Tyrosine intake and cardiovascular responses in a motivated performance situation

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Abstract

Ingesting the catecholamine precursor tyrosine can prevent decrements in, or improve, cognitive and motor performance in demanding situations. Furthermore, the biopsychosocial model of challenge and threat specifies that adrenal medullary catecholamine release plays a central role in the occurrence of a challenge state, which has been linked to better performance under pressure than a threat state. The present study thus examined whether acute tyrosine intake impacts upon challenge and threat states or influences cognitive and motor performance independently. A double-blind randomised crossover design with 49 participants (33 males; μ_{age} = 22.5 years, *SD* = 5.0) was used. Participants ingested tyrosine or placebo (150mg/kg body mass) 60 minutes before performing the N-Back task and a bean-bag throwing task. Cognitive self-reports and cardiovascular data before each task provided indicators of challenge and threat states. There were no significant differences between tyrosine and placebo on the cognitive and cardiovascular challenge and threat variables. Generalised Estimating Equations analyses found that tyrosine was associated with better performance than placebo on the bean-bag throwing task, but not on the N-Back task. A significant interaction effect showed that challenge and threat states were more positively related to performance in the placebo condition than in the tyrosine condition. This suggests that tyrosine may have attenuated the detrimental effect of a threat state. The present study breaks new ground in relating the impact of a dietary supplement to challenge and threat states and finding that tyrosine may in some cases attenuate the negative effects of a threat state.

Keywords: Biopsychosocial model, challenge and threat, cognitive task, demand-resource evaluations, motor task.

Tyrosine intake and cardiovascular responses in a motivated performance situation

The question of why some individuals excel in important situations whereas others struggle under pressure is of great importance, and due to the widespread occurrence of situations in which active performance is required to attain a self-relevant goal, this topic is of interest to sport, social, organisational, and clinical psychologists alike. The biopsychosocial model (BPSM) of challenge and threat (CAT; Blascovich, 2008) is a key framework for understanding performance variation under pressure across these disciplines. It was extended and applied to the domain of sports by the Theory of Challenge and Threat States in Athletes (TCTSA; Jones, Meijen, McCarthy, & Sheffield, 2009). In many studies, a challenge state has been associated with better performance than a threat state (for a review see Hase, O'Brien, Moore & Freeman, in press). This relationship has led researchers to study putative challenge-promoting interventions such as imagery, stress optimisation, and quiet eye training, and their effects on performance (Jamieson, Crum, Goyer, Marotta, & Akinola, 2018; Moore, Vine, Freeman, & Wilson, 2013; Williams & Cumming, 2012). These interventions typically aim at improving performance by optimising psychological antecedents of CAT states (e.g., self-efficacy, perceived control; Williams & Cumming, 2012), and by helping individuals interpret physiological arousal as more facilitative for performance (Jamieson et al., 2018; Moore et al., 2013). However, these interventions have all taken psychological approaches to manipulating CAT states. The current study therefore examined whether a nutritional intervention that targets a neurotransmitter group specified by the BPSM to be key to the occurrence of CAT states may promote a challenge state and enhance performance. Although some nutrients and supplements (e.g., sugar and caffeine; Grasser et al., 2016; Hartley, Lovallo, & Whitsett, 2004)

exhibited effects on the cardiovascular system akin to those of CAT states, research examining dietary interventions in a CAT context is scarce.

The BPSM describes CAT states as responses that only occur in motivated performance situations, which are goal-relevant, evaluative, potentially stressful, and require sufficient active performance in order for personal growth (Blascovich & Mendes, 2000). CAT states differ in their underlying cognitive evaluations and concomitant physiological responses. A challenge state occurs when perceived personal coping resources outweigh or equal perceived situational demands, whereas a threat state occurs when perceived situational demands outweigh perceived personal coping resources. These demand-resource evaluations are thought to be influenced by several factors, such as self-efficacy, achievement goal orientation, perceived control, danger, uncertainty, novelty, required effort, skills, knowledge, abilities, presence of others, attitudes, and beliefs (Jones et al., 2009; Blascovich, 2008). Physiologically, a challenge state has been hypothesised to involve an increase in sympathetic-adrenomedullary axis function. The sympathetic activation at the myocardium is thought to increase heart rate (HR; the number of heart beats per minute) and stroke volume (the volume of blood ejected by the left ventricle with each heart beat) by acting on β1 receptors at the myocardium, thereby increasing cardiac output (CO; volume of blood ejected by the left ventricle per minute). At the same time, adrenal medullary release of epinephrine is thought to act as a vasodilator by acting on β2 receptors in skeletal muscle beds and bronchi, thereby decreasing total peripheral resistance (TPR; the degree of systemic peripheral vascular constriction; Blascovich, 2008; Blascovich & Mendes, 2000; Brownley, Hurwitz, & Schneiderman, 2000).

