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Examining the effect of challenge and threat states on endurance exercise capabilities

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ABSTRACT

This paper presents the first two studies to explore the effect of challenge and threat states on endurance exercise capabilities. In study one, relationships between cardiovascular markers of challenge and threat states, ratings of perceived exertion (RPE), and exercise tolerance were explored during moderate- and severe-intensity cycling. Cardiovascular reactivity more reflective of a challenge state (i.e., relatively higher cardiac output and/or lower total peripheral resistance reactivity) predicted lower RPE throughout moderate- but not severe-intensity cycling. Building on these findings, study two experimentally manipulated participants into challenge, threat, and neutral groups, and compared 16.1 km time-trial performances, where pacing is self-regulated by RPE. Participants completed familiarisation, control, and experimental visits while physiological (oxygen uptake), perceptual (RPE), and performance-based (time to completion [TTC] and power output [PO]) variables were assessed. When compared to the threat group, the challenge group demonstrated cardiovascular responses more indicative of a challenge state, and delivered faster early-race pacing (PO) at similar RPE. Although there were no significant differences in TTC, results revealed that augmentations in PO for the challenge group were facilitated by tempered perceptions of fatigue. The findings suggest that an individual's pre-exercise psychophysiological state might influence perceived exertion and endurance exercise capabilities.

1. Introduction

Investigations into the determinants of endurance performance have been boosted by participation trends, where growing competition applications have increased the relevance of research-led ergogenic strategies (Blanchfield, Hardy, De Morree, Staiano, & Marcora, 2014). While numerous physiological predictors of performance have been pinpointed (Midgley, McNaughton, & Jones, 2007), the mechanistic causes of fatigue (i.e., a transient decrease in the capacity to perform physical actions; Enoka & Duchateau, 2008) remain controversial, and are likely regulated by psychological factors (Abbiss & Laursen, 2005; Marcora, 2010; Tucker & Noakes, 2009). Various psychological skills can affect endurance performance (e.g., self-efficacy, imagery; see McCormick, Meijen, & Marcora, 2015 for a review), however, further exploration into cognitive and motivational determinants is required (Smirmaul, Dantas, Nakamura, & Pereira, 2013). The current research is the first to examine the effects of challenge and threat states, determinants of cognitive and behavioural performance (Behnke & Kaczmarek, 2018; Hase, O'Brien, Moore, & Freeman, 2018), on endurance exercise capabilities.

The biopsychosocial model (BPSM) of challenge and threat states (Blascovich & Tomaka, 1996; Blascovich, 2008) offers an opportunity for sport and exercise psychologists to examine prospective psychophysiological determinants of endurance performance using a well-tested theoretical framework. The BPSM explains individual responses to motivated performance situations (e.g., exams, sporting competitions), where individuals are motivated to attain important self-relevant goals (Seery, 2011). Specifically, the BPSM contends that evaluations of situational demands and perceived coping resources determine the states of challenge and threat, which are considered anchors of a single bipolar continuum (Seery, 2011). Crucially, these dynamic psychophysiological states only emerge when individuals are actively engaged in a task, which is indexed by increases in heart rate (HR) and reductions in cardiac pre-ejection period (Seery, 2011). Furthermore, these states are highly dynamic, and are influenced by numerous interrelated socio-psychological antecedents; including: self-efficacy, task familiarity, required effort, social support, and skills and abilities (Blascovich, 2008; Jones, Meijen, McCarthy, & Sheffield, 2009). A

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challenge state occurs when perceived coping resources are evaluated as sufficient to meet or exceed perceived situational demands, whereas a threat state arises when coping resources are evaluated as insufficient to meet situational demands (Seery, 2011).

Importantly, challenge and threat states are accompanied by distinct neuroendocrine and cardiovascular reactivity patterns, proposed to result from one's underlying demand and resource evaluations (Seery, 2011). Specifically, a challenge state promotes comparative increases in blood flow and rapid energy mobilisation to large skeletal muscles, empirically quantified by higher cardiac output (CO; the amount of blood pumped by the heart per minute), and lower total peripheral resistance (TPR; a measure of the net constriction versus dilation in the arterial system), reactivity (Blascovich, 2008). Such a cardiovascular response can promote superior attentional control, more facilitative emotions and interpretations of emotions, and enhancements in kinematic and/or neuromuscular efficiency, compared to a reactivity pattern more consistent with a threat state (Moore, Vine, Wilson, & Freeman, 2012; Moore, Wilson, Vine, Coussens, & Freeman, 2013; Vine, Freeman, Moore, Chandra-Ramanan, & Wilson, 2013). These distinct cardiovascular reactivity patterns are also proposed to provide an objective, indirect measure of underlying demand and resources evaluations (and thus challenge and threat states), which do not rely on conscious attention or reflection (Seery, 2011). This is important, as the demand and resource evaluation process is said to occur in a more subconscious (i.e., automatic) rather than conscious manner, meaning that individuals cannot always reliably report evaluations of situational demands and personal coping resources (Blascovich, 2008).

In line with these proposals, the BPSM provides a testable hypothesis: that the cardiovascular reactivity pattern accompanying a challenge state will predict more adaptive responses to motivated performance situations than the reactivity pattern elicited during a threat state. Indeed, a challenge state has been related to superior sporting performance in closed (e.g., golf putting, Moore et al., 2012; 2013; Moore, Vine, Wilson, & Freeman, 2014) and open (e.g., cricket, Turner et al., 2013) skills. For example, Turner et al. (2013) showed that an athlete's pre-competition cardiovascular reactivity profile could predict subsequent performance in a pressurised cricket batting task, with challenge-like responses relating to more proficient batting scores than responses more reflective of a threat state. The Theory of Challenge and Threat States in Athletes (TCTSA) further postulates that a challenge state facilitates more adaptive outcomes in terms of decision-making and anaerobic power (Jones et al., 2009). However, despite being similarly susceptible to stress-related behavioural variability (Abbiss & Laursen, 2005), a lack of evidence has examined challenge and threat states in motivated *endurance* exercise. This is surprising, as an individual's pre-exercise cognitive and cardiovascular reactivity response to task-related stress will often persist during aerobic exercise (Rousselle, Blascovich, & Kelsey, 1995). Similarly, such psychophysiological responses can be strategically manipulated via various interventions that are accessible to endurance athletes (e.g., arousal reappraisal; Jamieson, Mendes, Blackstock, & Schmader, 2010; preperformance routines; Moore et al., 2013). Therefore, investigations into the effects of challenge and threat states on endurance exercise capabilities offers both practical and theoretical significance to psychologists.

