Cardiovascular and cerebral haemodynamic responses to ego depletion in a pressurized sporting task.

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Abstract

This study examined the effects of ego depletion on challenge and threat states and cerebral haemodynamic responses to a pressurized muscular endurance task requiring self-control. Following ethical approval, 58 participants (39 males, 19 females; M_{age} = 28 years, *SD* = 12) were randomly assigned to either an experimental or control group. Participants then completed self-report measures of trait anxiety and self-control. Next, the experimental group performed a written transcription task requiring self-control, while the control group transcribed the text normally. Finally, before the pressurized muscular endurance task, challenge and threat states were assessed using demand and resource evaluations and cardiovascular reactivity; while cerebral perfusion in Fp1 and Fp2 was assessed using near-infrared spectroscopy. The results supported the effectiveness of the self-control manipulation, with the experimental group transcribing fewer words, making more errors, and regulating their writing habits more than the control group. Although there were no differences between the groups in terms of muscular endurance performance or challenge and threat states, there was a significant interaction of time (pre vs. post) x group (experimental vs. control) in cerebral perfusion. These findings suggest that ego depletion might not influence challenge and threat states, but may lead to reduced cerebral perfusion. As such, cerebral perfusion may be a novel marker which could be used to assess ego depletion.

Keywords: self-control, stress, cognitive appraisal, cerebral perfusion, challenge and threat states, self-regulation

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Optimising performance under pressure is vital for success in various domains (e.g., sport, education, business, military, and aviation). The biopsychosocial model (BPSM) of challenge and threat states provides a theoretical framework that attempts to explain why individuals might perform differently under pressure (Blascovich, 2008). Specifically, when entering a pressurized situation, the BPSM suggests that an individual evaluates how demanding the situation is, and whether they possess the resources required to cope with those demands (Blascovich, 2008). A challenge state is experienced when coping resources are evaluated as sufficient to meet or exceed situational demands. In contrast, a threat state is experienced when coping resources are evaluated as insufficient to meet situational demands (Blascovich, 2008). It is important to note that challenge and threat are typically considered as anchors of a single bipolar continuum rather than two discrete states, leading researchers to often examine relative rather than absolute differences in challenge and threat (i.e., greater versus lesser challenge or threat; Seery, 2013). Furthermore, challenge and threat states are conceptualised as relatively dynamic, and are proposed to occur at a more subconscious (or automatic) than conscious level (Seery, 2013).

The aforementioned demand resource evaluation process is thought to trigger distinct neuroendocrine and cardiovascular responses (Seery, 2013). Thus, challenge and threat states can be measured via subjective self-report items and objective physiological markers (Blascovich, 2008). Specifically, due to an increase in sympathetic-adrenomedullary activity and the release of catecholamines (e.g., adrenaline), a challenge state is proposed to result in increases in cardiac output (CO) and decreases in total peripheral resistance (TPR; Seery, 2013). The increased CO, combined with the decreased TPR, is thought to provide more efficient oxygenated blood flow to the brain and muscles (Seery, 2013). In contrast, due to increases in both sympathetic-adrenomedullary and pituitary adreno-cortical (or hypothalamic pituitary adrenal axis) activity, and the resulting release of cortisol, a threat state is proposed to lead to little change or a decrease in CO and little change or an increase in TPR (Seery, 2013). Previous research has validated these cardiovascular markers which are thought to reflect subconscious (or underlying) demand and resource evaluations (Blascovich, 2008), and has shown that task engagement, a prerequisite for challenge and threat states to occur, is indexed by increases in heart rate (HR; Seery, 2013).

In line with the predictions of the BPSM (Blascovich, 2008), previous research has demonstrated that individuals in a challenge state tend to outperform individuals in a threat state during both cognitive (e.g., modified Stroop; Turner, Jones, Sheffield, & Cross, 2012) and sporting (e.g., golf putting; Moore, Vine, Wilson, & Freeman, 2012) tasks. Due to the small but relatively robust effect of challenge and threat states on the performance of pressurized tasks (Behnke & Kaczmarek, 2018; Hase, O'Brien, Moore, & Freeman, 2018), more research is needed to identify the factors that influence these states, so that interventions that promote a challenge state, or prevent a threat state, can be developed. Indeed, while limited, the research conducted to date has shown that personality traits can influence challenge and threat states, including underlying demand and resource evaluations (e.g., emotional intelligence; Kilby, Sherman, & Wuthrich, 2018), and accompanying cardiovascular responses (e.g., conscientiousness; Allen, Frings, & Hunter, 2012). Furthermore, research has shown that situational factors can influence challenge and threat states, including underlying evaluations (e.g., task difficulty; Moore, Vine, Wilson, & Freeman, 2014), and associated cardiovascular responses (e.g., social comparison; Mendes, Blascovich, Major, & Seery, 2001). One possible factor that remains to be investigated is self-control. This is surprising given that the ability to resist immediate and automatic impulses in specific situations is key to many aspects of performance, and the inability to resist these impulses is thought to problematic under pressurised conditions (Englert & Bertrams, 2012).

The strength model of self-control has been used as a framework for exploring self-control processes within sports psychology (Englert, 2016). This model suggests that self-control is a limited resource that can be depleted (Baumeister & Heatherton, 1996). It is hypothesized that the exertion of self-control during an initial task (e.g., the control of dominant responses such as emotions, behavioural impulses, and habits; Friese, Gieseler, Loschelder, Frankenbach, & Inzlicht, 2018), can have detrimental effects on the performance of subsequent self-control tasks (Hagger, Wood, Stiff, & Chatzisarantis, 2010). The depletion of this limited resource is often termed 'ego depletion' (Baumeister & Heatherton, 1996). The negative effects of ego depletion have been seen across sporting tasks requiring both perceptual-motor skill (e.g., dart-throwing; McEwan, Ginis, & Bray, 2013), and physical endurance (Giboin & Wolff, 2019).

However, recently the validity of the strength model has come under scrutiny, questioning its empirical (Carter, Kofler, Forster, & McCullough, 2015; Hagger et al., 2016), and mechanistic credibility (Beedie & Lane, 2012). Hagger and colleagues (2010) originally reported a medium to large effect size of ego depletion, however, after re-analysis the original effect size was thought to be overestimated due to publication bias (Hagger et al, 2016). This assumption has been further supported by a recent survey among ego depletion research (Wolff, Baumann & Englert, 2018). The inconsistent findings surrounding the ego depletion effect lead Hagger and colleagues (2016) to conduct a Registered Replication Report. This report failed to find a significant ego depletion effect, however, Hagger et al (2016) emphasised that further investigation is necessary to ascertain the causes for these null findings, rather than implying that the ego depletion effect doesn't exist.