In addition to sympathetic-adrenomedullary activation, a threat state is also thought to involve pituitary-adrenocortical axis activation that inhibits the sympathetic-adrenomedullary axis (Blascovich & Mendes, 2000). This leads to relatively small increases in HR, little change or minor decreases in CO, and little change or small increases in TPR during a threat state. The BPSM conceptualises CAT states as opposite ends to a bipolar continuum, meaning that one can be more or less strongly challenged or threatened, but not challenged and threatened at the same time. It also specifies task engagement, which is conceptualised as an increase in HR or ventricular contractility (VC; the contractile state of the left ventricle; operationalised by the BPSM as the inverse of the pre-ejection period), as a prerequisite for CAT states to occur in motivated performance situations. Hence, without task engagement neither a challenge nor a threat state will be experienced (Blascovich, 2008).

Significant relationships between CAT states and performance have been found across diverse contexts. A recent systematic review of 38 studies that conceptualised CAT in a manner consistent with the BPSM found that a challenge state was related to better performance than a threat state in 28 of those studies (Hase et al., in press). This relationship was generally supported regardless of CAT variable (cognitive, physiological, and dichotomous), outcome task (cognitive and behavioural), and research design used (correlational, quasi-experimental, direct experimental, and indirect experimental studies). For example, Turner, Jones, Sheffield, and Cross (2012) found that a physiological challenge state was related to better cognitive and motor task performance than a threat state, using a modified Stroop and a netball shooting task. Interestingly though, the available experimental studies only used psychological manipulations to induce CAT states. For example, some studies manipulated CAT with

instructional sets targeting resource and demand evaluations (e.g., Feinberg & Aiello, 2010; Turner, Jones, Sheffield, Barker, & Coffee, 2014), and others targeted proposed psychological antecedents of CAT states (e.g., perceived required effort; Moore, Vine, Wilson, & Freeman, 2014). The lack of physiological manipulations might be due to pioneering studies that successfully changed cardiovascular reactivity via manipulations of cognitive CAT evaluations, but did not succeed in evoking cognitive CAT evaluations via physiological manipulations, namely cold water immersion and physical exercise (Tomaka, Blascovich, Kibler, & Ernst, 1997). To our knowledge, however, no study has examined the effects of a catecholamine-based intervention on CAT states. The BPSM of CAT specifies the catecholamine epinephrine to be centrally involved in the occurrence of a challenge state via stimulation of the vascular and cardiac epinephrine system (Blascovich & Mendes, 2000). Hence, a catecholamine-based CAT intervention could hold the potential to promote a challenge state and complement previous interventions. A possible catecholamine-based CAT intervention is tyrosine intake.

Tyrosine is a naturally occurring, non-essential amino acid. It is synthesised from phenylalanine and is converted into the dopamine precursor L-3,4-dihydroxyphenylalanine (L-DOPA) by the rate-limiting enzyme tyrosine hydroxylase. Tyrosine, but not its precursor phenylalanine, is able to stimulate catecholamine production in the brain, which has been observed directly and indirectly (for a review, see Fernstrom & Fernstrom, 2007). As tyrosine hydroxylase is usually about 75% saturated (Carlsson & Lindqvist, 1978), there is a modest, but significant potential to increase L-DOPA synthesis by increasing serum tyrosine levels, which should increase when demand is heightened due to greater neuronal activity (Fernstrom & Fernstrom,

2007). In the catecholamine pathway, tyrosine can be converted into L-DOPA, dopamine, and eventually norepinephrine and epinephrine. Importantly, an increase in serum tyrosine can be achieved through dietary supplementation. For example, Strüder et al. (1998) found that an acute dose of 10g of tyrosine significantly increased serum tyrosine levels in trained male cyclists within 45 minutes of ingestion, and tyrosine levels remained significantly elevated for 60 minutes following 150 minutes of cycling. Similarly, Tumilty and colleagues found that 150mg/kg body mass of tyrosine significantly increased serum tyrosine levels within 60 minutes (Tumilty, Davison, Beckmann, & Thatcher, 2014). It should be noted, however, that other amino acids compete with tyrosine for uptake into the brain, and therefore it is advisable to administer tyrosine in a pure form and to restrict protein intake before administration in order to maximise brain tyrosine uptake (Fernstrom & Fernstrom, 2007).