The generalisability of the BPSM to endurance exercise is reinforced by proposals that fatigue is regulated through psychophysiological mechanisms that are potentially associated with challenge and threat states. The psychobiological model of endurance (Marcora, Bosio, & de Morree, 2008; Marcora & Staiano, 2010; Marcora, Staiano, & Manning, 2009) contends that motivated performances are ultimately determined by perceived exertion (i.e., conscious sensations of how hard, heavy, and strenuous a physical task is; Marcora, 2010), a dynamic interoceptive process shaped by cognitive, sensory, motivational, and affective elements (Pandolf, 1983). These proposals claim that established determinants of endurance events, including both psychological (e.g., self-efficacy) and physiological (e.g., cardiorespiratory capacities) inputs, affect performance *indirectly* through altering this interpretation of afferent sensory information. Notably, antecedents of challenge states have been consistently linked with reducing ratings of perceived exertion (RPE; e.g., high task familiarity, Micklewright, Papadopoulou, Swart, & Noakes, 2010; high self-efficacy, Hutchinson, Sherman, Martinovic, & Tenenbaum, 2008; and low required task effort; Paterson & Marino, 2004), whereas environmental conditions that limit cardiovascular reactivity tend to inflate such perceptions of fatigue (e.g., Gonzalez-Alonso, Calbet, & Nielsen, 1999). Therefore, exploration into the interplay between challenge and threat states, perceived exertion, and performance outcomes presents an exciting line of enquiry for psychologists, as any factor associated with reducing RPE is proposed to enhance endurance exercise capabilities (Marcora, 2010).

However, the role of psychophysiological mechanisms in regulating exercise is partly determined by the characteristics of the task itself (Blanchfield et al., 2014; Rejeski, 1985). For example, in 'open-loop' tasks, defined by the absence of a known endpoint (e.g., time to exhaustion tests), the rate of increase in RPE will determine how long work can be maintained (Marcora, 2010). Alternatively, in 'closed-loop' tasks (e.g., time-trials), which involve completing a task until a predetermined endpoint, work-rate is self-regulated by the athlete, meaning that any factor altering RPE can result in pacing adjustments (Marcora, 2010). The intensity of exercise further influences the relationships between psychophysiological variables during endurance exercise, with cognitive influences on RPE greater during moderate- (i.e., below the gas exchange threshold) compared to severe-intensity (i.e., above the gas exchange threshold) workloads (Ekkekakis, 2003). Consequently, investigation into the predictive value of the BPSM in this complex, interdisciplinary domain is required.

The present research is the first to explore the effects of challenge and threat states on motivated endurance exercise capabilities. Specifically, we first observed whether the cardiovascular markers of challenge and threat states were related to RPE and exercise tolerance during open-loop cycling (study 1), before furthering our causal understanding, by testing whether manipulating challenge and threat states influenced cycling time trial performance (study 2). This two-part design facilitated exploration into the predictive validity of the BPSM; first using an observational design in a relatively controlled setting, and then via a validated experimental design in a more applied setting.

2. Study one

The first study initiated enquiry into whether challenge and threat states predict endurance exercise performance. Specifically, the relationships between cardiovascular indices of challenge and threat states (i.e., CO and TPR reactivity), and measures of RPE and exercise tolerance were investigated during bouts of moderate- and severe-intensity cycling. Here, any delay in the time taken to reach exhaustion (TTE) would signify an increase in endurance capability (Coyle, Coggan, Hopper, & Walters, 1988). It was hypothesised that the cardiovascular markers of challenge and threat states would predict RPE and exercise tolerance, with reactivity patterns more indicative of a challenge state (i.e., higher CO and/or lower TPR reactivity) relating to lower RPE and longer TTE. The study received approval from the Department of Sport and Health Sciences Ethics Committee at the University of Exeter, and written informed consent was obtained from all participants prior to data collection.

2.1. Material and methods

2.1.1. Participants

In accordance with a power calculation (α: $p = .05$; $1\text{-}\beta = 0.8$) using an effect size from a pilot study (via G*Power software, version 3.1.3), nineteen participants were recruited for this study (15 male, 4 female; Mean $_{age} = 23.62 \pm 4.84$ years, $\dot{V}O_{2peak} = 40.49 \pm 6.42\,\text{ml kg}^{-1}.\text{min}^{-1}$). In order to minimise the effects of previous experience on exercise tolerance (Micklewright et al., 2010), all participants were recreationally active, unfamiliar with experimental exercise procedures, and novice cyclists (according to Chapman, Vicenzino, Blanch, & Hodges, 2007). Participants were asked to refrain from consuming caffeine or food in the hour preceding testing, and to arrive rested and hydrated.

2.1.2. Measures

Cardiovascular markers of challenge and threat states. An impedance cardiograph device (Physioflow, PF05L1, Manatec Biomedical, Paris, France) estimated HR, CO, and TPR. Following skin preparation using alcohol wipes and abrasive gel, spot electrodes were positioned on 6 anatomical sites (for a description of the electrode configuration see Moore et al., 2012). The device was calibrated over 30 heart cycles, using resting systolic and diastolic blood pressure values that were taken immediately before the recording period by a digital monitor (Model UA-767PC, Medical Co., Saitama, Japan). Participants then sat silently fitted to the device for 5 min of baseline recording, and for a further minute after receiving standardised task instructions (to permit the assessment of cardiovascular reactivity between the final minute of baseline and the minute after the task instructions).

