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Cognitive effects of acute aerobic exercise: Exploring the influence of exercise duration, exhaustion, task complexity and expectancies in endurance-trained individuals

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ABSTRACT

The cognitive effects of acute aerobic exercise were investigated in endurance-trained individuals. On two occasions, 21 cyclists; 11 male (VO_{2max}: 57 ± 9 $mL \cdot kg^{-1} \cdot min^{-1}$) and 10 female ($VO_{2max}$: 51 ± 9 $mL \cdot kg^{-1} \cdot min^{-1}$), completed 45 min of fixed, moderate-intensity (discontinuous) cycling followed by an incremental ride to exhaustion. Cognitive function was assessed at Baseline, after 15 and 45 min of exercise (15EX and 45EX) and at Exhaustion using a 4-Choice Reaction Time (CRT) test and the Stroop test (Incongruent and Congruent Reaction Time [RT]). A sham capsule was administered on one occasion to determine whether the cognitive response to exercise was robust to the influence of a placebo. CRT, Congruent RT and Incongruent RT decreased (improved) at 15EX, 45EX and Exhaustion compared to Baseline (p's<0.005). While CRT and Congruent RT were faster at 45EX than 15EX (p's<0.020), Incongruent RT was not (p= 1.000). The sham treatment did not affect cognition. When performed at a moderate-intensity, longer duration exercise (up to 45 min) may improve cognition to a greater extent than shorter duration exercise; however, the magnitude of improvement appears to decrease with increasing task complexity. HI/EE performed following a sustained bout of dehydrating activity may not impair cognition.

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Cognition; dehydration; high-intensity exercise; exercise duration; distributional analysis; expectancy effects

1. Introduction

A considerable amount of scientific research has investigated the effect of acute exercise on cognitive performance in healthy adult populations, with several meta-analyses indicating that it is likely to have a small (i.e. Cohen's d = ~0.10–0.25), but significant, positive effect during and up to ~15 min post-exercise (Chang et al., 2012; Etnier et al., 1997; Lambourne & Tomporowski, 2010). However, individual studies have generated mixed results. While a number of contextual factors (e.g., age, sex, training-status/fitness of participants, duration, intensity, mode of exercise, cognitive domain assessed and timing of the assessment) have been proposed to explain this inconsistency (Chang et al., 2012), their precise influence requires clarification. This influence is of particular interest to trained (athletic) populations in whom cognitive responses to exercise are reported to differ (Brisswalter et al., 1997; Labelle et al., 2013; Llorens et al., 2015) and where findings have the potential to inform strategic decisions in sports that are physically and cognitively demanding.

It is generally accepted that moderate-intensity exercise (MIE) (e.g., ~65–75% of maximum heart rate [HR_{max}]) improves cognitive performance (Chang et al., 2012; Lambourne & Tomporowski, 2010; Tomporowski, 2003). However, consensus on the impact of high intensity/exhaustive exercise (HI/EE) is lacking. Unlike MIE, HI/EE has been proposed induce "over-arousal" (i.e. high cortical concentrations of catecholamines) resulting in inhibited cognitive processing (Lambourne & Tomporowski, 2010; McMorris, 2009); a premise supported by studies utilising neuroelectric techniques (Kamijo et al., 2004, 2007). Other physiological disturbances associated with HI/EE (e.g., metabolic acidosis, fatigue) have also indicated cognitive-impairing effects (McMorris et al., 2015). Yet, both positive and negative cognitive responses to HI/EE have been documented (Browne et al., 2017). This inconsistency could be due to differences in the complexity of the cognitive tasks(s) employed. Indeed, a recent review of studies investigating the impact of HI/EE (i.e. >80% peak power output [PPO]) on cognitive performance in trained individuals (VO_{2max} range: ~51–66 $mL \cdot kg^{-1} \cdot min^{-1}$) suggested that "simple" cognitive skills (i.e. information processing tasks, simple reaction time (RT)) were less likely to be impaired than "complex" skills (i.e. attention, executive function, memory). However, few studies have directly investigated this interaction (Browne et al., 2017). In any case, results from these studies should be interpreted with caution as only short duration exercise interventions have been assessed (~5.6 ±3.0 min, range: 1–10 min) (Browne et al., 2017). Longer duration sporting events also often involve episodes of HI/EE (e.g., intermittent "bursts" during team sports, "surges" during or at the conclusion of endurance events) and these "episodes" may elicit contrasting cognitive effects, due to the development of central fatigue, heat stress, dehydration and depleted endogenous carbohydrate (CHO) stores (Cian et al., 2001, 2000; Grego et al., 2005; Williams et al., 2017). Research investigating the effect of HI/EE (performed within or following