In contrast to the strength model, research has suggested that self-control is more of a conscious process, with the allocation of self-control reflecting a value-based decision. (Botvinick & Braver, 2015; Westbrook & Braver, 2015). Indeed, Job and colleagues (2010) offered an alternative to the resource theory, suggesting that self-regulatory failure following exertion of self-control or willpower results from people's belief about their availability of self-control resources rather than a true lack of resources (Job, Dweck & Walton, 2010). Essentially, it is suggested that depletion will only occur in individuals who believe that their self-control can be depleted (Job et al., 2010). Thus, there appears to be some debate in the literature about whether self-control, and its depletion/availability is due to an individual's belief of self-control or is detected at a more subconscious level. The BPSM could help shed some light on this issue. Indeed, if self-control is affected by conscious thoughts and beliefs, then those who view their self-control availability as reduced, should evaluate the subsequent task as more of a threat (i.e., insufficient resources to cope with task demands), thus resulting in more threat-like cardiovascular responses (i.e., little change or decreases in CO and little change or increases in TPR; Seery, 2013). However, if not open to consciousness, a reduction in self-control availability should not impact self-reported demand and resource evaluations, but may still result in more threat-like cardiovascular reactivity (i.e., relatively lower CO and higher TPR reactivity; Seery, 2013).

Another difficulty that has been discussed in relation to the ego depletion phenomenon is the inability for researchers to stipulate a plausible and tangible physiological mechanism that is either 'reduced' or associated with the availability of self-control (Elkins-Brown, Berkman, & Inzlicht, 2016). Indeed, the presence of ego depletion has mostly been measured based on a deterioration in the performance of a second self-control task, following an initial self-control task, using the sequential task paradigm (Hagger et al., 2010). However, recent research suggests that there may be a disconnect between perceived fatigue and performance, due to there being no gold standard to measure mental fatigue across domains (Pattyn, Cutsem, Dessy & Mairesse, 2018) Therefore, the notion of 'depletion' of self-control from observable performance and/or the conceptual description of fatigue may not be accurate (Pattyn et al, 2018). Research from cognitive neuroscience offers a potential physiological measurement, with a large body of research having investigated the neural correlates of self-control (Botvinick & Braver, 2015; Shenhav et al., 2017; Cohen & Lieberman, 2010), with research pointing to the central role of the prefrontal cortex (PFC). As a marker of PFC activation, previous studies have used the change in tHb, a marker of cerebral perfusion (Faulkner et al., 2017). Changes in cerebral perfusion in the PFC has been shown to be able to distinguish between declines (Hillis et al., 2002) and improvements (Hillis et al., 2002) in cognitive performance, as well as changes in posture during exercise (Faulkner et al., 2017). Given that self-control is suggested to activate the PFC (Friese, Binder, Luechinger, Boesiger, & Rasch, 2013; Cohen & Lieberman, 2010), it seems logical that cerebral perfusion may change in response to an ego-depletion task.

The PFC is proposed to be involved in emotion regulation, decision making, and habitual responses (Friese et al., 2013), whilst also being strongly connected to sensory and motor system structures which are relevant for voluntary behavioural control (Miller & Cohen, 2001). Previous research suggests that the level of self-control allocation is associated with varying levels of brain activity, particularly in the PFC (Friese et al., 2013), again highlighting it as a key structure in the exertion of self-control (Cohen & Lieberman, 2010).

The theory of expected value of control (EVC; Shenhav, Botvinivk,& Cohen, 2013) aims to explain the differing levels of activation within the PFC. In simple terms, EVC represents the net cost value associated with allocating control to a given task. EVC theory assumes such costs are 'effortful' (Shenhav et al., 2017). Therefore, the allocation of control is the sum of the estimated reward outcome and the effort cost (for a comprehensive mechanistic review of EVC see; Shenhav et al., 2017; Shenhav et al., 2013). The degree to which self-control is allocated may be reflected in differing prefrontal activations and subsequently, differing cardiovascular responses under pressure (and subsequently performance) due to the PFC also being involved in stress regulation.

In particular, the PFC regulates the hypothalamic pituitary adrenal axis (Smith & Vale, 2006). This axis is a crucial component of the cardiovascular responses accompanying a threat state (Blascovich, 2008; Smith & Vale, 2006). Self-control performance has been shown to be affected under highly pressurized conditions (Englert & Bertrams, 2015). It is therefore possible that the allocation of self-control could influence challenge and threat states. For example, too little allocation could lead to the PFC activating the hypothalamic pituitary adrenal axis (associated with a threat state), whereas a greater allocation of self-control could result in only activating the sympathetic-adrenomedullary axis (associated with a challenge state). As self-control is a cognitive faculty, the central nervous system and cardiovascular markers of challenge and threat states, may therefore be particularly effective mechanisms to explore a construct as complex as self-control, and the ego depletion phenomenon.

The aim of this study was to investigate the potential impact of ego depletion on challenge and threat states and cerebral haemodynamic responses during a pressurized muscular endurance task requiring self-control. First, the ego depletion group were expected to perform worse in the pressurized muscular endurance task than the control group. Second, assuming that the reduction in actual or perceived self-control resources would be consciously perceptible, the ego depletion group were expected to evaluate the pressurized task as more of a threat (i.e., insufficient resources to cope with task demands), and display a cardiovascular response more akin to a threat state (i.e., lower CO and/or higher TPR reactivity) than the control group. If not open to conscious awareness, the reduction in actual or perceived self-control resources was only expected to result in the ego depletion group exhibiting a more threat-like cardiovascular response than the control group, with no differences between the groups in self-reported demand and resource evaluations. Finally, due to the reduction in actual or perceived self-control resources, the ego depletion group were expected to exhibit reduced cerebral perfusion than the control group.

Method

Participants

Following institutional ethical approval, 60 university undergraduate and postgraduate students were recruited. However, two participants were excluded from the final data analysis due to having more than one missing data point. As such, 58 participants (39 males, 19 females; M_{age} = 28 years, *SD* = 12) were included in all analyses. All participants read an information sheet and provided written informed consent prior to all testing. Moreover, all participants reported being free from illness or infection, and having no known family history of cardiovascular or respiratory disease. Furthermore, all participants were instructed not to perform vigorous exercise or ingest alcohol for 24 hours before testing, and to not consume food for 4 hours and caffeine for 12 hours before testing. Finally, all participants reported they were recreationally active but not handgrip trained such as in tennis, climbing, or lifting, etc. Recreationally active was defined as a minimum of 1 hours structured exercise for a minimum of 3 days a week (in accordance with the American College of Sports Medicine guidelines).