Task engagement was assessed using HR reactivity, with greater increases reflecting greater engagement (Seery, 2011). Furthermore, challenge and threat states were assessed using CO and TPR reactivity (as in Moore et al., 2012), with TPR calculated from the formula: [mean arterial pressure × 80/CO] (Sherwood et al., 1990). Mean arterial pressure was calculated using: [(2 × diastolic blood pressure) + systolic blood pressure/3] (Cywinski & Tardieu, 1980). Cardiovascular data during the final minute of baseline recording were missing for two participants, both due to equipment failure, and were replaced using the mean from the previous successfully recorded minute (i.e., minutes 3 and 4 of baseline recording). No post-instruction cardiovascular data were identified as missing. Reactivity values were converted into z-scores, assigning TPR a weight of −1 and CO a weight of +1. Z-scores were then combined to provide a challenge and threat index (CTI; as in Seery, Weisbuch, & Blascovich, 2009), representing a single measure of CO and TPR reactivity whereby higher values denoted a cardiovascular response more indicative of a challenge state (i.e., higher CO and/or lower TPR reactivity).[1]

Physiological responses to exercise. Pulmonary gas exchange and ventilation were measured breath-by-breath using an online gas analyser (Cortex Metalyzer 2R, Cortex, Leipzig, Germany). Before analysis, data were averaged over consecutive 10 s periods, and values for pulmonary oxygen uptake ($\dot{V}O_2$), expired carbon dioxide ($\dot{V}CO_2$), and minute ventilation ($\dot{V}_E$) were taken for each minute of exercise. During the incremental test, $\dot{V}O_{2\ peak}$ was determined as the highest 30 s average value attained before volitional exhaustion. The gas exchange threshold was defined as: the first disproportionate increase in $\dot{V}CO_2$ from visual inspection of individual plots of $\dot{V}CO_2$ versus $\dot{V}O_2$; and an increase in $\dot{V}_E/\dot{V}O_2$ with no increase in $\dot{V}_E/\dot{V}CO_2$ (Beaver, Wasserman & Whipp, 1986).

Perceived exertion. RPE was recorded during the final 15 s of each minute, using Borg's 15-point scale (Borg, 1970), which was displayed throughout the cycling test. Participants were instructed to verbally report how "hard, heavy, and strenuous" the task felt using this widely-used scale for reference. Values ranging from 6 (no exertion at all) to 20 (maximal exertion) were averaged over moderate-intensity exercise ($RPE_{0\text{-}10}$), where they stabilised, but not during severe-intensity exercise, where they increased exponentially. To enable temporal comparisons of RPE during severe-intensity exercise, ratings at 11 min, 50% TTE, and 100% TTE were recorded (as in Blanchfield et al., 2014).

Exercise tolerance. Time to exhaustion (TTE) was measured in seconds from the onset of severe-intensity exercise until volitional exhaustion, operationally defined as a pedal frequency of less than 60 rpm for more than 5 s (as in Marcora et al., 2009).

2.1.3. Procedures

All participants attended two laboratory sessions within a two-week period, separated by at least 72 h, and scheduled for the same time of day (±1 h) and under constant laboratory conditions (18–22 °C; 45–60% humidity). All exercise was performed on the same cycle ergometer (Monark Ergomedic 894 E Peak Bike friction-braked ergometer, Monark Exercise AB, Vansbro, Sweden).

Visit one. Following a 3-min self-paced warm-up, participants completed a step incremental exercise test (60 W + 30 W.min^{-1}) for determination of workloads in experimental exercise. Participants cycled at a fixed cadence (80 rpm) at progressively increasing workloads (+30 W.min^{-1}) until exhaustion (defined above). Saddle and handlebar height were adjusted for each participant, and recorded for replicability. Participants were familiarised with Borg's RPE scale (Borg, 1970) by rating perceived exertion at each work-rate. Workloads equating to 90% of the gas exchange threshold (90% GET), and 80% of the difference between gas exchange threshold and $\dot{V}O_{2\ peak}$ (80% Δ), were calculated.

Visit two. Participants sat quietly for baseline and post-instruction cardiovascular measurements, which were dispersed around the delivery of neutral standardised task instructions. Despite highlighting consistent task demands, these instructions (see Supplementary files) asked participants to 'cycle for as long as possible' to 'improve the accuracy' of their results, highlighting the evaluative nature of the exercise test. Such emphasis on the importance and meaningfulness of results was targeted to promote task engagement, a prerequisite for challenge and threat states (Vine, Moore, & Wilson, 2016). Following these resting cardiovascular measurements, participants completed a constant work-rate exercise protocol. This consisted of a single bout, involving a self-paced warm-up (3 min) prior to moderate- (90% GET, 10 min) and severe- (80% Δ) intensity workloads, performed without any rest or verbal encouragement until volitional exhaustion. Pulmonary gas exchange and HR were measured continuously, RPE was recorded every minute, and TTE was noted upon exercise termination.

2.1.4. Statistical analyses

First, the data was screened, with no univariate outliers being detected (> 3.29 SD ± mean, $p < .001$; as recommended by Osbourne, 2013). As a manipulation check, a dependent *t*-test assessed whether HR significantly increased following the delivery of task instructions. Furthermore, to assess the efficacy of workload normalisation procedures, implemented to minimise the influence of aerobic fitness on experimental exercise capacities (as proposed by Lansley, Dimenna, Bailey, & Jones, 2011), Pearson's correlation analyses identified associations between $\dot{V}O_{2\ peak}$ and TTE. Hierarchal multiple regression analyses examined the extent to which CTI predicted RPE during moderate- ($RPE_{0\text{-}10}$) and severe- (11 min, 50% TTE, and 100% TTE) intensity exercise. RPE was entered as the dependent variable, with age (step 1), body mass (step 2), and CTI (step 3) values entered respectively. Identical models identified the extent to which CTI predicted TTE. Effect sizes were estimated using Cohen's *d* values (Cohen, 1992). Significance was accepted at $p < .05$, and mean data is presented as ± SD.

2.2. Results and discussion

2.2.1. Manipulation checks

HR reactivity was significantly elevated following task-instructions

[1] Supplementary demand and resource evaluation scores (e.g., as used in Feinberg & Aiello, 2010; Moore et al., 2012) were not utilised in the study, after pilot data ($n = 5$) showed insufficient variance in self-reported situational demands (mean = 6; SD = 0). This effect was attributed to the uniformly-high (i.e., exhaustive) demands of the exercise test, and limitations in the sensitivity of self-report measures for detecting subconscious evaluations (discussed in Blascovich, 2008), as reflected in maximal reported values in all participants.