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a sustained bout of activity) on simple and complex cognitive functions is therefore required.

Unlike exercise intensity, few studies have directly investigated the effect of exercise duration (i.e. at a fixed intensity) on cognitive performance. As such, our understanding of this factor is largely based on findings from meta-analytic investigations comparing results from different studies that have evaluated cognitive performance following a fixed duration of exercise. Findings suggest that exercise must be >10 min duration to enhance cognition, when testing is conducted shortly (i.e. <15 min) following exercise cessation (Chang et al., 2012). However, because these analyses average effects across studies employing different methodologies, this conclusion may be confounded by other variables. Chang et al. (2015) recently attempted to clarify the effect of exercise duration on cognitive performance, having participants (n= 26 untrained males; VO_{2max}: 42.5 ±6.5 mL·kg^{-1}·min^{-1}) rest (30 min) or complete 10, 20 or 45 min of MIE (~75% HR_{max}; RPE: ~13–15) prior to performing the Stroop Word-Colour Association test ("Stroop"). Results suggested that 20 min of MIE, but not 10 or 45 min, improved cognitive performance compared to rest (i.e. it decreased RT and increased response accuracy to congruent and incongruent stimuli) (Chang et al., 2015). However, this finding contradicts previous studies involving trained individuals that have demonstrated a benefit of longer duration MIE exercise, e.g., 60 min (Irwin et al., 2018; McCartney et al., 2019a), 90 min (Serwah & Marino, 2006) and 180 min (Grego et al., 2005). Hence, the relationship between exercise duration and cognitive performance in trained individuals remains unclear.

It is also important to recognise other factors that may influence results when investigating the effect of acute exercise on cognitive performance. For instance, cognitive function exhibits temporal variation (i.e. fluctuating from one occasion to the next) (Rabbitt et al., 2001; Salthouse & Berish, 2005). Yet, few studies repeat cognitive assessments under standardized conditions to verify the magnitude and direction of exercise-induced changes (Irwin et al., 2018; McCartney et al., 2019a). Some evidence also suggests that cognitive performance is susceptible to expectancy-driven effects (Oken et al., 2008). In fact, it was recently suggested that the cognitive impairment sometimes observed with higher intensity exercise may be a "nocebo effect" (i.e. resulting from a negative expectation) (Oberste et al., 2017). To our knowledge, however, no study has investigated the impact of a positive expectancy on cognitive responses to HI/EE. Finally, consideration for the method of analysing cognitive function data (specifically, RT data) is required. The typical approach of collapsing RT data to derive an overall measure of central tendency (e.g., mean or median result) can lead to false-negative reports and overlook subtle changes in the "shape" of a RT distribution (Heathcote et al., 1991). Yet, higher sensitivity analytical procedures (e.g., ex Gaussian distributional analyses) are rarely employed (Davranche et al., 2006; McCartney et al., 2019a).