Measures

Trait measures

Sport anxiety scale (SAS-2). Individual differences in trait anxiety were measured using the 12-item SAS-2 (Smith, Smoll, Cumming, & Grossbard, 2006). The SAS-2 is comprised of three sub scales: (1) worry (e.g., “I worry I will let others down”), (2) somatic anxiety (e.g., “I feel tense in my stomach”), and (3) concentration disruption (e.g., “I cannot think clearly during the game”). Each subscale contained 4-items. Items were rated using a 4-point Likert scale anchored between *not at all* (1) and *very much* (4). Items were summed for each subscale, with higher scores indicative of greater worry, somatic anxiety, and concentration disruption. This measure has been used in previous ego depletion research (e.g., Englert & Bertrams, 2014), and has been shown to be valid and reliable (Smith et al., 2006). Cronbach alpha (α) = 0.91). For the current study α = 0.92.

Brief self-control scale. Individual differences in trait self-control were assessed using the 13-item brief self-control scale (Tangney, Baumeister, & Boone, 2004). Participants indicated the degree to which they agreed with each item on a 5-point Likert scale anchored between *not at all* (1) and *very much* (5). The scores from all items were summed, with a higher score indicating greater trait self-control. This scale has been used in previous ego depletion research (e.g., McEwan et al., 2013), and has been shown to be valid and reliable (Tangey et al., 2004; α = 0.92). For the current study α = 0.7.

Self-control manipulation and manipulation checks

Self-control was experimentally manipulated using a written transcription task (as Bertrams, Englert, & Dickhauser, 2010). Importantly, this task has been repeatedly shown to deplete self-control resources in previous research (e.g., Englert, Zwemmer, Bertrams, & Oudejans, 2015; Englert & Bertrams, 2014). Specifically, during the task, participants were instructed to transcribe a neutral text by hand for 6 minutes. In the ego depletion group, participants were asked to omit the letters “e” and “n”, an act that required self-control due to the suppression of typical writing habits. In contrast, the control group were told to transcribe the text conventionally in full, requiring little or no self-control.

Performance during the written transcription task was measured using the number of words transcribed and the number of errors per group (as Englert & Bertrams, 2014). Errors constituted grammatical mistakes (i.e., spelling, lack of capital letters, etc.), missing words or sentences, and failing to miss out the letters “e” and “n” (for the ego depletion group only).

Furthermore, following the written transcription task, participants were asked “How strongly did you have to regulate your writing habits?” participants responded on a 4-point Likert scale anchored between *not at all* (1) and *very much* (4) (as Englert & Bertrams, 2014; Furley, Bertrams, Englert, & Delphia, 2013). In addition, participants were asked “How effortful did you find the writing task?” which was assessed using the rating scale of mental effort (Zijlstra, 1985). Participants responded on a vertical 9 item scale anchored between *absolutely no effort* (0) and *extreme effort* (150)

Muscular endurance performance

Consistent with previous research (e.g., Fryer et al., 2015), participants were presented with a fingerboard apparatus with five vertical lights, with each light representing a different level of applied strength pressure. Specifically, when completing the task, participants were asked to rest the elbow of their non-dominant arm on the apparatus, with only their fingertips positioned over an indoor artificial rock climbing hold, and pull down on the hold to generate force. Peak handgrip strength was determined using three individual two-second maximum voluntary contraction (MVC) trials, each trail separated by one minute of rest. Following this, participants were asked to sustain 40% of their peak MVC for as long as possible, and time was recorded in seconds. Visually, on the apparatus, 40% of their MVC was represented by a central green light. In order to regulate the 40% MVC, two amber lights above and below the green light were used to inform the participant whether they were contracting too much or too little, respectively. The amber lights represented 5% deviation from the target 40% MVC required; deviating outside of this 5% window for more than two seconds terminated the test. This ensured that a consistent force was applied to assess actual time to failure. Participants performed this hand grip endurance task twice (i.e., trial 1 and trial 2), with each trial separated by the self-control manipulation (i.e., written transcription task). The first trial represented a baseline measurement, while the second trial was performed under elevated pressure (see procedure below for more details). Task performance was calculated in terms of the difference in time (s) between the first and second trials (i.e., trial two minus trial one), with a positive score indicating better performance, and a negative score reflecting a poorer performance, during the second pressurized trial of the muscular endurance task.

Challenge and threat states

Demand and resource evaluations. Two items from the cognitive appraisal ratio were used to assess evaluations of task demands and personal coping resources (Tomaka, Blascovich, Kelsey, & Leitten, 1993). Task demands were assessed by asking "How demanding do you expect the upcoming task to be?", while personal coping resources were measured by asking "How able are you to cope with the demands of the upcoming task?" Both items were rated on a 6-point Likert scale anchored between *not at all* (1) and *extremely* (6). A demand resource evaluation score (DRES) was then calculated by subtracting evaluated demands from resources (range = -5 to +5), with zero or a positive score reflecting an evaluation more reflective of a challenge state (i.e., coping resources match or exceed task demands), and a negative score reflecting an evaluation more consistent with a threat state (i.e., task demands exceed coping resources). Previous research has used this measure to assess challenge and threat states (e.g., Moore, Wilson, Vine, Coussens, & Freeman, 2013).

Cardiovascular reactivity. A continuous non-invasive ambulatory blood pressure monitoring system (Portapres-2, Finapres Medical Systems, Amsterdam, The Netherlands) was used to estimate HR, CO, and TPR. A finger cuff was attached to the middle finger on each participants' non-dominant hand and inflated to continuously estimate cardiovascular data. Previous research has shown the Portapres-2 to be both valid and reliable (Zanstra, Johnston & Rasbash, 2010; Hirschl, Woisetschlager, Waldenhofer, Herkner & Bur, 1999). HR, CO, and TPR were estimated during baseline (i.e., 15 minutes upright rest), and post-pressure instruction (i.e., 1-minute upright rest while reflecting on the pressure manipulation instructions and upcoming task), time periods. In line with previous research (e.g., Moore, Vine, Wilson & Freeman, 2015), cardiovascular reactivity, or the difference between the final minute of baseline and the minute after pressure instructions, was used in all analyses. Specifically, HR reactivity was used to determine whether participants were actively engaged in the task (a prerequisite of challenge and threat states, with larger increases in HR reflecting greater task engagement), and CO and TPR reactivity were used to determine whether cardiovascular responses were more indicative of a challenge or threat state (with a challenge state marked by relatively higher CO and/or lower TPR reactivity; Seery, 2013).

