs. These interactional processes provide for the specification of potential actions, and the competition between potential actions while subjected to a variety of biasing influences such as rewards, costs or risks. For action specification, areas within, for instance, the dorsal visual systems have been shown to perform transformations that convert

information about objects in sensory coordinates into the parameters of potential actions [87, 88]. Competition between potential actions is hypothesised to occur within the fronto-parietal cortex, while a variety of biasing influences are provided by prefrontal regions and the basal ganglia. The same brain areas that specify potential actions ultimately guide the execution of those actions. Recent studies have supported these suggestions [87, 112]. For example, it was found that when a monkey was presented with two opposite potential reaching actions, neural activity in the premotor cortex specified both directions simultaneously [87] (see also Cisek and Kalaska [88]). When information for selecting one action over the other became available, the activity of the chosen direction was strengthened while that of the unwanted direction was suppressed [87]. For an extensive overview of research that has examined the AC-hypothesis in neuropsychological and neurophysiological research, the reader is referred to Cisek and Kalaska [88].

The AC-hypothesis suggests that the precise order in which decisions appear across the cerebral cortex are highly task dependent. In support of this, it was found that in tasks requiring stimulus salience, such as a pop-out visual search task, parietal regions reflected the choice before prefrontal regions. Conversely, if a task involves biasing factors that require complex stimulus-rule conjunctions, such as conjunction search, prefrontal regions reflected the choice before propagating back to the parietal cortex [113]. In pacing it has been shown that sensory negative cues that accompany high-intensity exercise can influence prefrontal regions and conscious awareness to influence performance. Regarding the existing literature on decision making in pacing, this is consistent with the idea proposed by Edwards and Polman that pacing control is distributed throughout the subconscious and conscious brain [6, 72].

5 Discussion

Over the last decades, studies from various approaches have contributed to the establishment of a wide range of aspects that might be involved in the determination of an athlete's pacing strategy. The present review aimed to bring these findings together in a transcending theoretical pacing framework, and to further understand mechanisms involved in pacing in the context of decision making in action regulation. Literature revealed that pacing is closely related to various interoceptive and exteroceptive circumstantial factors (i.e. psychological, physiological, biomechanical and environmental; Table 1) that are integrated and act as a guide in appropriate action regulation. More specifically, the importance of both neurophysiology [76]

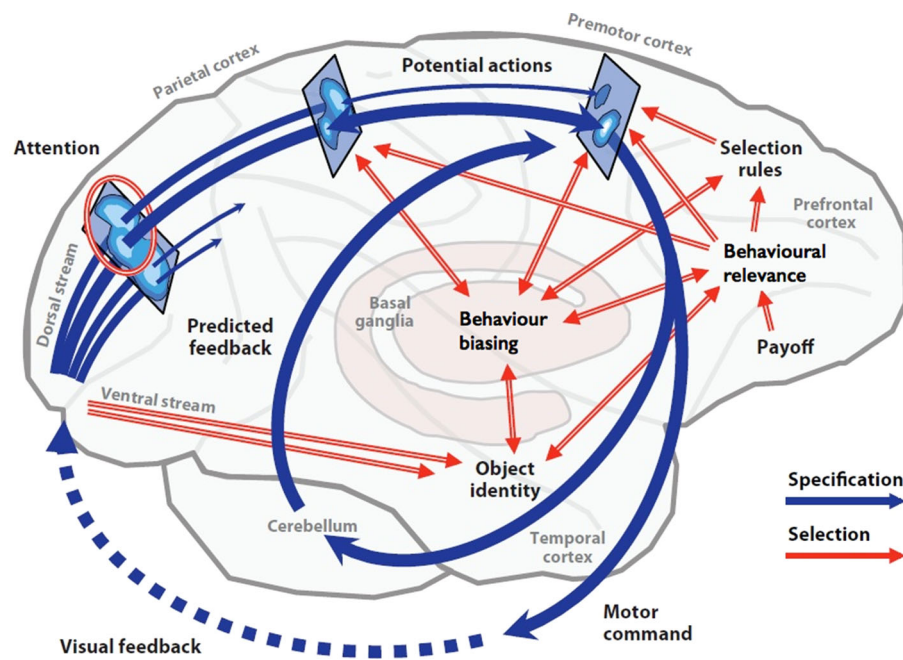


Fig. 1 Summary of the affordance competition hypothesis in the context of visually guided movement. The *filled dark blue arrows* represent processes of action specification. These are launched by the occipital cortex and go into the direction of the premotor cortex via the dorsal visual stream, suggesting that this stream mainly mediates visually guided actions, instead of building a unified representation of the world. *Polygons* represent three neural populations along the stream, which are depicted as maps where the *lightest regions* correspond to peaks of tuned activity. Peaks that appear simultaneously within a single cortical region compete for further processing. This is biased by input from the basal ganglia and prefrontal cortical