The aim of this study was to explore the effect of acute aerobic exercise on cognitive performance in endurance-trained athletes. Specifically, our intent was to examine the impact of different exercise durations (completed at fixed moderate intensity) and a subsequent bout of HI/EE on simple (i.e. RT) and complex (i.e. executive function) cognitive functions. To address previous limitations, two standardised trials were conducted (i.e. to assess reliability), a placebo treatment was administered (i.e. to determine the influence of expectation) and RT data were analysed using global and distributional approaches. We hypothesized that compared to resting conditions: (1) short (i.e. 15 min) and longer (i.e. 45 min) duration moderate-intensity exercise would improve simple and complex cognitive abilities; (2) HI/EE would improve simple cognitive abilities, and; (3) HI/EE would impair complex cognitive abilities, with this effect attenuated by the delivery of a sham treatment suggested to enhance cognitive performance (i.e. positive expectation).

2. Materials and methods

2.1. Participant characteristics

Endurance-trained cyclists/triathletes aged 18–45 y were eligible to participate in this investigation. A sample size calculation (G*Power Version 3.1.9.2, University Kiel Germany, 2014) using a power (1-β) of 0.85, α = 0.05 and a Cohen's d_z effect size of 0.60 (R= 0.80) (based on data from (McCartney et al., 2019a)) indicated that 21 participants would be required to detect a significant effect of MIE on CRT. Twenty-four volunteers were recruited to account for attrition. Two participants withdrew because of unavailability to schedule trials; and a third was lost to follow-up. Thus, 21 participants; 11 male (age: 31.3 ±7.5 y; VO_{2max}: 57.0 ±8.5 mL·kg^{-1}·min^{-1}; PPO: 383 ±26 W) and 10 female (age: 33.5 ±7.4 y; VO_{2max}: 50.9 ±8.5 mL·kg^{-1}·min^{-1}; PPO: 252 ±47 W) completed both experimental trials. This investigation was approved by Griffith University's Human Ethics Committee (ref: 2017/969) and the procedures were conducted in accordance with the Declaration of Helsinki.

2.2. Study design

Participants attended the laboratory on three occasions to complete one preliminary screening and two repeated-measures trials. The median number of days between the initial screening and the first trial, and then between the first and second trials was 9 (interquartile range (IQR): 7–14 d) and 7 (IQR: 5–14 d), respectively. Trials involved 45 min of fixed, moderate intensity (discontinuous) cycling followed by an incremental ride to volitional exhaustion. Cognitive performance and "subjective feelings" (i.e. ability to concentrate, alertness) were assessed at Baseline, after 15 min and 45 min of exercise (15EX and 45EX), and at Exhaustion. Participants received a placebo treatment (i.e. an inert oral capsule) at 15EX on one trial and told that it "*was designed to enhance cognitive (mental) function*". Treatment order was counterbalanced using an incomplete Latin square design.

2.3. Preliminary screening

Volunteers were initially screened for eligibility. Individuals were excluded if their responses to a medical screening questionnaire indicated an active psychiatric disorder, head trauma or other central nervous system injury, or recent (<6 months) use of illicit psychoactive drugs. Participants then completed a graded exercise test on an electronically braked cycle ergometer (Lode Excalibur Sport, Lode BV, Groningen, Netherlands; Medgraphics Ultima, MGC Diagnostics and Medisoft, USA) to determine maximal aerobic capacity (VO_{2max}) and peak sustainable power output (PPO) (Jeukendrup et al., 1997) using previously described protocols for trained males (Campagnolo et al., 2017) and females (McCartney et al., 2019b).

2.4. Pre-experimental procedures

Prior to each trial, participants were instructed to: (1) abstain from alcohol and strenuous exercise (≥24 h); (2) avoid caffeinated products (≥12 h); (3) keep a record of all food and beverages consumed (~24 h); (4) consume a standardized prepackaged evening meal (60 kJ·kg^{-1}) (Campagnolo et al., 2017); (5) fast overnight (~10 h); and, (6) collect a first-morning urine sample and consume ~200 mL of water before arriving at the laboratory. Participants received a copy of their 24 h food record (i.e. after their initial trial) and were instructed to replicate the dietary behaviour prior to the subsequent trial.