Near-infrared spectroscopy

Near-infrared spectroscopy (NIRS) is a non-invasive technique that allows for monitoring of regional cerebral haemodynamics. Specifically, it can measure changes in the concentration of oxy-haemoglobin (O_2Hb) and deoxy-haemoglobin (HHb), the combination of which is tHb, a marker of cerebral perfusion (Faulkner et al., 2017). NIRS has been shown to be both precise and accurate (Ferrai, Mottola, & Quanesima, 2004). NIRS relies on the different absorption properties of haemoglobin in the near-infrared wavelength range from 700 to 1000nm (Obrig et al., 1996). By measuring the returned scattered light at a specific wavelength, the relative absorption of HbO_2 and HHb within the tissue can be determined (Ferrai et al., 2004). Evidence suggests that there is a linear relationship between neural activity and hemodynamics within the brain (Gratton, Goodman-Wood, & Fabiani, 2001). Individual nerve cells produce electrical signals when a specific area of the brain becomes metabolically active. Each of these signals causes an increase in oxygen and glucose consumption, and therefore an increase in cerebral blood flow and cerebral blood volume (Shibasaki, 2008). Research has shown that NIRS produces results consistent with other brain imaging techniques (e.g., electroencephalography and functional magnetic resonance imaging; Strangman, Culver, Thompson & Boas, 2002; Zama & Shimada, 2015), and provides a reliable measure of PFC activation (Shibasaki, 2008).

The current study used a continuous-wave NIRS (cw-NIRS) device (PortaLite, Artinis Medical Systems BV, the Netherlands) which is comprised of a single wireless optode consisting of three light-emitting diodes, positioned 30mm, 35mm, and 40mm from a single receiver. This cw-NIRS device has been shown to be both reliable and valid against the criterion, frequency-domain NIRS (Stone, Fryer, Ryan & Stoner, 2016). The cw-NIRS device employs spatially-resolved spectroscopy in order to determine absolute haemoglobin concentrations. The spatial profile of the intensity of backscattered light is measured as a function of the distance from the light transmitter, with the shape of this function being related to the absorption coefficient, from which absolute haemoglobin concentrations can be calculated (Patterson, Chance & Wilson, 1989; Suzuki, Takasaki, Ozaki & Kobayashi, 1999). As cw-NIRS cannot measure the scattering of light in tissue, a reasonable and constant light scattering coefficient (μs) must be assumed (Jue & Masuda, 2013; Scholkmann et al., 2014). Furthermore, cw-NIRS relies on the modified Lambert-Beer law (Delpy et al., 1988) to obtain values of concentration change between oxygenated and deoxygenated haemoglobin. When the law is applied to biological tissue a differential path-length factor (DPF) is incorporated to account for the increase of the optical pathlength due to the scattering in the tissue.

For the current study, the cw-NIRS device measured PFC perfusion by assessing the emitting and receiving wavelengths at 760 and 850 nm to detect relative changes in concentrations of oxygenated haemoglobin (O_2Hb) and deoxygenated haemoglobin (HHb), which, in combination, make up the variable of interest, total haemoglobin (tHb).The sampling rate was set at 10 Hz, and in accordance with manufacturing guidelines a DPF of 6.0 was used.

This DPF has previously been used to determine tHb in the PFC (Faulkner et al., 2017). NIRS signals were assessed during 15 minutes at rest, and for 60 seconds after the pressure manipulation instructions, which is consistent with the time periods used to calculate reactivity for the cardiovascular markers of challenge and threat (Moore et al., 2014). Thus, we calculated the relative concentration change of tHb by subtracting the level obtained at baseline (last minute) from the minute following the pressure manipulation instructions, when participants were sat quietly reflecting on the upcoming muscular endurance task.

Prior to the assessment, the participants' forehead was cleaned using alcohol wipes, and the cw-NIRS optode was fixed to the skin with bi-adhesive tape and covered with an opaque cloth to prevent signal contamination by ambient light (in accordance with Stone et al., 2016). The optope was placed at Fp1 and Fp2, landmarks of the international EEG 10-20 electrode placement system (Jasper, 1957), which in brief, consists of locating the nasion and inion, measuring the distance between the two sites, then finding 10% up from the nasion. Then, from this 10% location, measure 5% to the left (Fp1) and right (Fp2). The mid-point on the cw-NIRS probes were placed over F1 and Fp2, with the light emitters being closet to the nasion, and the light receiver being furthest away. Fp1 and Fp2 are located within the prefrontal cortex, Fp1 is said to be associated with logical attention (e.g., decision making, task completion), and Fp2 is associated with emotional attention (e.g., sense of self, restraint of impulses; Cerqueira, Osbourne, Almeida, & Sousa, 2008). Both Fp1 and Fp2 are involved in self-regulation and self-control (Friese et al., 2013).

Procedure

First, participants were randomly assigned to either an ego depletion or control group. Participants then completed the trait anxiety and self-control measures. Next, participants completed three 2-second MVC trials using the muscular endurance handgrip dynamometer.

Following this, participants completed trial one of the muscular endurance task, which required participants to hold 40% of their MVC for as long as possible (as Bray, Ginis, Hicks, & Woodgate, 2008). Next, participants were fitted with the Portapres-2 and the NIRS devices. Baseline data was then collected for 15 minutes while participants were in a seated position and quietly resting. Following the recording of baseline data, participants completed the self-control manipulation (or written transcription task). Next, participants received instructions about the upcoming muscular endurance task (trial 2), which were designed to elevate pressure. Specifically, based on the instructions used in previous research (e.g., Moore et al., 2015), participants were informed that top performers would be awarded prizes, while poor performers would be interviewed at length about their poor performance. Participants were also informed that their performance would be published on a leader board, and that video footage of their performance would be taken and may be used in future presentations to their peers. Participants then reflected on these instructions and the upcoming task for one minute while cardiovascular and NIRS data was recorded, before then completing the two items assessing demand and resource evaluations. Finally, both groups completed trial two of the muscular endurance task, again holding 40% of their MVC for as long as possible (as Bray et al., 2008). Finally, participants were thanked and debriefed about the study aims.