The main mechanism of action by which tyrosine is thought to be effective is its stabilising influence on catecholamine levels in situations of heightened cognitive or physiological demands (e.g., cognitive load, extreme temperature), thereby preventing a performance decline. The importance of catecholamine function for cognitions, emotions, and behaviour has been demonstrated by depletion studies in which tyrosine and phenylalanine were removed from participants' diet to elicit a depletion of brain catecholamine levels. Such a catecholamine depletion led individuals to behave in a less motivated manner (Cawley et al., 2013; McLean, Rubinsztein, Robbins, & Sahakian, 2004; Roiser et al., 2005), experience cognitive impairments (Harmer, McTavish, Clark, Goodwin, & Cowen, 2001), and become more susceptible to the detrimental effects of low light exposure (Cawley et al., 2013). Further, O'Brien and colleagues argued that catecholamine depletion may explain performance decrements in

144 demanding situations, but that this may be mitigated by tyrosine consumption (O'Brien,
145 Mahoney, Tharion, Sils, & Castellani, 2007). Indeed, a recent systematic review found
146 that tyrosine intake protected or improved cognitive and motor performance under
147 demanding conditions, while no beneficial effect was found for endurance exercise
148 performance (Hase, Jung, & aan het Rot, 2015). For example, beneficial effects of
149 tyrosine intake were found on reaction times following heat exposure (Kishore et al.,
150 2013), on working memory performance following cold exposure (Mahoney, Castellani,
151 Kramer, Young, & Lieberman, 2007; Shurtleff, Thomas, Schrot, Kowalski, & Harford,
152 1994), and on working memory performance under cognitive load (Thomas, Lockwood,
153 Singh, & Deuster, 1999).

154 Given the previously presented work showing that 1) catecholamines are
155 involved in CAT states (Blascovich, 2008), 2) a challenge state generally relates to
156 better performance than a threat state (Hase et al., in press), 3) tyrosine intake can
157 increase serum tyrosine and catecholamine levels (Fernstrom & Fernstrom, 2007), and
158 4) research has found tyrosine intake to improve cognitive and motor performance, we
159 concluded that this evidence merits an examination of the impact of tyrosine on CAT
160 states. Thus, the aim of the present study was to examine whether the beneficial effect
161 of tyrosine intake on cognitive and motor performance is associated with a facilitation
162 of a challenge state at physiological and psychological levels. We hypothesised that
163 participants would exhibit relatively greater challenge reactivity (greater CAT index
164 calculated from CO and TPR reactivity from baseline to post-task instructions) after
165 tyrosine ingestion than after ingestion of a placebo (H1). In an exploratory manner, we
166 also examined a potential effect of tyrosine on cognitive CAT evaluations. We also
167 hypothesised that participants would perform better on a cognitive and a motor task

after tyrosine ingestion than after placebo ingestion (H2). Finally, we hypothesised that a challenge state (measured as cardiovascular responses and cognitive evaluations) would be related to better performance than a threat state (H3).

Method

Participants

The sample consisted of 49 students and staff members (33 male, 16 female) at a UK university, who were recruited with convenience sampling in person and through the university e-mail system. Participants were 18 to 46 years old, with a mean of 22.5 years (*SD* = 5.1). Participants' mean height and body mass were 175.0 cm (*SD* = 10.0) and 74.7 kg (*SD* = 13.6), respectively. All participants reported being healthy, right-handed or ambidextrous, and most participants were native English speakers (61%)[1]. A minimum sample size of 41 was determined with a power calculation in G*Power 3.1.9.2., using the N-Back task effect sizes (average d = 1.04) reported in Hase et al.'s (2015) systematic review, because no further effect sizes were found for the effect of tyrosine on motor performance or CAT states. Hence, the calculation used effect size d = 1.04 (f = 0.52), $\alpha = 0.05$, and 90% desired power for a two-group, two-measurement comparison.

Materials

Cardiovascular data. The Portapres Model-2 (Finapres Medical Systems BV, Amsterdam, the Netherlands) was used to record cardiovascular variables: HR, TPR, and CO. Its measurement method is based on the arterial volume-clamp method of Peñáz (1973) and the physiological calibration criteria for the proper unloading of the finger arteries of Wesseling (1996). Further, it uses a height correction unit to

[1] Native language (coded dichotomously for English versus Non-English), was not significantly correlated with performance on either of the two tasks.

compensate for hydrostatic pressure changes due to movement of the hand. It has been used in previous CAT research and allows for continuous data recording (Moore, Young, Freeman, & Sarkar, 2018; Zanstra, Johnston, & Rasbash, 2010). It has been validated against the Finapres and the Oxford method in previous research and was found to be accurate, reliable, and cause no more missing data due to artefacts than the Oxford method (Hirschl, Woisetschläger, Waldenhofer, Herkner, & Bur, 1999; Imholz et al., 1993). Data were converted and downloaded with Beatscope version 1.1a.