2.5. Experimental procedures

Participants verbally acknowledged compliance to the pre-trial procedures on arrival at the laboratory (~5–7 AM) and first-morning urine samples were analysed to determine urine specific gravity (U_{SG}; Palette Digital Refractometer, ATAGO, USA). All samples had U_{SG} values <1.024, suggesting participants were euhydrated on arrival (Armstrong et al., 2010). Euhydrated participants then familiarized themselves with the cognitive tests (~10 min) and voided their bladders completely before measuring nude body mass (BM) (SECA 804 digital scales, ECOMED Trading Pty Ltd) and completing the Baseline cognitive tests and subjective feelings questionnaire (while seated on the cycle ergometer).

Exercise was performed on an electronically braked cycle ergometer (Lode Excalibur Sport; Lode BV, Groningen, Netherlands) in a stable laboratory environment (25 ±1°C, 61 ±6% relative humidity [RH], nil fan/wind). Participants initially cycled for 45 min at a fixed workload. For females, this workload represented 50% PPO (123 ±18 W) and for males, 55% PPO (211 ±13 W). Heart rate (HR) (Ambit3 Peak, Suunto®, Vantaa, Finland) and ratings of perceived exertion (RPE) on the Borg scale (Range: 6–20) (Borg, 1998) were recorded at 15 min intervals. Participants ceased exercise (but remained seated on the ergometer) to complete the 15EX and 45EX cognitive tests and subjective feelings questionnaire; the tasks were administered as soon as exercise ceased via a laptop computer on a height-adjustable table. This approach was employed to ensure performance was not compromised by having participants attempt the cognitive tasks and cycle simultaneously, which would create problems for analysis comparing performance at rest to that under exercise conditions. The incremental test to volitional exhaustion began immediately after the 45EX assessment, commencing at the previous workload and increasing by 1 W every 6 s until volitional exhaustion. Exhaustion was determined when the participant voluntarily ceased exercise or when their pedal cadence dropped below the threshold level (70 and 75 rpm for females and males, respectively) for a third time (after receiving two initial warnings). Individuals did not receive any feedback on elapsed time or encouragement while exercising to exhaustion; instead, a financial incentive was offered for best average performance (i.e. W·kg^{-1}) across trials to encourage engagement and sustained effort. Immediately upon cessation of exercise, participants completed the Exhaustion cognitive tests and subjective feelings questionnaire. Time to exhaustion (TTE), PPO and the maximum HR attained were also recorded. After exercise, individuals towel dried themselves thoroughly before measuring nude BM. The change in BM was calculated and used to estimate sweat loss (Armstrong, 2005). Fluid consumption was not permitted during exercise.

2.5.1. Placebo intervention

Participants received a sham treatment on one of the trials. The treatment was administered at 15EX (after cognitive performance and subjective feelings had been assessed) so that test-retest reliability could first be measured under both resting (i.e. baseline) and exercise conditions. The intervention consisted of two capsules filled with soluble fibre (psyllium husk). Participants were told that the intervention was "*an 'over-the-counter supplement', designed to enhance cognitive (mental) function*", and that "*although studies had demonstrated it was effective under resting conditions, no studies had tested its effects under exercise conditions*" (i.e. partial-positive information). They were also told that the formulation would "*take effect in just over 30 min*", in preparation for the "Exhaustion" assessment. No other information on factors that could influence cognitive function (e.g., dehydration, exercise) was provided.

2.5.2. Cognitive testing and subjective feelings

Participants completed two discrete, computerized (Inquisit 4 Lab; Millisecond software, LLC, Seattle, Washington) cognitive tests (each approximately two minutes in duration), at Baseline, 15EX, 45EX and Exhaustion. The tests were selected to measure performance changes across different cognitive domains (e.g., information processing, executive function). Participants were instructed to respond to all stimuli as "*quickly and as accurately as possible*". HR was recorded at the onset and conclusion of each test and used to estimate average HR throughout.