Statistical analyses

Unfortunately, due to signal problems, cerebral NIRS data and CV reactivity data was not recorded for two participants, as such these participants were removed from the final analysis. To assess task engagement, a dependent *t* test was conducted on the HR reactivity data to establish that, in the sample as a whole, HR increased significantly from baseline (i.e., HR reactivity greater than zero). Furthermore, to differentiate challenge and threat states, each participant's CO and TPR reactivity scores were converted into z-scores and then summed to create a challenge and threat index (CTI; as Moore et al., 2013). In line with previous research (e.g., Moore et al., 2013), CO was assigned a weight of +1 and TPR a weight of −1, such that a larger CTI value corresponded with a cardiovascular response more akin to a challenge state (i.e., relatively higher CO and/or lower TPR reactivity; Seery, 2013).

To ensure all data was normally distributed, outlier analyses were performed. Consistent with previous research (Moore et al., 2013), data with z-scores greater than two were excluded from further analyses. This resulted in two values being removed for DRES, and four values being removed for CTI. Following this outlier analysis, all data was normally distributed as skewness and kurtosis z-scores did not exceed 1.96. Independent *t*-tests were then performed on the self-control scale and the anxiety scale, as well as self-control manipulation scale, CTI and DRES. A mixed model repeated measures ANOVA with post hoc pre and post *t*-tests was used to assess potential group and time differences in hemodynamic and endurance variables. For all *t*-tests, the degrees of freedom, *t* statistic, and *p*-value were corrected for homogeneity of variance assumption violations using the Levene's test for equality of variances. Effect sizes were calculated using Cohen's *d*, where 0.2, 0.5, and 0.8 represented small, medium, and large effect sizes or Eta squared, where 0.01, 0.06, and 0.14 represented small, medium, and large effect sizes, respectively (Fleiss, 2011).

Results

Trait measures

The results revealed no significant differences between the groups in terms of trait anxiety, and specifically somatic anxiety ($t_{(54)} = -1.31$, $p = .194$, $d = 0.35$), worry ($t_{(56)} = -0.11$, $p = .907$, $d = 0.03$), or concentration disruption ($t_{(53)} = 0.22$, $p = .820$, $d = 0.06$). Furthermore, the results revealed no significant differences between the groups in terms of trait self-control ($t_{(56)} = 0.72$, $p = .475$, $d = -0.18$). The trait self-report data is presented in Table 1.

Table 1. Means and standard deviations (SD) for all trait self-report measures.

		Ego Depletion		Control	
Trait Measures	**Sub-scale**	**Mean**	**SD**	**Mean**	**SD**
Sport Anxiety	Somatic	7.96	2.21	8.86	2.83
	Worry	10.96	4.33	11.10	4.48
	Concentration	6.69	1.91	6.58	1.52
Trait Self-control		41.53	8.80	39.96	7.78

Self-control manipulation checks

Compared to the control group, the ego depletion group transcribed significantly fewer words ($t_{(54)}$ = -7.50, p < .001, d = 2.00), whilst making more errors ($t_{(46)}$ = 6.79, p < .001, d = 1.80), and they reported having to regulate their writing habits more ($t_{(56)}$ = 5.37, p < .001, d = 1.40), and noting that the task required more effort ($t_{(56)}$ = 2.07, p = .042, d = 0.54). In accordance with previous research, our experimental manipulation of self-control strength is seen as successful due to the difference in task difficulty and effort (Bertrams et al., 2010; Englert et al., 2015). The self-control manipulation check data is presented in Table 2.

Table 2. Means and standard deviations (SD) for all self-control manipulation check data.

	Ego Depletion		Control	
Depletion Manipulation Checks	**Mean**	**SD**	**Mean**	**SD**
Number of words	73.92	19.86	110.78***	16.74
Number of errors	10.42	4.12	4.13***	2.69
Regulation of writing habits	3.17	0.72	2.20***	0.66
Effort	66.60	26.07	52.66***	25.04

Note: significantly different from the ego depletion group, $^{***}p$ < .001

Challenge and threat states

The HR reactivity results revealed that in the entire sample, HR did not significantly or meaningfully increase from baseline (M = 74.05 bpm; SD = 8.86) to the 1-minute reflection point (M = 74.92 bpm; SD = 9.29), ($t_{(44)}$ = -0.12, p = .904, d = -0.03). Furthermore, the results revealed no significant differences between the ego depletion and control groups in either DRES ($t_{(53)}$ = 1.29, p = .201, d = 0.35), or CTI ($t_{(44)}$ = 1.15, p = .256, d = 0.34). The challenge and threat data is presented in Table 3.

Muscular endurance performance

For the dependent variable, muscular endurance performance, a two way mixed model repeated measures ANOVA found no significant or meaningful differences for the main effects of group ($F_{(1,48)}$ = 0.04, p = .847, η_p^2 = .001), or time ($F_{(1,48)}$ = 0.54, p = .470, η_p^2 = .01), and the interaction of time*group ($F_{(1,48)}$ = 0.21, p = .648, η_p^2 = .00).

Table 3. Means and standard deviations (SD) for the DRES, CTI, and muscular endurance performance data.

	Ego Depletion		**Control**	
Challenge and threat	**Mean**	**SD**	**Mean**	**SD**
DRES	0.34	0.93	0.00	1.03
CTI	-0.04	0.99	-0.38	0.96
Endurance performance	4.21	92.62	16.35	64.00

Cerebral perfusion

For the dependent variable, THb Fp1, a two way mixed model repeated measures ANOVA found no significant or meaningful differences for the main effects of group ($F_{(1,52)}$ = 0.40, p = .529, η_p^2 = .01), or time ($F_{(1,52)}$ = 0.01, p = .934, $\eta_p^2 < .001$). However, there was a significant interaction of time*group ($F_{(1,52)}$ = 5.02, p = .029, η_p^2 = .09). Post-hoc paired samples *t*-tests found no significant within-group differences pre and post for the groups control ($t_{(26)}$ = -.571, p = 0.085, *d* (repeated measures) = 0.34) and ego ($t_{(26)}$ = 1.454, p = .158, *d* = 0.28).