Dietary supplements. Consistent with comparable previous studies (e.g., Shurtleff et al., 1994; Tumilty et al., 2014), the protocol used 150 mg / kg body mass of L-tyrosine in powder form (Myprotein.co.uk, Meridian House, Cheshire, UK) for the tyrosine condition and 150 mg / kg body mass of microcrystalline cellulose (Blackburn Distributions Ltd, Nelson, Lancashire, UK) for the placebo condition. Both powders were mixed with 200 ml of 100% pure squeezed orange juice (Tesco Stores Ltd., Welwyn Garden City, Hertfordshire, UK).

Demand-resource evaluations. Demand-resource evaluations were assessed with two items used by previous research (e.g., Vine, Freeman, Moore, Chandra-Ramanan, & Wilson, 2013). The items were: "How demanding do you expect the upcoming task to be?" for demands and "How able are you to cope with the demands of the upcoming task?" for resources. All items were scored on a seven-point Likert scale anchored by *not at all* (1) and *extremely* (7). A cognitive CAT variable was then created from these items by subtracting demands from resources, meaning that possible scores ranged from -6 to 6 and denoted more challenge as values increased.

N-back task. The N-Back task is a test of working memory that has been used in previous tyrosine supplementation research (e.g., Colzato, Jongkees, Sellaro, &

Hommel, 2013). A Qualtrics survey presented a string of 23 letters for five seconds each. Starting at the fourth letter, participants were prompted to indicate (by selecting one of two boxes indicating *yes* or *no*) whether the letter shown on the current screen was the same as the letter shown three earlier (3-back condition). Thus, there were 20 items in total, 10 of them requiring *yes* and 10 of them requiring *no* as the correct answer. The maximum time was five seconds, after which the page automatically advanced if no response had been given. The number of correct answers was used as the performance outcome.

Bean bag throwing task. Bean-bag throwing has been used as a task in previous CAT research (Turner et al., 2014). This task consisted of 20 throws of a bean bag from a distance of 4 m to a 50x50 cm quadratic target on the laboratory floor. The bean bag weighed 80 g and was approximately 6 cm long, 5 cm wide, and 5 cm high. Participants scored one point each time the bean bag came to rest on the target. This scoring method was adopted in order to ensure commensurability with N-Back task scores. The number of points scored was used as the performance outcome.

Procedure

The study was approved by an institutional ethics committee and used a double-blind randomised crossover design. The total duration of each session was 90 minutes. One day before testing, the experimenters sent participants a list of tyrosine- or protein-rich foods to avoid in the 12 hours before testing, instructed participants not to consume any psychoactive substances (including alcohol and caffeine), and asked participants to avoid consuming any food or drinks (except water) in the last three hours before testing. Upon entering the laboratory, participants were given an information sheet and provided informed consent. The information sheet explained the study and highlighted that

rewards would be given to the best three performers on each task. Participants were randomly assigned to receive either tyrosine or the placebo in the first of two testing sessions. Participants were then weighed on a SECA 770 scale (Vogel & Halke, Hamburg, Germany) in order to calculate the appropriate supplement dosage, which was mixed with orange juice by an experimenter who was not involved in the rest of the study. After consuming the drink, participants waited for 60 minutes outside of the laboratory. After that, a second experimenter blind to the supplement condition called participants in to sit in front of a computer, on which a Qualtrics survey was opened to guide them through the study. For the first week, participants were asked to provide demographic information and questions about their food intake on the test day before moving on to the main part of the study. The experimenter then put the Portapres on the left hand of participants, with the cuff around the middle finger and the height correction sensor around the upper arm at the height of the sternum. Participant age, sex, height, and weight were entered to calibrate the Portapres. Participants sat still for the entire duration of the cardiovascular recordings.

The order of the two tasks was randomised on each measurement occasion. Before starting each task, cardiovascular responses were recorded for a baseline of three minutes. Participants then read through the respective task instructions ($M_{\text{Reading time}}$ = 29.00 s, SD = 22.28 s). For each task, the survey reminded participants of the £30, £20, and £10 rewards for the best three performers, and that a quicker task completion time would determine the winner between participants with the same score. Participants then confirmed that they had read and understood the instructions. Participants were then instructed to sit still and think about the upcoming task for one minute. This minute provided the task-specific cardiovascular reactivity to be compared against the last

minute of baseline. Participants subsequently completed the demand-resource evaluation items, before beginning the first task. After participants finished the first task, the procedure was repeated for the second task (baseline, task instructions, one-minute reactivity recording, demand-resource evaluation items, perform task). Approximately six minutes separated the end of the first task from the beginning of the second task. After finishing both tasks, participants were thanked for their time and reminded to return one week later at the same time to repeat the process with the other supplement.