For the choice reaction time (CRT) test (administered first), four black boxes programmed to turn red at random intervals (400–2000 ms) were displayed on a white background. Participants were instructed to press the keyboard key corresponding to the box that turned red (positioned directly below the stimulus) as quickly as possible. The proportion of correct responses (CRT Accuracy), Median CRT and the ex-Gaussian distribution parameters: (1) μ, the mean, (2) σ, the standard deviation (SD) of the Gaussian (normal) component (i.e. fastest reaction times) and, (3) τ, the mean and SD of the exponential component (i.e. the degree of positive skew) (Whelan, 2008) were determined for each set of 40 stimuli.

For the Stroop test, colour words (red, green, blue and black) written in one of these colours (randomly allocated) were displayed on the screen. Participants were instructed to indicate the colour of the word (not the meaning) by pressing the corresponding keyboard key as quickly as possible. The test involved 56 stimuli, randomly sampled as Congruent (i.e. same colour as word) and Incongruent (i.e. different colour from word) trials. An inter-stimulus interval of 200 ms and error feedback of 400 ms was applied. The proportion of correct responses (Congruent and Incongruent Accuracy), Median Congruent and Incongruent reaction times (RTs) and the ex-Gaussian distribution parameters were determined for each set of stimuli.

The subjective feelings questionnaire involved answering the questions "How alert do you feel?" and "how well can you concentrate?" using 100 mm visual analogue scales (VAS) where 0 represented "*not at all*" and 100 represented "*extremely*" using a computerized modifiable software programme (Adaptive Visual Analogue Scales; Marsh-Richard et al. (2009)).

2.6. Study completion procedures

At the conclusion of the second trial, participants indicated whether or not they thought various factors (e.g., exercise, dehydration) could influence cognitive function (yes/no), what they believed the "supplement" was (open-ended), and if they thought the supplement improved their cognition (6-point Likert scale, 1 = "Definitely" to 6 = "Definitely Not", including an "Unsure" category).

2.7. Statistical analysis

Analyses were conducted using SPSS Statistics, Version 25.0 (IBM Corp. 2017, Armonk, N.Y., USA). All measures were tested for normality (Shapiro-Wilk test, p's>0.05) and sphericity (Mauchly's test). Where assumptions of sphericity were violated, the Greenhouse-Geisser statistic was applied. Pre-experimental conditions (BM and U_{SG}), BM loss, performance on the cycling test (PPO and TTE) and maximum HR attained (as a percentage of age-predicted maximum [HR_{max}]) were compared across trials using Treatment × Sex split-plot analyses of variance (ANOVA). Treatment × Time × Sex split-plot ANOVAs were used to test the remaining variables. Pairwise comparisons (Bonferroni) were conducted where significant main effects were detected. Post hoc comparisons on interaction effects were performed using paired and independent t tests (for within and between-subject analyses, respectively); the alpha level was adjusted (i.e. p= 0.05 divided by the number of tests performed) to account for multiple comparisons. As the placebo treatment was "time dependent" (i.e. only capable of influencing mood and/or cognitive function at 45EX and Exhaution), an interaction including both Treatment and Time as factors was required to indicate a significant placebo effect (for this reason, tests for main effects of Treatment were not conducted). Effect sizes (ESs) were calculated as η_p^2 and Hedges' g (Hedges, 1981) using the spreadsheet by Lakens (2013). Prior to analysing the cognitive performance data, all incorrect responses (CRT: n= 139; Stroop: n= 290); correct-responses with RT <200 ms (CRT: n= 0; Stroop: n= 0); correct CRT responses >1000 ms (n= 16); and correct Stroop responses >3000 ms (n= 16) were removed (Whelan, 2008). This resulted in the elimination of ~2.9% of the total data. Ex-Gaussian parameters were obtained using the quartile maximum likelihood estimation procedure in QMPE 2.18 (Cousineau et al., 2004); all fits converged within 70 iterations. Intra-class correlation coefficients (ICCs) were calculated to determine the reliability of CRT/Stroop performance at Baseline and 15EX across trials using the two-way mixed average measures (absolute agreement) model. The co-efficient of variation (CV) was also calculated using the mean and SD. Statistical significance was accepted as p<0.05. All data are reported as Mean±SD.