For the dependent variable, THb Fp2, a two-way mixed model repeated measures ANOVA found no significant or meaningful differences for the main effects of group ($F_{(1,52)}$ = 0.01, p = .906, $\eta_p^2 < .001$), or time ($F_{(1,52)}$ = 0.54, p = .466, η_p^2 = .01). However, there was a significant interaction of time*group ($F_{(1,52)}$ = 4.86, p = .032, η_p^2 = .09). Post-hoc paired samples t-tests found no significant within group differences pre and post for the groups control ($t_{(26)}$ = -1.254, p = 0.221, *d* (repeated measures) = 0.24) and ego ($t_{(26)}$ = 1.814, p = 0.081, *d* (repeated measures) = 0.35).

Table 4. Mean and standard deviation (SD) for the cerebral perfusion data.

		Ego		**Control**	
Cerebral perfusion (µmol)	**Time**	**Mean**	**SD**	**Mean**	**SD**
tHb FP1	Pre	-13.1	15.57	-12.22	17.58
	Post	-15.1	15.69	-11.15	17.06
tHb FP2	Pre	-17.67	21.7	-20.06	23.89
	Post	-19.42	22.47	-18.96	23.45

Discussion

Although limited, previous research has shown that personality traits and situational factors can influence challenge and threat states (Kilby et al., 2018; Moore et al., 2014). Due to small but relatively robust effect of challenge and threat states on the performance of pressurized tasks (Behnke & Kaczmarek, 2018; Hase et al., 2018), more research is needed to identify the factors that influence these states. Thus, this study examined one potential antecedent; reduced self-control, using a novel technique such as NIRS to assess cerebral perfusion. The aim of the current study was to investigate the impact of ego depletion on challenge and threat states and cerebral hemodynamic responses during a pressurised sporting task.

Consistent with previous research (e.g., Englert & Bertrams, 2014; McEwan et al., 2013), the ego depletion group transcribed fewer words and made more errors than the control group. Furthermore, the ego depletion group indicated that the written transcription task that they performed required more effort, and greater regulation of writing habits, than the written transcription task completed by the control group. In accordance with previous research (e.g., Englert & Bertrams, 2012), these results imply a potential reduction in self-control availability for subsequent tasks, thought to be due to greater mental fatigue effort. However, in contrast to previous ego depletion research, this reduction in self-control availability had no effect on the performance of the subsequent pressurized muscular endurance task, which also required self-control. Although this finding is inconsistent with earlier research (Bray et al, 2008), research has shown that performance and the perception of cognitive fatigue has repeatedly failed to correlate (Wolff, Sieber, Bieleke, & Englert, 2019). This may be due to cognitively orientated activities being more multifaceted than physical fatigue and therefore they are more difficult to specify (Burke et al., 2018). Although cognitive fatigue and self-control should not be confused, the validity of performance-based measures of cognitive fatigue within self-control research should be questioned because they may fail to accurately capture fatigued resources (Wolff et al., 2019).

Despite the manipulation checks supporting the effectiveness of the written transcription task in reducing self-control resources, there was no significant difference between the ego depletion and control group in either measure of challenge and threat states. Specifically, ego depletion had no effect on self-reported evaluations of task demands and/or personal coping resources (i.e., DRES). Furthermore, ego-depletion had no significant influence on the central cardiovascular markers of challenge and threat states (i.e., CO and TPR reactivity combined into CTI). As such, it appears that ego depletion had no effect on challenge and threat states. There are two possible explanations for this 1) HR failed to increase significantly from baseline across the entire sample. Within the challenge and threat literature (Blascovich, 2008; Moore et al, 2014) this would suggest that participants might not have been actively engaged in the pressurized muscular endurance task. 2) Self-control has previously been associated with the neuroviceral integration model (Thayer & Lane, 2009), which suggests that an increase in parasympathetic activation occurs (Seery, 2013; Segerstrom & Nes, 2007), whereas challenge and threat has been associated with an increased sympathetic activation (Seery, 2013). Therefore, these opposing systems of nervous control could have counteracted each other and not significantly changed HR from baseline, and thus task-engagement could still have occurred. Interestingly, another factor which suggests that task engagement might have occurred in the current study, irrespective of the HR reactivity data, is the significant interaction of time*group in cerebral perfusion at Fp1 and Fp2. During the one-minute reflection period, there was a significant interaction of time*group in cerebral perfusion at Fp1 and Fp2 suggesting that the two groups, ego and control, reacted differently. Whilst the post-hoc within comparisons were not significantly different from pre to post, there was a small effect size in the both groups. Given that decreases in cerebral perfusion in the PFC have previously been shown to hinder cognitive performance (Hillis et al., 2002), it may be possible that changes in perfusion at FP1 and FP2 in the current study, reflects task engagement. However, this is speculative and further research is needed to confirm this.

With respect to cerebrovascular and central cardiovascular responses to a task, previous research has suggested that there is a top-down prefrontal approach to the way we make resources available (Laborde, Mosley, & Mertgen, 2018). Previously, empirical evidence has suggested that greater engagement of the vagus nerve leads to an increased activation of the parasympathetic system, and facilitates better executive performance (Laborde & Raab, 2013; Laborde, Raab & Kinrade, 2014). Therefore, for executive self-control tasks such as the one in the current study, it may be better to increase the parasympathetic nervous response, and thus cause a reduced energy demand to the periphery, making more resources available for the cerebrovascular system, based on top-down prefrontal approach (Laborde et al., 2018). However, more research is needed in this area to further explore this potential mechanism, particularly given there was no performance decrease in the current study.

In conclusion, there was no significant impact of ego depletion on a muscular endurance performance requiring self-control, or challenge and threat states. However, there was a significant interaction of time*group in cerebral perfusion (tHb), with the ego depletion group showing less perfusion in both Fp1 and Fp2 than the control group. Whilst post hoc analysis suggested no within group differences at Fp1 and Fp2, the small effect size could be attributed to different activation levels in the sympathetic and parasympathetic nervous systems, with activation of the parasympathetic nerve being associated with a top-down prefrontal approach. However, future research using a larger sample size, is needed to confirm this speculation.

References

Allen, M. S., Frings, D., & Hunter, S. (2012). Personality, coping, and challenge and threat states in athletes. *International Journal of Sport and Exercise Psychology*, *10*(4), 264-275.

Baumeister, R. F., & Heatherton, T. F. (1996). Self-regulation failure: An overview. *Psychological inquiry*, *7*(1), 1-15.

Beedie, C. J., & Lane, A. M. (2012). The role of glucose in self-control: Another look at the evidence and an alternative conceptualization. *Personality and Social Psychology Review*, *16*(2), 143-153.