Statistical Analysis

Consistent with previous research using the BPSM of CAT (e.g., Mendes, Blascovich, Hunter, Lickel, & Jost, 2007), mean HR, TPR, and CO values were calculated for the final minute of each baseline and also for the one minute of each reactivity period. Four univariate outliers (values more extreme than three standard deviations from the mean; Stevens, 2009) were winsorised to be 1% more extreme than the next non-outlying score (adapted from Shimizu, Seery, Weisbuch, & Lupien, 2011). The baseline values for CO and TPR were then regressed on their respective reactivity values with the standardised residuals being saved to create residualised change scores in order to adjust for baseline differences (RCS; Burt & Obradovic, 2013). TPR RCS were then multiplied by -1 and summed with the CO RCS to create a single physiological CAT index for each task. To test task engagement, a paired-samples t-test compared mean HR between the baseline and reactivity period.

To test the first hypothesis, paired-samples t-tests compared physiological CAT scores between the experimental conditions on each task. As an exploratory analysis, these tests were repeated for evaluations of cognitive CAT, demands, and resources.

Furthermore, a correlation analysis controlling for condition examined the association between cognitive and physiological CAT scores for each task. To test the hypotheses that CAT states are associated with performance, and that performance would be better on tyrosine than on placebo, two generalised estimating equations (GEE) models were run to analyse the relationship between performance on each task with experimental condition, cognitive CAT, physiological CAT, and the two-way interaction terms of condition with cognitive and physiological CAT[2]. The GEE models were selected because they allow for the test of relationships between a set of independent variables and a dependent variable across different measurements, which is a parsimonious alternative to multiple separate analyses, and also allows for the inclusion of interaction effects between predictors. Significant interaction effects in the GEE analyses were probed by multiple linear regression analyses that determined simple slopes for the relationship between CAT and task performance for the respective task and condition using both CAT variables as predictors.

Results

Two participants failed to attend the second test, leading to a final sample of 47. All final analyses excluded cases that did not indicate physiological engagement with the respective task, which is a premise for the analysis of CAT states within the BPSM (Blascovich, 2008). This lack of task engagement was evidenced by a lack of increase in HR from baseline to post-instructions[3]. For the remaining participants (37 on the N-

[2] In order to control for potential confounders, these analyses were repeated including age, completion time, sex, and task order as predictors. As there were no significant effects for these control variables on either task, they were not included in the main analyses. Ancillary GEE analyses also showed that they were not significantly associated with physiological CAT, although a marginally significant trend (p = 0.07) toward more challenge at older age was observed on the N-Back task.

[3] On the N-Back task, 36 cases (40%) were excluded. On the bean-bag throwing task, 44 cases (49%) were excluded. Since this type of analysis has not been done before, we also report the results of our

Back task and 36 on the bean-bag throwing task), HR increased significantly from baseline to post-instructions [$M_{\text{N-Back}}$ = 5.34, *SD* = 3.63, *t*(53) = 10.81, *p* <.001, *d* = 1.47; $M_{\text{Bean-bag}}$ = 4.79, *SD* = 3.53, *t*(44) = 9.09, *p* <.001, *d* = 1.35]. There were no significant differences between baseline cardiovascular values for the first and second task, indicating that participants returned to their baseline values after performing ($M_{\text{Task1-Task2}}$ = -1.02; *t*(44) = -0.84, *p* = .40).

Comparison of CAT by Experimental Condition and Task

Table 1 presents descriptive statistics for systolic, diastolic, and mean arterial blood pressure; HR; CO; and TPR by task and condition. Table 2 summarises the paired-samples t-test comparing the placebo and tyrosine conditions on physiological CAT. cognitive CAT, demands, and resources for both tasks. There were no significant differences between conditions on the two tasks for any of the variables. Cognitive and physiological CAT were not significantly correlated on the N-Back task (*r* = -.07, *p* = .61) or the bean-bag throwing task (*r* = -.10, *p* = .51).

Task Performance Analysis

N-Back Task. Table 3 summarises the GEE analysis of performance on the N-Back task. There were no significant main or interaction effects.