3. Results

3.1. Standardisation procedures

Pre-exercise values for BM and U_{SG} differed significantly by Sex (Table 1); however, no main effects of Treatment or Treatment × Sex interactions were observed (p's>0.05). Temperature (25 ±1°C), t(20) = 1.45, p= 0.162; and RH (61 ±6%), t(20) = 0.615, p= 0.545; were similar across trials.

3.2. Sub-maximal and maximal intensity exercise

All participants successfully completed the same 45 min exercise protocol at both trials. A main effect of Time was identified for HR, $F_{[1.2,23.0]}$ = 58.1, p<0.001, η_p^2 = 0.75; and RPE, $F_{[1.2,22.2]}$ = 34.9, p<0.001, η_p^2 = 0.65; HR also indicated a main effect of Sex, $F_{[1,19]}$ = 4.38, p= 0.050, η_p^2 = 0.19. Pairwise comparisons revealed that HR and RPE increased between 15 min (M: 76 ±6% HR_{max}; F: 71 ±6% HR_{max}; RPE: 12 ±1) and 30 min (M: 80 ±7% HR_{max}; F: 74 ±7% HR_{max}; RPE: 13 ±1) of exercise, and 30 and 45 min (M: 83 ±7% HR_{max}; F: 75 ±7% HR_{max}; RPE: 14 ±1) of exercise (p's<0.001). These RPE values correspond to "*somewhat hard*" or "*hard (heavy)*" exercise (Borg, 1998). No other differences were detected (p's>0.05). The incremental cycling test to volitional exhaustion began immediately after the 45EX

Table 1. Pre-trial and exercise conditions (n= 21).

	Male Participants		Female Participants		Treatment Effect			Sex Effect		
	No Treatment	Placebo	No Treatment	Placebo	$F_{[1,19]}$	p-value	η_p^2	$F_{[1,19]}$	p-value	η_p^2
Pre-Exercise U_{SG}	1.018 ± 0.006	1.016 ± 0.005	1.014 ± 0.004	1.012 ± 0.003	3.53	0.076	0.16	5.11	0.036	0.21
Pre-Exercise BM (kg)	79.40 ± 7.40	79.28 ± 7.73	59.94 ± 6.53	60.06 ± 6.42	0.001	0.981	<0.01	39.4	<0.001	0.68
BM Loss (%)	2.30 ± 0.30	2.27 ± 0.36	1.69 ± 0.35	1.63 ± 0.43	0.617	0.442	0.03	18.9	<0.001	0.50
PPO (W)	323 ± 42	322 ± 42	240 ± 36	244 ± 45	0.034	0.856	<0.01	21.5	<0.001	0.53
PPO ($W{\cdot}kg^{-1}$)	4.1 ± 0.5	4.1 ± 0.6	4.0 ± 0.4	4.0 ± 0.5	0.017	0.897	<0.01	0.100	0.756	0.01
TTE (sec)	684 ± 228	675 ± 225	671 ± 86	704 ± 147	0.177	0.679	0.01	0.011	0.917	0.03
Max. HR (%HR_{max})	93 ± 5	95 ± 6	92 ± 7	93 ± 9	2.96	0.101	0.14	0.129	0.733	0.01

BM: Body mass; max. Max. HR: Maximum heart rate attained; PPO: Peak power output; TTE: Time to exhaustion; U_{SG}: Urine specific gravity. Values are Mean ± SD. No significant Treatment × Sex interactions (p's>0.05).

cognitive assessment; descriptive data from this test are summarized in Table 1. Overall, this stage lasted an average of ~11.4 ±2.8 min, with participants achieving a maximum HR of ~93 ±7% HR_{max}, irrespective of Treatment and Sex. On average, males and females lost 2.3 ±0.3 and 1.7 ±0.3% of their BM and had a PPO of 323 ±40 W (4.1 ±0.6 W·kg^{-1}) and 242 ±40 W (4.0 ±0.4 W·kg^{-1}), respectively; these parameters did not differ by Treatment or indicate a Treatment × Sex interaction.