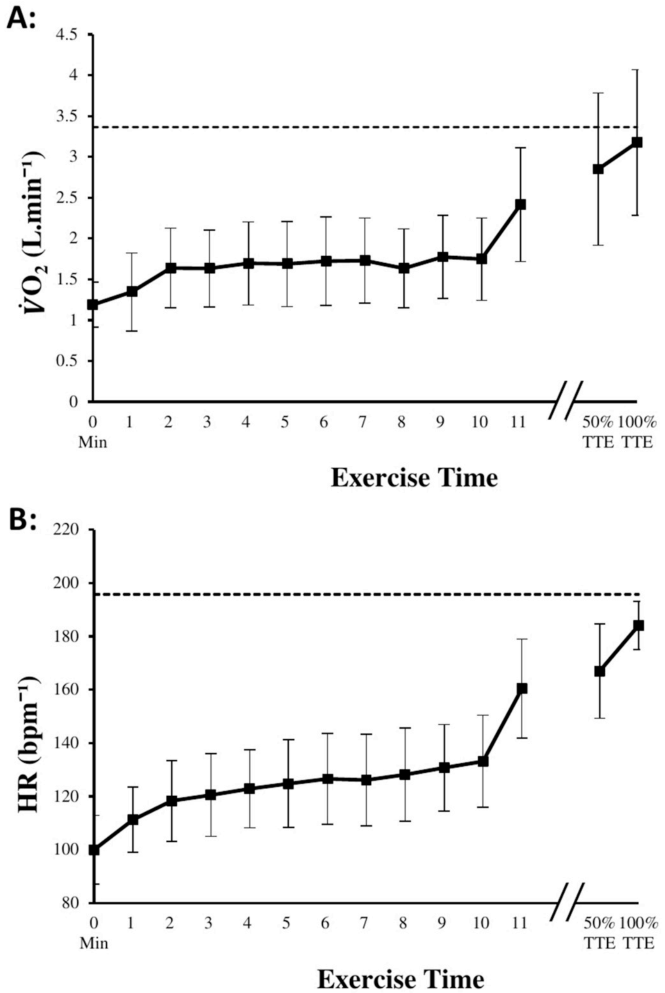

Figure 1. Physiological Responses to Exercise in Study One. Average (± SD) $\dot{V}O_2$ (A; L.min) and HR (B; bpm) over time during moderate- (0–10min) and severe-intensity exercise (11min, 50%TTE, 100%TTE). Dotted line: Mean $\dot{V}O_2$ peak at baseline (A), mean age-predicted maximum HR (B).

(mean difference: 6.43 ± 5.43 bpm; $t_{[16]} = -4.89$, $p < .001$, $d = 1.19$), with increases evident in all participants, confirming task engagement and permitting the investigation of challenge and threat states via CTI (Blascovich, 2008). Data from two participants were excluded from statistical analyses after showing $\dot{V}O_2$ kinetic profiles indicative of workloads above the gas exchange threshold. The remaining physiological data ($n = 17$; Figure 1) suggest that exercise was performed within the targeted intensity domains. Correspondingly, TTE and $\dot{V}O_{2\ peak}$ values were unrelated ($p > .05$), suggesting that the impact of physical fitness on exercise capacity was neutralised through the normalisation procedures (Lansley et al., 2011).

2.2.2. Primary analysis

As hypothesised, hierarchical regression analyses (Table 1) revealed that CTI significantly predicted RPE during moderate- (RPE_{0-10}: $\Delta R^2 = 0.29$, $\beta = -0.57$, $p = .031$) and severe- (11 min: $\Delta R^2 = 0.32$, $\beta = -0.59$, $p = .017$) intensity exercise, over and above age and body mass (RPE_{0-10}: $R^2 = 0.06$; 11min: $R^2 = 0.14$; 50% TTE: $R^2 = 0.05$), although these associations became non-significant towards the end of exercise (50% TTE: $\Delta R^2 = 0.10$, $\beta = -0.33$, $p = .239$). Thus, in general, participants who responded to the task instructions with a more challenge-like cardiovascular response (i.e., relatively higher CO and/or lower TPR reactivity) reported lower RPE than those who reacted with a response more indicative of a threat state. Therefore, this study is

Table 1
Results from hierarchical regression analyses performed on data in study one.

Dependent variable	Step (where relevant)	Independent variable	B	SE B	t
RPE_{0-10}	1	Age	0.05	0.09	0.57
	2	Body Mass	−0.02	0.03	−0.75
	3	CTI	−0.49	0.20	−2.41*
RPE (11 min)	1	Age	−0.08	0.10	−0.84
	2	Body Mass	−0.04	0.04	−1.23
	3	CTI	−0.59	0.22	−2.73*
RPE (50%TTE)	1	Age	0.03	0.05	0.67
	2	Body Mass	−0.01	0.02	−0.52
	3	CTI	−0.17	0.14	−1.23
TTE	1	Age	0.21	0.09	2.20*
	2	Body Mass	0.07	0.03	2.41*
	3	CTI	0.22	0.22	0.98

RPE: ratings of perceived exertion (RPE_{0-10}: average ratings during moderate-intensity exercise); CTI: challenge and threat index; TTE: time to exhaustion; $^*p < .05$

the first to suggest that there may be an association between cardiovascular markers of challenge and threat states and RPE. Although these results are novel, links between reduced blood flow and increased perceived exertion have long been established (e.g., Bainbridge, 1931). Therefore, the observed relationship between inflated RPE and a more threat-like cardiovascular response (i.e., reduced CO and/or increased TPR reactivity) is perhaps unsurprising, particularly given that this response is indicative of reduced blood flow (Seery, 2011). Our results also align with previous observations that psychophysiological factors exert more influence on RPE during moderate-intensity, as opposed to severe-intensity, workloads (Ekkekakis, 2003), since relationships became non-significant towards the latter stages of the exercise (Table 1). This effect may have resulted from homogenous preferences towards internally-focused attentional stimuli (e.g., muscle pain) at heightened levels of fatigue, which dilute the influence of motivational factors on RPE (Tenenbaum et al., 2001).