Behnke, M., & Kaczmarek, L. D. (2018). Successful performance and cardiovascular markers of challenge and threat: A meta-analysis. *International Journal of Psychophysiology*, *130*, 73-79.

Bertrams, A., Englert, C., & Dickhäuser, O. (2010). Self-control strength in the relation between trait test anxiety and state anxiety. Journal of Research in Personality, 44(6), 738-741.

Blascovich, J. (2008). Challenge and threat. In A.J. Elliot (Ed.), *Handbook of approach and avoidance motivation* (pp. 431-445). New York; Psychology Press

Botvinick, M., & Braver, T. (2015). Motivation and cognitive control: from behavior to neural mechanism. *Annual review of psychology*, *66*, 83-113.

Bray, S. R., Ginis, K. A., Hicks, A. L., & Woodgate, J. (2008). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology*, *45*(2), 337-343.

Burke, S. E., Samuel, I. B. H., Zhao, Q., Cagle, J., Cohen, R. A., Kluger, B., & Ding, M. (2018). Task-based cognitive fatigability for older adults and validation of mental fatigability subscore of pittsburgh fatigability scale. *Frontiers in aging neuroscience, 10*.

Carter, E.C., Kofler, L.M., Forster, D.E., & McCullough, M.E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General*, *144*, 796-815

Cerqueira, J. J., Almeida, O. F., & Sousa, N. (2008). The stressed prefrontal cortex. Left? Right! *Brain, behavior, and immunity*, *22*(5), 630-638.

Cohen, J. R., & Lieberman, M. D. (2010). The common neural basis of exerting self-control in multiple domains. *Self-control in society, mind, and brain*, *9*, 141-162.

Delpy, D. T., Cope, M., van der Zee, P., Arridge, S. R., Wray, S., & Wyatt, J. S. (1988). Estimation of optical pathlength through tissue from direct time of flight measurement. *Physics in Medicine & Biology*, *33*(12), 1433.

Elkins-Brown, N., Berkman, E., & Inzlicht, M. (2016). The neuroscience of "Ego Depletion": how the brain can help us understand why self-control seems limited. In *Social Neuroscience* (pp. 111-133). Routledge.

Englert, C. (2016). The strength model of self-control in sport and exercise psychology. *Frontiers in psychology*, *7*, 314.

Englert, C., & Bertrams, A. (2012). Anxiety, ego depletion, and sports performance. *Journal of Sport and Exercise Psychology*, *34*, 580-599.

Englert, C., & Bertrams, A. (2014). The effect of ego depletion on sprint start reaction time. *Journal of Sport and Exercise Psychology*, *36*, 506-515.

Englert, C., Bertrams, A., Furley, P., & Oudejans, R. R. (2015). Is ego depletion associated with increased distractibility? Results from a basketball free throw task. *Psychology of sport and exercise*, *18*, 26-31.

Englert, C., Zwemmer, K., Bertrams, A., & Oudejans, R.R. (2015). Ego depletion and attention regulation under pressure: Is a temporary loss of self-control strength indeed related to impaired attention regulation? *Journal of Sport and Exercise Psychology*, *37*, 127-137.

Faulkner, J., Stoner, L., Grigg, R., Fryer, S., Stone, K., & Lambrick, D. (2017). Acute effects of exercise posture on executive function in transient ischemic attack patients. *Psychophysiology*, *54*(8), 1239-1248.

Ferrari, M., Mottola, L., & Quaresima, V. (2004). Principles, techniques, and limitations of near infrared spectroscopy. *Canadian journal of applied physiology*, *29*(4), 463-487.

Fleiss, J. L. (2011). *Design and analysis of clinical experiments* (Vol. 73). New York, NY: John Wiley & Sons.

Friese, M., Binder, J., Luechinger, R., Boesiger, P., & Rasch, B. (2013). Suppressing emotions impairs subsequent stroop performance and reduces prefrontal brain activation. *PloS one*, *8*(4), e60385.

Fryer, S., Stoner, L., Lucero, A., Witter, T., Scarrott, C., Dickson, T., Cole, M., & Draper, N. (2015). Haemodynamic kinetics and intermittent finger flexor performance in rock climbers. *International journal of sports medicine*, *36*(02), 137-142.

Giboin, L., & Wolff, W. (2019). The effect of ego depletion or mental fatigue on subsequent physical endurance performance: a meta-analysis. https://doi.org/10.1016/j.peh.2019.100150

Gratton, G., Goodman-Wood, M. R., & Fabiani, M. (2001). Comparison of neuronal and hemodynamic measures of the brain response to visual stimulation: an optical imaging study. *Human brain mapping*, *13*(1), 13-25.

Hagger, M. S., Chatzisarantis, N. L., Alberts, H., Anggono, C. O., Batailler, C., Birt, A. R., ... & Calvillo, D. P. (2016). A multilab preregistered replication of the ego-depletion effect. *Perspectives on Psychological Science*, *11*(4), 546-573.

Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: a meta-analysis. *Psychological bulletin*, *136*(4), 495.

Hase, A., O'Brien, J., Moore, L.J., & Freeman, P. (2018). The relationship between challenge and threat states and performance: A systematic review. *Sport, Exercise, and Performance Psychology*.

Hillis, A. E., Wityk, R. J., Barker, P. B., Beauchamp, N. J., Gailloud, P., Murphy, K., Cooper, O., & Metter, E. J. (2002). Subcortical aphasia and neglect in acute stroke: the role of cortical hypoperfusion. *Brain*, *125*(5), 1094-1104.

Hirschl, M. M., Woisetschläger, C., Waldenhofer, U., Herkner, H., & Bur, A. (1999). Finapres vs portapres. *Journal of human hypertension*, *13*(12), 899.

Jasper, H. H. (1958). The 10-20 electrode system of the International Federation. *Electroencephalogr Clin Neurophysiol*, *10*, 371-375.

Job, V., Dweck, C. S., & Walton, G. M. (2010). Ego depletion—is it all in your head? Implicit theories about willpower affect self-regulation. *Psychological science, 21*(11), 1686-1693.

Jue, T., & Masuda, K. (Eds.). (2013). *Application of near infrared spectroscopy in biomedicine*. Springer Science & Business Media.

Kilby, C. J., Sherman, K. A., & Wuthrich, V. (2018). Towards understanding interindividual differences in stressor appraisals: A systematic review. *Personality and Individual Differences*, *135*, 92-100.