3.3. Cognitive performance and mood

3.3.1. Heart rate during cognitive testing

Participants' average HRs differed significantly by Time during the CRT, $F_{[3,57]} = 402$, $p<0.001$, $\eta_p^2 = 0.96$; and Stroop, $F_{[2.2,42.4]} = 215$, $p<0.001$, $\eta_p^2 = 0.92$; tests, and indicated a significant Time × Sex interaction; $F_{[3,57]} = 6.20$, $p= 0.001$, $\eta_p^2 = 0.25$; $F_{[3,57]} = 5.21$, $p= 0.003$, $\eta_p^2 = 0.22$, respectively. Post hoc comparisons applying an adjusted alpha-level ($p= 0.006$) revealed participants completed each CRT and Stroop test at a different HR (p's<0.001). While average HR did not differ (p's>0.006) by Sex at Baseline (37 ±5% HR_{max}) or Exhaustion (78 ±5% HR_{max}) during CRT testing, or at any stage of Stroop testing (Baseline: 37 ±5% HR_{max}; 15EX: 51 ±5% HR_{max}; 45EX: 58 ±6% HR_{max}; Exhaustion: 63 ±5% HR_{max}), males performed the 15EX (65 ±6 vs. 58 ±4% HR_{max}, $p= 0.006$) and 45EX (74 ±6 vs. 65 ±6% HR_{max}, $p= 0.004$) CRT tests at a higher percentage of their HR_{max} than females. No other significant effects were detected in these analyses (p's>0.05).

3.3.2. Performance reliability

CRT, Congruent RT and Incongruent RT indicated moderate–good reliability (Koo & Li, 2016), with ICCs of 0.79, 0.82 and 0.74, respectively (p's<0.001) calculated across trials at Baseline; and 0.88, 0.74 and 0.70, respectively (p's<0.001) calculated at 15EX. The degree of variability (CV) in CRT, Congruent RT and Incongruent RT across trials was determined as 3.8%, 7.6% and 11.2% at Baseline; and 2.8%, 8.3% and 8.4% at 15EX, respectively.

3.3.3. Global CRT and Stroop performance

Median CRT, Congruent RT and Incongruent RT are displayed in Table 2; Hedges' g effect sizes are summarised in Figure 1. CRT, Congruent RT and Incongruent RT differed significantly by Time. Pairwise comparisons revealed that CRT, Congruent RT and Incongruent RT all decreased (i.e. improved) at 15EX, 45EX and Exhaustion compared to Baseline (p's<0.005). While CRT and Congruent RT were faster at 45EX (p's<0.020) and Exhaustion (p's<0.030) compared to 15EX; Incongruent RT did

Table 2. The effect of exercise and the placebo treatment on Global RT and the parameters of the ex-Gaussian RT distribution ($n= 21$).