In spite of strong negative relationships between RPE and TTE (e.g., 11 min: $R = -0.67$, $p = .003$), CTI did not significantly predict TTE ($\Delta R^2 = 0.04$, $\beta = 0.20$, $p = .343$) over and above age and body mass (Table 1; $R^2 = 0.47$). This contradicts previous research showing the performance benefits of a challenge state (e.g., Turner et al., 2013), and contrasts with observations that any factor successful in reducing RPE prolongs TTE (e.g., Blanchfield et al., 2014; Mauger, Jones, & Williams, 2010). Instead, the null findings are suggestive of a more complex picture, whereby effects are countered by compensatory processes. Causal interpretations are, however, limited by the lack of psychological measures and the observational design, warranting further experimental studies that manipulate challenge and threat states prior to endurance performance. Consequently, in isolation, these findings must be interpreted cautiously, until they are examined in a 'closed-loop' endurance task, where psychophysiological factors have a greater influence on RPE and work-rate (Smirmaul et al., 2013).

3. Study two

The second study developed upon the exploratory findings of study one, and used an experimental design to investigate the effects of manipulating challenge and threat states on simulated 16.1 km cycling time-trial performance. This approach enabled a more causal understanding of whether reductions in RPE, relative to work-rate, can be yielded through manipulating challenge and threat states. Comprising a 'closed-loop' format, time-trials entail conscious regulation of work and fatigue to meet requisite, exhaustive exercise demands (de Koning, Bobbert, & Foster, 1999), meaning that any reductions in RPE would likely increase self-selected pacing (Marcora, 2010; Tucker & Noakes,

Table 2
Group descriptive statistics (mean ± SD) for demographic, body size, and familiarisation data in study two.

	Challenge Group	Threat Group	Neutral Group
Age (years)	21.86 ± 2.10	23.00 ± 2.45	24.29 ± 3.99
Height (cm)	178.36 ± 9.50	176.93 ± 9.38	176.96 ± 10.67
Weight (kg)	71.76 ± 11.76	71.49 ± 15.95	71.56 ± 17.37
Training Experience (years)	4.00 ± 2.00	5.00 ± 3.32	6.43 ± 7.43
Weekly Training Time (min)	505.00 ± 535.33	492.86 ± 253.29	508.57 ± 241.28
TTfam Average $\dot{V}O_2$ (ml.kg/min)	37.86 ± 8.91	35.79 ± 13.09	37.39 ± 8.60
TTfam Average PO (W.kg)	2.46 ± 1.03	2.28 ± 0.84	2.46 ± 0.76
TTfam TTC (min)	34.64 ± 9.41	34.56 ± 6.40	32.59 ± 4.48

TTfam: familiarisation time-trial; $\dot{V}O_2$: pulmonary oxygen uptake; PO: power output; TTC: time to completion; no significant differences between groups ($p > .05$).

2009). Given our earlier results, where higher CTI scores corresponded with lower RPE at a fixed workload, we examined *self-selected* power output (PO) during 4.025 km quartiles of the time-trials. This enabled exploration into whether any differences in pacing, or RPE relative to work-rate, emerged. It was hypothesised that participants who were manipulated into a challenge state would select higher PO's than those manipulated into a threat state, and that this would result in comparatively faster completion times.

3.1. Material and methods

3.1.1. Participants

A different sample of 21 novice cyclists were recruited for study 2 (see Table 2 for characteristics), with a sample of 18 deemed sufficiently powered (1-β: 0.8) to detect significant effects in cardiovascular indices of challenge and threat, RPE, and performance (α: p = .05), according to analysis of previous studies (Marcora et al., 2009; Micklewright et al., 2010; Moore et al., 2012; calculated using G*power software, version 3.1). To limit excessive baseline variability in antecedents of challenge and threat (e.g., knowledge, skills, and ability), participants were included if they had no previous time-trial experience, but engaged in regular training for alternative endurance-based sports (≥2 weekly sessions; Runners $n = 15$, Rowers: $n = 3$, Swimmers: $n = 3$). Participants completed 48-h food diaries before testing, and were required to replicate dietary behaviours across visits. Furthermore, they were instructed to arrive hydrated, rested, and free of injury and illness, as well as to abstain from caffeine (for 12 h), alcohol (48 h), and vigorous exercise (48 h) before visits. Participants remained naïve to the objectives of the study until completion of all visits. Institutional ethical approval was granted, and written informed consent was obtained from each participant before data collection.

3.1.2. Measures

Manipulation checks. Task engagement and challenge and threat states were assessed using HR reactivity and CTI respectively (following the same procedures used in study 1).

Exercise responses. As in study 1, RPE were reported verbally using Borg's 15-point scale (Borg, 1970), at the end of warm-ups and at 4-km race quartiles (4 km: RPE_{Q1}, 8 km: RPE_{Q2}, 12 km: RPE_{Q3}, and 16 km: RPE_{Q4}). Pulmonary gas exchange measures ($\dot{V}O_2$) were recorded using an online gas analyser (Cortex Metalyzer 2R, Cortex, Leipzig, Germany; as in study 1), with average values taken for warm-ups, each 4.025-km race quartile, and for the overall duration of the time trial.

Performance. Power output (PO; converted into $W.kg^{-1}$), distance (km), and time (min) were monitored continuously by a PowerTap power meter (CycleOps, Madisson, USA), a device proven valid and reliable for research purposes, which consists of an onboard data logger, sensor cable, and an eight-strain-gauge instrumented rear-wheel hub (Bertucci, Duc, Villerius, Pernin, & Grappe, 2005). The power meter was calibrated in accordance with manufacturer instructions (as in Bertucci et al., 2005). The time taken to complete 16.1 km (time to completion; TTC) was measured from the onset of cycling to trial completion. To illustrate pacing profiles, average PO for each warm-up, 4.025 km race quartile (0–4 km: PO_{Q1}; 4–8 km: PO_{Q2}; 8–12 km: PO_{Q3}; 12–16 km: PO_{Q4}), and for the overall 16.1 km were taken.