Bean-bag Throwing Task. Table 4 summarises the GEE analysis of performance on the bean-bag throwing task. There was a significant main effect for condition (*B* = -1.94, Wald χ^2 = 4.03, *p* =.05, 95% CI [-3.82, -0.05]), with superior performance in the tyrosine condition than in the placebo condition. There also was a

analyses using the traditional approach in an online supporting material. The significant condition effect favouring tyrosine over placebo on the bean-bag throwing task, but not the significant condition*physiological CAT interaction effect was replicated in these analyses. Though HR increased significantly on the N-Back task (*M* = 1.80, *t*(89) = 2.48, *p* = .02, *d* = 0.26), it did not significantly increase on the bean-bag throwing task (*M* = 0.47, *t*(88) = 0.57, *p* = .57, *d* = 0.06).

significant interaction effect for condition*physiological CAT (B = 1.15, Wald χ^2 = 5.51, p =.02, 95% CI [0.19, 2.11]), with physiological CAT more positively related to performance in the placebo condition than the tyrosine condition. The additional regression analyses showed that physiological CAT was neither significantly related to performance in the placebo (B = 0.58, t[19] = 1.53, p = .14, sr^2 =.10), nor in the tyrosine condition (B = -0.58, t[20] = -1.76, p = .09, sr^2 = .13). The same was found for cognitive CAT in the placebo (B = 0.35, t[19] = 1.28, p = .22, sr^2 =.07) and in the tyrosine condition (B = 0.05, t[20] = 0.15, p = .88, sr^2 = .00).

Discussion

The present study tested whether tyrosine intake enhances challenge responses (H1) and improves performance relative to placebo on a cognitive and a motor task (H2). It also tested whether challenge responses are related to better performance than threat responses (H3). While the data did not support the first hypothesis, partial support was found for the second hypothesis as tyrosine was related to better performance than placebo on the motor task. Finally, there were no main effects for CAT states on performance, although a significant interaction effect showed that physiological CAT was more positively related to performance in the placebo condition than in the tyrosine condition.

There were no significant differences between conditions on physiological CAT. The loss of participants due to lack of task engagement may have been partially responsible for this, as small effect sizes were observed on both tasks ($d_{\text{N-Back}}$ = 0.18, $d_{\text{Bean-bag}}$ = 0.23; Cohen, 1992). As tyrosine has been found to be most effective in situations with high cognitive load or strong environmental stressors (Hase et al., 2015), it may be that stronger effects would be found in future studies that impose more

cognitive load or stress on participants than the current study did, thereby increasing demand evaluations. This could be done by manipulating determinants of demand evaluations like uncertainty, danger, and required effort (Jones et al., 2009). The BPSM (Blascovich, 2008) provides another potential explanation for the null findings, as it suggests that cognitive evaluations trigger physiological responses, and not vice versa. Specifically, Tomaka et al. (1997) demonstrated that evoking cardiovascular responses consistent with CAT states via exercise (versus rest) and warm (versus cold) water immersion prior to a cognitive task did not alter cognitive evaluations. As such, tyrosine might not influence cognitive evaluations. However, the BPSM acknowledges the dynamic nature of CAT states at a psychological level, for example via reappraisal. Hence, a physiological intervention that produces a noticeable effect on the psychological level might also effectively manipulate perceived coping resources and demands via reappraisal. The lack of association between the two CAT measures across both experimental conditions further complicates the conclusions drawn from the present study and poses a critical finding to the predictions of the BPSM, which posits cognitive and physiological CAT states to be interrelated (Blascovich, 2008).

Tyrosine was associated with superior motor performance. Similarly, O'Brien et al. (2007) found that tyrosine facilitated marksmanship performance, but that effect followed cold water immersion. The current findings are thus unique in highlighting that the beneficial effect of tyrosine on motor performance is not contingent on cold water immersion. The lack of significant differences between tyrosine and placebo on the present cognitive task is inconsistent with previous findings from studies with and without cold exposure (Colzato, Jongkees, Sellaro, & Hommel, 2013; Mahoney, Castellani, Kramer, Young, & Lieberman, 2007; O'Brien et al., 2007). However, only

one of these studies used the N-Back task (Colzato et al., 2013). Although that study found significant differences between tyrosine and placebo on a less demanding condition of the N-Back task (2-Back), it featured a greater number of stimuli, shorter presentation time per stimulus, and shorter stimulus-onset asynchrony. It is unclear whether these differences caused participants to perceive higher demands and feel more pressurised. An alternative explanation could be that the 2-back condition simplified the working memory component of the task enough to let other domains of cognitive function become the deciding factor in determining performance (e.g., sustained attention or response execution rather than working memory). This could serve to explain why different results were found in the past and present studies.