regions (*red double-line arrows*) that collect information for action selection. Cells with similar parameter preferences excite each other, while cells with different preferences inhibit each other. If activity associated with a given choice eventually becomes sufficiently strong by exceeding a certain threshold, it suppresses its opponents and conclusively wins the competition. The final selected action is released into execution and causes overt feedback through the environment (*dotted blue arrow*) as well as internal predictive feedback through the cerebellum [87, 88]. Reproduced from Cisek and Kalaska [88], with permission

and behavioural mechanisms involving perception and action are emphasised. Although the importance of the brain is stressed, and references are given to a computing governor, explanations about how integration of the various factors takes place are not fully clear yet. Furthermore, analysis based on an information processing approach does not explain how perception and action are integrated in the continuous regulation of exercise intensity. An ecological approach to decision making in pacing was considered in which perception and action are intrinsically linked. A central notion in this approach is that of affordances. To contribute to the neuropsychology of decision making in exercise regulation the AC-hypothesis was explored, in which neural processing of internal and external information is continuous and the brain begins to prepare several actions in parallel while collecting evidence for selection.

Within the AC-hypothesis, multiple potential actions compete through mutual excitation and inhibition. Relating this to pacing, the exciting and inhibiting cells that influence action regulation should be involved in, or affected by, the process responsible for maximising performance as well as preventing the development of exhaustion. The

pacing literature suggests that significant changes in homeostats and fatigue are involved in such a process. Furthermore, it has been proposed that the development of exhaustion is a relative event in which the sensation of fatigue should be regarded as a symptom, acting as an additional exercise intensity modulator. Fatigue, then, could well be related to information that specifies the degree to which homeostasis is disturbed. This is in line with the proposal that RPE relates to the overall conscious perception of all the physiological activity in the body [27]. Hence, the relativity of the sensation of fatigue may be part of an individual's ability to cope with discomfort [4, 93], which, in turn, could be a bias factor during affordance competition.

In the pacing literature, several authors have stressed the importance of the brain, and numerous control mechanisms are suggested [64, 71, 72]. The black box approach of a central governor [64] leaves much room to speculate on behavioural, neurophysiological, and neuropsychological mechanisms involved. It seems that the proposed dominant governor model does not explain all processes associated with fatigue and pacing that occur in daily life. As an

alternative, it has been proposed that the regulation of physical effort is distributed across the conscious and subconscious brain [6, 72]. Task disengagement would occur when the effort required by the prolonged constant-power exercise is equal to the maximum effort the athlete is willing to exert, or when the athlete believes themselves to have exerted a true maximal effort [71]. These arguments imply that there is no specific region in the brain that is most important in pacing. Rather, internal processes in the mind are directly and reciprocally linked to processes in the body. Subsequently, pacing could be considered to be the mediation process of sensorimotor interaction in the here and now, on the basis of a continuous flow of perceptual information as well as prior knowledge and experiences. Hence, the current assumption that afferent and efferent pathways are coordinated in such a way that exercise intensity does not exceed the limits of the body [2] could be consistent with ideas that follow from an ecological approach, with the remark that neural processing is based on reciprocal perception/action coupling and not organised in distinct serial stages within a governor region.

Recently, two RPE-based scores have been proposed that attempt to understand action regulation based on perception and (conscious) decision making. Although no conclusive evidence for reliability and validation exist yet, these scores are valuable attempts to relate conscious sensations of fatigue to information from the body and the environment as well as to cognitive factors such as motivation, and could serve as a catalyst in exploring the potential/usefulness of RPE data in ‘decision making in pacing’ research. The Hazard-score [48] is the product of the momentary RPE and the fraction of race distance remaining, incorporating both internal cues as well as external information. A high score means homeostatic disturbance, facing the choice of reducing intensity or not finishing. Swart and colleagues [20] proposed that physical sensations of effort act as the template regulating performance during exercise and that deviation from that template produces an increase in the sense of mental effort. The latter was measured with the Task Effort and Awareness score (TEA-score). It was concluded that the conscious decision of whether to maintain or change the current workload could be the outcome of a balance between motivation, affect and sense of mental effort [20]. Both the Hazard- and TEA-score (in which RPE is incorporated) could contribute to research on the influence of fatigue in pacing and decision making because of their attempt to understand action regulation based on perception and (conscious) decision making.

In animal behaviour research, attention has been given to the role of energy expenditure in decision making/action regulation. Whereas in predation risk-insignificant situations animals choose where and how to forage, and what to eat, solely by measuring energy return from food per unit

of energy or time of searching [114–118], in more precarious situations they reduce their rate of food intake [119–121] or sacrifice foraging efficiency by raising their energy expenditure [122] in order to lower predation risk. Some predator species have longer chase distances in successful than in unsuccessful hunts and any longer unsuccessful hunts are generally initiated by juveniles [123]. This indicates that they are able to gauge their chances of success, decide to give up early if failure is predicted to conserve energy for further hunts, and that, as with pacing athletes, experience-based anticipation is a key factor in action regulation [72]. These studies show that research in animal behaviour may also provide more insights into underlying neural action-regulation processes involved in pacing. It is, for instance, proposed that the anterior cingulate cortex (ACC) is involved in making decisions about the amount of effort to invest for rewards [124]; the orbitofrontal cortex affects the decision–time to wait for rewards [124]; and activity in the ACC and mesolimbic dopamine pathways influence decision making when facing easily obtainable small rewards and less accessible greater rewards [125]. So, with the suggestions made in neuropsychological and neurophysiological research in humans and animals, brain regions can be identified that may contribute to the biasing process while making a trade-off between choosing to persist in a given activity or pace and switching to a different one.