3.1.3. Procedures

Following a single-blind, randomised control design, participants attended three sessions, separated by a minimum of 48 h, and scheduled for the same time of day (± 1 h). To control for the effects of familiarity and previous task experience on challenge and threat states (Blascovich, 2008), visits were performed in the same order for all participants. Each visit involved completing a 16.1 km trial on a time-trial bike (Planet X, Sheffield, UK) fitted with a Powertap G3 Hub (Powertap, Wisconsin, USA), and mounted on a turbo-trainer (Cycleops Super Magneto, Wisconsin, USA). Before starting trials from a 'natural' position, participants undertook a 3-min self-paced warm-up and selected a starting gear. Participants were blinded from performance feedback apart from elapsed distance.

Familiarisation trial (TT_{FAM}). After documentation of demographic information (i.e., age, height, weight, sport, competitive-level, and experience), participants completed their first 16.1 km time-trial, which served to familiarise them with the associated demands and procedures of each test. Before exercise, individual bike positioning was adjusted, recorded, and later reproduced in subsequent trials. Upon completion, participants were matched into trios, according to demographics and TTC (Table 2), which were then split and randomly allocated (using https://www.randomizer.org) to one of the three experimental groups (Challenge, $n = 7$; Threat, $n = 7$; Neutral-Control, $n = 7$).

Control trial (TT_{CON}). The second trial served as a control (TT_{CON}), whereby all participants received identical 'neutral' task instructions (see Supplementary files) as cardiovascular reactivity data were recorded. Participants remained seated silently while task instructions were delivered, with these instructions emphasising the comparative and evaluative nature of the task to elevate pressure (as Moore et al., 2012). Specifically, as in study one, maximal effort was encouraged to 'improve the accuracy' of the results. Furthermore, instructions stated that performances would be published on a leaderboard, and that top performers would be awarded prizes and worst performers would be interviewed about their poor performance. Thereafter, participants completed a warm-up and the subsequent time-trial, while physiological ($\dot{V}O_2$), perceptual (RPE), and performance (TTC, PO) measures were assessed.

Experimental trial (TT_{EXP}). Manipulation check and time-trial procedures were replicated in the third visit (TT_{EXP}), although different task instructions were provided to participants according to their experimental group. Although instructions remained identical to TT_{CON} for the neutral group, verbal instructions were used to manipulate perceptions of task demands and personal coping resources for the challenge and threat groups (see Supplementary files). The challenge group received instructions that reduced perceptions of task demands and increased perceptions of personal coping resources (e.g., people tend to "perform well"), whereas the threat group received instructions that inflated perceived demands and diminished perceived coping resources (e.g., emphasising that people have "struggled to perform well"). Similar, group-based instructions have been used previously to manipulate participants into challenge and threat states during laboratory-based sporting tasks (e.g., Moore et al., 2012).

3.1.4. Statistical analysis

One-way ANOVAs were employed to detect any between-group differences in demographic, familiarisation, and warm-up variables. Task engagement was assessed using dependent *t*-tests to examine whether HR increased significantly following the manipulation instructions in both TT_{CON} and TT_{EXP}. A manipulation check was conducted using a 2 (trial: TT_{CON}, TT_{EXP}) x 3 (group: challenge, threat, neutral) mixed ANOVA with CTI as the dependent variable. Thereafter, a series of 2 (trial: TT_{CON}, TT_{EXP}) x 3 (group: challenge, threat, neutral) x 4 (sector: Q1, Q2, Q3, Q4) ANOVAs examined group-by-trial differences in performance and exercise responses over time (i.e., PO, $\dot{V}O_2$, and RPE). Finally, overall group-by-trial alterations in performance were examined using a 2 (trial: TT_{CON}, TT_{EXP}) x 3 (group: challenge, threat, neutral) mixed ANOVA, with TTC as the dependent variable. Planned post-hoc comparisons utilised dependent and independent *t*-tests (adjusted using the Bonferroni correction). Where the sphericity assumption was violated, Greenhouse–Geisser corrections were applied. Significance was accepted at $p < .05$, and mean data is presented ± SD.

3.2. Results and discussion

3.2.1. Manipulation checks

There were no missing data or univariate outliers ($p < .001$) in the dataset, although two participants withdrew due to training-related injury, and one was excluded prior to statistical analyses after reporting illness, affording a final sample of 18 (Challenge group, $n = 7$; Threat group, $n = 6$; Neutral-Control group, $n = 5$). There were no significant differences between the groups in terms of the demographic or body size variables (all $ps > .05$). Furthermore, there were no significant differences between the groups in relation to TTC or average PO ($ps > .05$) during TT_{FAM}, suggesting matched-randomisation of groups was successful (Table 2). Finally, no significant between-group differences emerged for warm-up $\dot{V}O_2$, RPE, or PO (all $ps > .05$).

HR increased significantly following task instructions in TT_{CON} (mean difference: 4.89 ± 3.31 bpm^{-1}; $t_{[17]} = 6.27$, $p < .001$, $d = 1.48$) and TT_{EXP} (mean difference: 4.29 ± 4.69 bpm^{-1}; $t_{[17]} = 3.88$, $p = .001$, $d = 0.91$). This confirms task engagement, permitting further investigation of challenge and threat states (via CTI). The ANOVA revealed a significant 'trial-by-group' interaction for CTI ($F_{[2,15]} = 14.32$, $p < .001$). CTI significantly increased between TT_{CON} and TT_{EXP} for the challenge group (mean difference: 2.20 ± 1.05; $t_{[6]} = 5.55$, $p = .001$, $d = 2.10$), decreased for the threat group (mean difference: 2.48 ± 1.97; $t_{[6]} = -3.09$, $p = .027$, $d = -1.26$), and showed no significant changes in the neutral group (mean difference: 0.10 ± 1.67; $t_{[4]} = 0.14$, $p = .899$). This suggests that the instructions were successful in manipulating participants into challenge, threat, and neutral states (Table 3).