On the motor task, there was a significant interaction effect between condition and physiological CAT. In particular, physiological CAT was more positively related to performance in the placebo condition than in the tyrosine condition. Follow-up analyses revealed that although the regression slope for physiological CAT was in the predicted direction in the placebo condition, this trend was not statistically significant. In the tyrosine condition, the trend was in the opposite direction. This finding is inconsistent with the general predictions of the BPSM (Blascovich, 2008) and the findings of a recent systematic review of the relationship between CAT states and performance (Hase et al., in press). They might in part be explained by the temporal gap between CAT measurement and task performance, allowing for variation in CAT states, although previous research has found a relationship between CAT states and performance with comparable or even longer gaps (e.g., Blascovich, Seery, Mugridge, Norris, & Weisbuch, 2004). Similarly, the relatively large number of trials could also have provoked variation in CAT states throughout task performance, therefore

attenuating the relationship between the initial CAT measurement and performance at the end of the task. The fact that the relationship between physiological CAT and performance in the tyrosine condition was negative (albeit non-significantly so) might appear counterintuitive, but could suggest that tyrosine is particularly beneficial for those individuals experiencing a threat state and less helpful for those in a challenge state, potentially even hampering performance for strongly challenged individuals.

Given the lack of differences between conditions on the CAT variables in the present study, alternative pathways through which tyrosine exerts beneficial effects on performance warrant consideration. Rather than directly influencing CAT states, the current findings suggest that tyrosine may operate independently to improve motor performance. Although this independent mechanism has not been explored yet, a possible candidate could be an effect of tyrosine on dopamine function in the striatum, whose activation has been linked with areas associated with action preparation and execution, such as the postcentral gyrus, precentral gyrus, and supplementary motor area (Molenberghs, Trautwein, Böckler, Singer, & Kanske, 2016). However, future research should examine whether this finding can be replicated and explained in more detail. For example, research could identify whether tyrosine helps threatened individuals to actually adopt a challenge state while performing a task, or whether these individuals remain threatened, but still outperform challenged individuals.

Despite the strengths of the study in exploring the impact of a dietary supplement on CAT states and performance across both a cognitive and motor task, some limitations should be acknowledged. Although participants were encouraged to perform well and financial incentives were offered, task engagement was still low in some participants. Specifically, some participants showed decreases or no change in

HR, failing to meet the BPSM's premise of task engagement (Blascovich, 2008), and were subsequently excluded from the analyses. The lack of verbally delivered instructions and extrinsic motivators such as performance-contingent punishments and social evaluation might be partly responsible for this. Further, the mean increases in HR were rather small, although it should be noted that during the recordings, participants were seated and quietly imagined the upcoming task, which should provoke lesser increases in HR due to being less metabolically demanding than, for example, holding a speech (e.g., Blascovich et al., 2004). The lack of a VC measure also limits the study, as an index based on HR and VC could have been a more robust indicator of task engagement than HR reactivity alone (e.g., Streamer, Seery, Kondrak, Lamarche, & Saltsman, 2017).

Another limitation concerns the generalisability of the findings to well-learned tasks or metabolically demanding tasks (i.e., anaerobic performance; Jones et al., 2009), as both tasks in the present study were novel to the vast majority of participants and did not involve any strenuous physical exercise. A field study in a high-pressure environment (e.g., a professional sports competition) could prevent these limitations by examining expert performance in participants likely to show greater task engagement. A third limitation is the lack of a manipulation check comparing plasma tyrosine and catecholamine levels immediately before supplement ingestion and testing. However, similarly designed studies that used an equal or slightly lower dosage have found that plasma tyrosine increased significantly within 60 minutes of consumption (Strüder et al., 1998; Tumilty et al., 2014), and that tyrosine may increase plasma catecholamines relative to placebo (Kishore et al., 2013).

Future research could measure physiological CAT states throughout task performance in order to explore the dynamic relationship between CAT states and performance and the present finding that tyrosine can benefit individuals in a threat state more than those in a challenge state. More specifically, research could test whether the negative relationship between CAT states and performance on tyrosine will persist during task performance, or whether it promotes a challenge state in threatened participants during task performance, but not during task preparation. Future work could also benefit from increasing the ecological validity of tyrosine supplementation research by looking at CAT variables in the context of sports competitions or university exams. Indeed, the relationship between CAT states and performance has been explored in those contexts, but studies have yet to examine the impact of tyrosine intake on CAT states in those contexts (Blascovich et al., 2004; Seery, Weisbuch, Hetenyi, & Blascovich, 2010). Further, research on CAT manipulations is still limited. With the current exception, research has only manipulated psychological antecedents of CAT states with instructional sets or other psychological techniques (e.g., Feinberg & Aiello, 2010; Moore, Vine, Wilson, & Freeman, 2015). The BPSM of CAT provides other possibilities for physiological CAT interventions that warrant exploration (e.g., decreasing TPR with the nitric oxide precursor L-arginine; Moncada, Palmer, & Higgs, 1991). Ultimately, sports psychologists and other professionals should look to develop a multi-method toolkit containing several interventions that can reliably promote a challenge state or buffer the detrimental effect of a threat state on performance.