Laborde, S., & Raab, M. (2013). The tale of hearts and reason: the influence of mood on decision making. *Journal of Sport and Exercise Psychology*, *35*(4), 339-357.

Laborde, S., Mosley, E., & Mertgen, A. (2018). Vagal tank theory: the three rs of cardiac vagal control functioning–resting, reactivity, and recovery. *Frontiers in neuroscience*, *12*.

Laborde, S., Raab, M., & Kinrade, N. P. (2014). Is the ability to keep your mind sharp under pressure reflected in your heart? Evidence for the neurophysiological bases of decision reinvestment. *Biological psychology*, *100*, 34-42.

McEwan, D., Ginis, K. A. M., & Bray, S. R. (2013). The effects of depleted self-control strength on skill-based task performance. *Journal of sport and exercise psychology*, *35*(3), 239-249.

Mendes, W. B., Blascovich, J., Major, B., & Seery, M. (2001). Challenge and threat responses during downward and upward social comparisons. *European Journal of Social Psychology*, *31*(5), 477-497.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual review of neuroscience*, *24*(1), 167-202.

Moore, L. J., Vine, S. J., Wilson, M. R., & Freeman, P. (2012). The effect of challenge and threat states on performance: An examination of potential mechanisms. *Psychophysiology*, *49*(10), 1417-1425.

Moore, L. J., Vine, S. J., Wilson, M. R., & Freeman, P. (2015). Reappraising threat: How to optimize performance under pressure. *Journal of sport and exercise psychology*, *37*(3), 339-343.

Moore, L.J., Vine, S.J., Wilson, M.R., & Freeman, P. (2014). Examining the antecedents of challenge and threat states: The influence of perceived required effort and support availability. *International Journal of Psychophysiology*, *93*, 267-273

Moore, L.J., Wilson, M.R., Vine, S.J., Coussens, A.H., & Freeman, P. (2013). Champ or chump? Challenge and threat states during pressurized competition. *Journal of Sport and Exercise Psychology, 35*, 551-562.

Obrig, H., Hirth, C., Junge-Hulsing, J. G., Doge, C., Wolf, T., Dirnagl, U., & Villringer, A. (1996). Cerebral oxygenation changes in response to motor stimulation. *Journal of applied physiology*, *81*(3), 1174-1183.

Patterson, M. S., Chance, B., & Wilson, B. C. (1989). Time resolved reflectance and transmittance for the non-invasive measurement of tissue optical properties. *Applied optics*, *28*(12), 2331-2336.

Pattyn, N., Van Cutsem, J., Dessy, E., & Mairesse, O. (2018). Bridging Exercise Science, Cognitive Psychology, and Medical Practice: Is “Cognitive Fatigue” a Remake of “The Emperor’s New Clothes”?. *Frontiers in psychology*, *9*.

Scholkmann, F., Kleiser, S., Metz, A. J., Zimmermann, R., Pavia, J. M., Wolf, U., & Wolf, M. (2014). A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *Neuroimage, 85*, 6-27.

Seery, M. D. (2013). The biopsychosocial model of challenge and threat: Using the heart to measure the mind. *Social and Personality Psychology Compass*, *7*(9), 637-653.

Segerstrom, S. C., & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological science*, *18*(3), 275-281.

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: an integrative theory of anterior cingulate cortex function. *Neuron*, *79*(2), 217-240.

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a rational and mechanistic account of mental effort. *Annual review of neuroscience*, *40*, 99-124.

Shibasaki, H. (2008). Human brain mapping: hemodynamic response and electrophysiology. *Clinical Neurophysiology*, *119*(4), 731-743.

Smith, R. E., Smoll, F. L., Cumming, S. P., & Grossbard, J. R. (2006). Measurement of multidimensional sport performance anxiety in children and adults: The Sport Anxiety Scale-2. *Journal of Sport and Exercise Psychology*, *28*(4), 479-501.

Smith, S. M., & Vale, W. W. (2006). The role of the hypothalamic-pituitary-adrenal axis in neuroendocrine responses to stress. *Dialogues in clinical neuroscience*, *8*(4), 383.

Stone, K. J., Fryer, S. M., Ryan, T., & Stoner, L. (2016). The validity and reliability of continuous-wave near-infrared spectroscopy for the assessment of leg blood volume during an orthostatic challenge. *Atherosclerosis*, *251*, 234-239.

Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. *Neuroimage*, *17*(2), 719-731.

Suzuki, S., Takasaki, S., Ozaki, T., & Kobayashi, Y. (1999, July). Tissue oxygenation monitor using NIR spatially resolved spectroscopy. In *Optical Tomography and*

Spectroscopy of Tissue III (Vol. 3597, pp. 582-593). International Society for Optics and Photonics.

Tangney, J. P., Baumeister, R. F., & Boone, A. L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of personality*, *72*(2), 271-324.

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *33*(2), 81-88.

Tomaka, J., Blascovich, J., Kelsey, R.M., & Leitten, C.L. (1993). Subjective, physiological, and behavioral effects of threat and challenge appraisal. *Journal of Personality and Social Psychology*, *65*, 248-260.

Turner, M. J., Jones, M. V., Sheffield, D., & Cross, S. L. (2012). Cardiovascular indices of challenge and threat states predict competitive performance. *International Journal of Psychophysiology*, *86*(1), 48-57.

Westbrook, A., & Braver, T. S. (2015). Cognitive effort: A neuroeconomic approach. *Cognitive, Affective, & Behavioral Neuroscience, 15*(2), 395-415.

Wolff, W., Baumann, L., & Englert, C. (2018). Self-reports from behind the scenes: Questionable research practices and rates of replication in ego depletion research. *PloS one*, *13*(6), e0199554.

Wolff, W., Sieber, V., Bieleke, M., & Englert, C. (2019). Task Duration and Task Order do not Matter: No Effect on Self-Control Performance.

Zama, T., & Shimada, S. (2015). Simultaneous measurement of electroencephalography and near-infrared spectroscopy during voluntary motor preparation. *Scientific reports*, *5*, 16438.

Zanstra, Y. J., Johnston, D. W., & Rasbash, J. (2010). Appraisal predicts hemodynamic reactivity in a naturalistic stressor. *International Journal of Psychophysiology*, *77*(1), 35-42.

Zijlstra, F. R. H., & Van Doorn, L. (1985). *The construction of a scale to measure perceived effort*. University of Technology.