Thus far, the AC-hypothesis has mainly been engaged with an understanding of environmentally guided behaviour, with a focus on the role of perceptual information in the environment of the performer. Research on the role of the athlete’s action capabilities in coming to decisions, on the other hand, is relatively sparse [126]. In order to provide a better understanding of both environmental and action capability influences, current knowledge needs to be enriched with neurophysiological findings from neurotransmitter studies and studies on interoceptive influences in action regulation, such as exercise-induced fatigue [76]. As an example, it has been suggested that during physical fatigue the motor output from the primary motor cortex is primarily based on the degree of balance between sensory input from the peripheral system (inhibition) and motivational input (facilitation) [127], and that the mid/anterior insular cortex—involved in the evaluation of homeostatic processes—might not only integrate and evaluate sensory information from the periphery but also act in communication with the motor cortex [128]. These examples support the suggestion that there are relational body environment (i.e. affordance-based) factors that influence action regulation in order to maintain homeostasis and/or regulate sensations of fatigue, which is associated with pacing.

Though controlled experimental studies have led to a large body of knowledge on pacing, fatigue and

performance, based on the present review we would like to stress the importance of research incorporating the interaction with the environment. There are theoretical concerns over the representativeness of the design in studies of decision making in sport and exercise [129–131]. This concern specifically refers to the arrangement of conditions in an experiment so that they represent the behavioural context to which the results are intended to apply. These concerns might also be relevant for pacing research, in which athletes are often removed from their natural exercise environment and are placed in a highly controlled and possibly impoverished laboratory setting. For instance, in many studies participants perform on stationary exercise equipment. Unlike in natural unconstrained behaviour, most features of the sensory input are deliberately made independent of the athlete's actions; the response in a given moment usually does not determine the stimulus in the next moment. Although such settings are often designed based on strong methodological assumptions, they may have unintentionally altered the behavioural processes under investigation such that the results from a specific experiment are not representative of the functional behaviours in participants' natural environments. For instance, a recent study considered the effects of visual information on perceptual experience during exercise [132]. Results showed that variations in the speed of the environmental stimuli, such as when accelerating or decelerating during races, influence both perception and action. The provision of a slower optic flow, i.e. slower speed of the provided video footage in comparison to true cycled speed, was associated with lower RPE together with higher power output as a behavioural response [132]. Ideas emanating from the approaches presented in this review might aid the understanding of the correspondence between experimental task constraints and individual, behavioural and functional settings outside the laboratory. Another observation in this context is that athletes tend to self-select strategies closely related to their natural disposition for exercise [18]. Hence, the behavioural process of pacing can vary between athletes. The tendency to average data in statistical analyses can thus mask observations of functional levels of performance variability across individual participants [133], and a focus on individual data might provide different perspectives.

Most of the literature reviewed has focused on pacing and decision making in sports performance. However, in other performances, such as those that can be found in daily life, physically active lifestyles and medical and rehabilitation settings, the regulation of exercise intensity over a certain task is also important. Think, for instance, about patients with limited energy stores or complaints of fatigue, or about an individual that is starting a new exercise regimen. For these individuals it is important to

identify meaningful performer–environment relationships for pacing and how these relationships might change as a function of practice, training or habituation. For example, research has shown that in repetitive endurance-type activities, self-selected, motivational and stimulating music enhance affect, reduce ratings of perceived exertion and improve energy efficiency, leading to increased work output [134, 135]. Identifying affordances that can help participants overcome a strong urge (affordance) to stop continuation of their exercise programme, especially in the early stages, can in this way be a very important application in health sciences.

6 Conclusion

The current review explored divergent views on understanding underlying mechanisms in the regulation of exercise intensity. Instead of assuming that a higher-order governor manages behaviour by first passively constructing internal representations of the world, an approach that assumes that decision making is a behavioural expression of the perception of affordances was explored. Additionally, the AC-hypothesis was introduced, which proposes that during natural interactive behaviour at a neuropsychological level, action selection and specification are one and the same dynamic process. The use of ecological principles as a background in research within the field of sport and exercise may offer additional theoretical means to address the interdependence of perception and action and individual differences in the regulation of exercise intensity. The examination of pacing from this perspective could serve as a catalyst for gaining knowledge about how the many described circumstantial factors influence exercise intensity regulation, as well as how to set appropriate pacing strategies for the achievement of demanding goals in sports and exercise, medical and rehabilitation contexts, as well as in daily life.

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