3.2.2. Primary analysis

A marginally significant group-by-trial-by-distance interaction occurred for PO ($F_{[2.66,19.95]} = 3.22$, $p = .049$), highlighting that manipulation-dependent changes in workload emerged. Specifically, changes in PO_{Q1} between trials were greater in the challenge group compared to the threat group ($t_{[10.78]} = 2.63$, $p = .024$, $d = 1.25$), who utilised a more cautious early-race pacing profile. However, these differences were not maintained into the middle sectors of the trial (Figure 2). Therefore, this study shows that, through manipulating challenge and threat states, one can alter pacing behaviour during endurance events. Specifically, results indicate that a more challenge-like cardiovascular response can prompt an athlete to select higher a work-rate during the early stages of exercise. Notably though, in line with findings from study one, there were no significant group-by-trial-by-distance interactions for RPE ($F_{[3.99,29.92]} = 2.07$, $p = .110$), *despite* these differences in early-race pacing. This shows that the challenge group were able to adopt higher workloads than the threat group at a given RPE. Such differences reinforce the BPSM's proposals that a challenge state, as opposed to a threat state, promotes more favourable responses in motivated performance situations (Blascovich, 2008). Interestingly, given the distinct cardiovascular reactivity patterns displayed in each group (Table 3), no significant interaction effects emerged for $\dot{V}O_2$ ($F_{[3.28,24.57]} = 1.56$, $p = .222$). Therefore, results infer that the discrepancies in RPE and pacing might stem from subtle alterations in anaerobic energy systems and/or distortions in interoceptive accuracy (i.e., in the *perception* of sensory information).

No significant group-by-trial interactions emerged for TTC ($F_{[2,15]} = 1.36$, $p = .287$), meaning that no overall performance effects were observed. This was due to differences in the latter stages of TT_{EXP}, with more pronounced 'end-spurts' evident in the threat group relative to the challenge group (Figure 2). While seemingly contradictory to the propositions of the psychobiological model of endurance (i.e., that any factor which reduces one's RPE will enhance performance; Marcora, 2010), these null performance effects could be explained by the dynamic nature of challenge and threat states (Seery et al., 2009). It is possible that, in the threat group, increases in 'end-spurt' workloads coincided with individuals beginning to view the task as more of a challenge towards the end of exercise (e.g., due to lower perceived task demands and/or higher personal coping resources). Similarly, an increased focus towards movement execution, potentially resulting from increased reinvestment (Jones et al., 2009), may have facilitated these more pronounced compensatory 'end-spurts'. Therefore, the dynamic interplay between challenge and threat states, RPE, and endurance performance requires further investigation.

4. General discussion

The present research investigated the relationship between cardiovascular markers of challenge and threat states and endurance exercise capabilities. Collectively, the results are the first to show that relative to a cardiovascular response more akin to a threat state, a response more indicative of a challenge state can promote more favourable responses during endurance exercise, including reductions in RPE and increases in self-selected pacing. However, no overall performance effects were observed, suggesting that the applicability of the BPSM to endurance-based tasks is likely to be complex.

Reductions in RPE relative to individual work-rates were linked to a challenge state during both studies. Although novel, a number of antecedents of challenge and threat states have been linked to perceptions of fatigue in previous research. For example, during prolonged endurance events, reductions in RPE have been shown to correspond with higher pre-exercise self-efficacy and task familiarity (Hutchinson et al., 2008; Micklewright et al., 2010), factors that have been proposed to underpin a challenge state by increasing perceptions of coping resources relative to situational demands (Blascovich, 2008; Jones et al., 2009). In study two, these decreases in RPE facilitated increases in self-selected workloads during the early stages of exercise, effects that have also been produced by various ergogenic interventions (e.g., motivational self-talk, Blanchfield et al., 2014; caffeine ingestion, Cole et al., 1996). The findings therefore suggest that the adaptive psychophysiological responses fostered by a challenge state (i.e., reduced RPE) may enhance behaviour during metabolically-demanding events. However, while stress-related enrichments in muscular blood flow likely persist during exercise (Rousselle et al., 1995), and proposed enhancements in anaerobic oxygen-independent mechanisms remain possible (Jones et al., 2009), no physiological enhancements were detected during

Table 3
Group and trial averages (mean ± SD) for resting and exercise outcome measures in study two.

	Challenge Group		Threat Group		Neutral Group	
	TTcon	TTexp	TTcon	TTexp	TTcon	TTexp
CTI Score	−0.70 ± 1.34	1.50 ± 1.53*	0.77 ± 1.45	−1.71 ± 1.42*	0.04 ± 1.42	−0.06 ± 0.72
$\dot{V}O_2$ (ml.kg.min)	35.26 ± 8.53	39.72 ± 8.55	33.89 ± 9.48	34.41 ± 8.72	37.69 ± 7.28	35.07 ± 7.14
PO (W.kg)	2.91 ± 0.49	2.73 ± 0.84	2.34 ± 0.69	2.42 ± 0.68	2.45 ± 0.84	2.46 ± 0.83
TTC (min)	33.26 ± 8.15	33.03 ± 7.48	32.81 ± 6.18	31.99 ± 6.43	31.21 ± 4.29	31.58 ± 3.63

TTcon: control time-trial; TTexp: experimental time-trial; CTI: challenge and threat index; $\dot{V}O_2$: pulmonary oxygen uptake; PO: power output; TTC: time to completion; *significant difference between visits ($p < .05$).