Conclusion

The present study was the first to test the effects of tyrosine intake relative to placebo in a BPSM framework. In a financially incentivised competitive setting,

tyrosine was associated with better performance than placebo on a motor task. Tyrosine produced no significant differences on cognitive evaluations and cardiovascular responses. However, cardiovascular responses were negatively related to performance on tyrosine, while a positive trend was found on placebo. The finding that tyrosine improved motor performance holds relevance for individuals requiring fine motor performance, as tyrosine presents an effective and safe supplement to optimise their performance under pressure.

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Table 1

Descriptive Statistics for Cardiovascular Data by Task and Condition

	N-Back Task								Bean-Bag Throwing Task							
	Placebo				Tyrosine				Placebo				Tyrosine			
	BL		RP		BL		RP		BL		RP		BL		RP	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1. HR (bpm)	71.46	12.15	77.97	11.96	70.24	10.42	74.71	10.96	74.92	8.11	80.11	9.94	71.89	11.51	76.30	11.20
2. CO (lpm)	4.80	2.13	5.30	2.28	5.18	1.64	5.35	1.78	5.17	1.40	5.18	1.97	5.21	1.72	5.29	1.89
3. TPR (mmHg.s/ml)	1.30	0.62	1.29	0.88	1.16	0.50	1.13	0.58	1.13	0.49	1.20	0.61	1.12	0.61	1.24	0.80
4. SBP (mmHg)	134.33	37.23	137.67	30.88	129.74	34.28	129.22	36.11	125.40	35.18	126.22	36.18	120.17	26.40	120.76	20.66
5. DBP (mmHg)	72.58	22.02	74.87	20.18	69.52	17.86	68.84	18.27	72.12	19.63	71.95	17.79	68.49	17.14	69.85	15.31
6. MAP (mmHg)	90.28	24.83	91.90	21.80	86.61	20.45	85.48	20.98	88.16	22.75	87.60	21.89	83.88	17.75	85.14	15.73

Note. BL = Last minute of baseline period, DBP = Diastolic blood pressure, MAP = Mean arterial pressure, RP = Reactivity period, SBP = Systolic blood pressure.

Table 2

Descriptive Statistics and Paired-Samples T-Tests for Cognitive CAT, Physiological CAT, Demands, and Resources by Task

	N-Back Task							Bean-Bag Throwing Task						
	Placebo		Tyrosine					Placebo		Tyrosine				
	M	*SD*	*M*	*SD*	*t (df)*	*p*	*d*	*M*	*SD*	*M*	*SD*	*t (df)*	*p*	*d*
1. Cognitive CAT	1.00	2.15	0.70	1.80	1.01 (46)	.32	0.15	1.94	2.29	1.91	1.98	0.06 (46)	.95	0.01
2. Physiological CAT	0.21	2.23	-0.18	1.66	0.74 (16)	.47	0.18	0.34	1.59	0.06	1.78	0.69 (7)	.51	0.23
3. Demands	3.85	1.33	4.04	1.23	-1.01 (46)	.32	0.15	3.11	1.45	3.22	1.35	-0.48 (46)	.64	0.07
4. Resources	4.85	1.29	4.74	1.17	0.54 (46)	.59	0.08	5.05	1.44	5.13	1.27	-0.30 (46)	.77	0.04

Table 3

GEE Parameter Estimates (N-Back Task)

Source	*B*	Wald Chi-Square	Sig.
Condition	0.55	0.77	.38
Cognitive CAT	-0.39	1.39	.24
Physiological CAT	-0.27	0.69	.41
Condition * Cognitive CAT	-0.18	0.24	.63
Condition * Physiological CAT	-0.15	0.10	.76
Intercept	15.72	814.69	.00

Note. Dependent variable: Performance. $N = 37$.

Table 4

GEE Parameter Estimates (Bean-bag Throwing Task)

Source	*B*	Wald Chi-Square	Sig.
Condition	-1.94	4.03	.05
Cognitive CAT	0.05	0.04	.85
Physiological CAT	-0.58	2.23	.14
Condition * Cognitive CAT	0.30	0.68	.41
Condition * Physiological CAT	1.15	5.51	.02
Intercept	8.01	207.89	.00

Note. Dependent variable: Performance. $N = 36$.