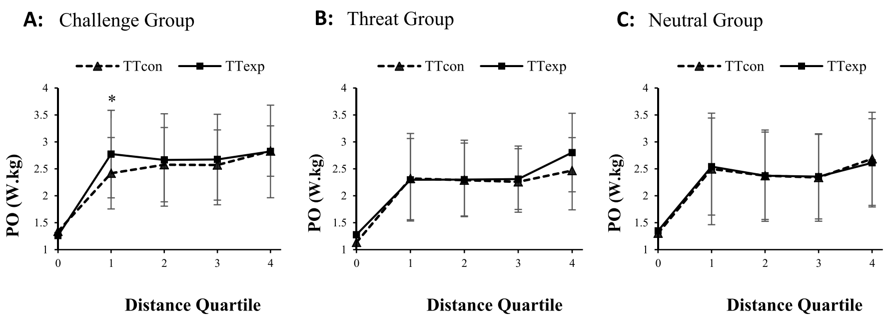

Figure 2. Pacing Profiles during Time-Trials in Study Two. Average power output (PO; W.kg) over 4.025-km race quartiles (0–4 km: Q1, 4–8 km: Q2; 8–12 km: Q3; 12–16 km: Q4) for challenge (A), threat (B) and neutral (C) groups during control (TTcon) and experimental (TTexp) 16.1 km time-trials. *Significant difference between trials (p < .05).

exercise in either study. Further research into distorted interoceptive accuracy, potentially via threat-related perceptual biases (see Vine et al., 2016), is particularly promising, as attentional mechanisms have been prominently linked with RPE (e.g., LaCaille, Masters, & Heath, 2004; Pennebaker & Lightner, 1980; Rejeski, 1985). Such investigations may wish to focus on the potentially-mediating effects of associative and dissociative cognitive processes, strategies proven to alter both RPE and performance in endurance events (e.g., Morgan, Horstman, Cymerman, & Stokes, 1983; see McCormick et al., 2015 for a review).

Interestingly, no overall performance effects emerged in either study, contesting suggestions that the adoption of a more challenge-like cardiovascular response is likely to enhance performance more than a response akin to a threat state (Blascovich, 2008). Our data instead presents a more complex picture, particularly in the latter stages of exercise, where cardiovascular reactivity (i.e., CTI) became unrelated to RPE (Table 1), and more pronounced 'end-spurts' occurred for those participants who displayed reactivity more indicative of a threat state (Figure 2). These findings align with a meta-analysis recently conducted by Behnke and Kaczmarek (2018), who found that the majority of performance variance in research remains unexplained after accounting for the effects of challenge and threat states. Results also reinforce observations that the effects of perceived exertion becomes less predictable towards the end of endurance events (Tucker & Noakes, 2009), where heightened markers of fatigue dilute central influences on RPE (Rejeski & Ribisl, 1980).

4.1. Implications and future research

The present research supports interdisciplinary explanations of human performance. Firstly, the results offer novel evidence for the theories of challenge and threat states (e.g., BPSM and TCTSA), reinforcing views that a challenge state can enhance individual responses (i.e., reduce RPE) during motivated performance situations. While no performance effects were revealed, the likely role of compensatory processes in minimising such effects support recent interpretations that a threat state is not always detrimental to performance if additional resources are mobilised (e.g., effort; Vine et al., 2016). Second, the results also support propositions made by the psychobiological model of endurance (Marcora et al., 2009, 2008; Marcora & Staiano, 2010), in that self-selected work-rates are reduced by predictors of inflated RPE. To further integrate these theories, future research should analyse the precise mechanisms through which these effects occur, with the examination of specific attentional bias tendencies (e.g., associative or dissociative cues) warranting particular exploration.

The key findings reported here, that important determinants of endurance performance (e.g., RPE and pacing) can be altered through the verbal manipulation of challenge and threat states, has implications for sporting and non-sporting contexts (e.g., cycling, team-based activities, armed forces, health settings). Notably, the reductions in RPE associated with a challenge state could be targeted, as they prove predictive of numerous favourable outcomes such as enhanced endurance capabilities, reduced internal training load, and more proficient motor performances (Marcora et al., 2009, 2008; Royal et al., 2006; Snyder, Jeukendrup, Hesselink, Kuipers, & Foster, 1993). Various interventions have been shown to promote a more 'challenge-like' cardiovascular response (e.g., arousal reappraisal; Jamieson et al., 2010; Moore, Vine, Wilson, & Freeman, 2015; Sammy et al., 2017), which, on the basis of the present research, offer potentially-adaptive outcomes in fatigue-related domains. Future research should therefore examine whether these interventions can enhance performance-based, and/or health-related outcomes that are associated with RPE, such as overtraining syndrome (Matos, Winsley, & Williams, 2011) and/or adherence to physical activity (Ekkekakis & Lind, 2006).

The limitations of the present research also highlight directions for prospective research. Firstly, alterations in the cardiovascular markers of challenge and threat states were not monitored during exercise in either study, due to concerns surrounding the influence of movement artefacts (Siebenmann et al., 2015). The interpretation of the effects occurring at the end of exercise are therefore speculative, as evaluated demands and personal coping resources will have likely differed from when they were measured. For example, increases in self-efficacy, an antecedent of a challenge state (Jones et al., 2009), would be expected as uncertainties surrounding one's ability to complete the task are reduced (Tucker & Noakes, 2009). As such, future investigations should attempt to monitor challenge and threat states *during* exercise, potentially via self-report items and/or hormonal measures (e.g., salivary cortisol; as in Jamieson et al., 2010). Second, the absence of self-report measures of demand and resource evaluations limits our overall understanding of how challenge and threat states influence RPE and exercise capabilities. Although experimental task instructions in study two specifically targeted perceptions relating to task demands and the ability to cope with these demands, further scrutiny is warranted into the potentially-influential roles of the cognitive, social, and physiological components integrated within the BPSM (e.g., uncertainty, social support, neuroendocrine activity, Blascovich, 2008; Seery, 2011). Future research should utilise multiple psychological and physiological assessments of challenge and threat states to enable a more complete picture. Such scrutiny could not only aid our theoretical understanding, but also the development of future applied interventions in endurance sports (McCormick et al., 2015).

To conclude, the present research is the first to demonstrate that the cardiovascular reactivity patterns marking challenge and threat states impact upon perceptions of fatigue and physical functioning during endurance-based exercise. Indeed, a cardiovascular response more indicative of a challenge state (i.e., relatively higher CO and/or lower TPR reactivity) was associated with reduced RPE at a given work-rate, and quicker pacing during the beginning of endurance exercise. However, no overall performance effects were observed. Future investigations into whether a challenge state can be manipulated to reduce perceptions of fatigue, and thus potentially alter exercise capabilities, are warranted.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2019.04.017.

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