	No Treatment				Placebo Treatment				Time Effect		
	Baseline	15EX	45EX	Exhaustion	Baseline	15EX	45EX	Exhaustion	F-ratio	p-value	η_p^2
Global RT (ms)											
CRT [a, b]	435 ± 43	420 ± 44	405 ± 45	406 ± 47	442 ± 44	428 ± 39	410 ± 50	412 ± 47	$F_{[3,57]} = 17.9$	<0.001	0.49
Congruent [a, b]	638 ± 144	601 ± 141	572 ± 116	547 ± 93	627 ± 130	587 ± 99	564 ± 95	555 ± 88	$F_{[2.1,40.3]} = 31.1$	<0.001	0.62
Incongruent [a]	722 ± 225	666 ± 181	645 ± 195	629 ± 221	743 ± 218	647 ± 139	635 ± 124	634 ± 140	$F_{[3,57]} = 13.3$	<0.001	0.51
μ-parameter (ms)											
CRT [a, b]	405 ± 47	385 ± 38	371 ± 43	366 ± 44	406 ± 41	398 ± 42	380 ± 40	382 ± 47	$F_{[3,57]} = 15.9$	<0.001	0.46
Congruent [c]	562 ± 95	543 ± 142	505 ± 82	500 ± 79	568 ± 124	528 ± 91	495 ± 75	501 ± 85	$F_{[3,57]} = 14.1$	<0.001	0.43
Incongruent [c]	603 ± 196	569 ± 132	571 ± 182	529 ± 187	639 ± 224	574 ± 116	530 ± 119	559 ± 131	$F_{[3,57]} = 5.91$	0.001	0.24
σ-parameter (ms)											
CRT	31 ± 23	28 ± 18	29 ± 20	25 ± 17	36 ± 16	32 ± 22	28 ± 15	33 ± 21	$F_{[3,57]} = 0.513$	0.675	0.03
Congruent	76 ± 52	89 ± 64	45 ± 29	69 ± 40	87 ± 85	66 ± 42	70 ± 40	84 ± 56	$F_{[2.1,40.2]} = 2.44$	0.097	0.11
Incongruent	76 ± 73	84 ± 54	95 ± 84	73 ± 69	112 ± 105	92 ± 77	72 ± 63	85 ± 72	$F_{[3,57]} = 0.367$	0.777	0.02
τ-parameter (ms)											
CRT	37 ± 36	43 ± 32	46 ± 27	53 ± 35	43 ± 37	40 ± 30	38 ± 26	38 ± 28	$F_{[3,57]} = 0.380$	0.768	0.02
Congruent	104 ± 120	70 ± 79	97 ± 93	63 ± 78	74 ± 57	76 ± 67	81 ± 82	67 ± 60	$F_{[3,57]} = 1.58$	0.205	0.08
Incongruent	157 ± 103	141 ± 130	87 ± 126	126 ± 83	129 ± 123	96 ± 98	149 ± 107	104 ± 82	$F_{[3,57]} = 1.09$	0.360	0.05

Values are Mean ± SD. *a*, Baseline significantly different from 15EX, 45EX and Exhaustion; *b*, 15EX significantly different from 45EX and Exhaustion; *c*, Baseline significantly different from 45EX and Exhaustion. No significant main effects of Sex or interaction effects including Time as a factor (p's>0.05).

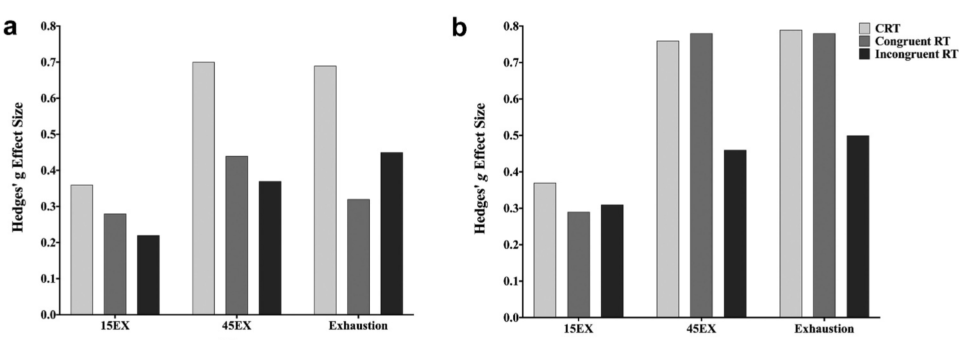

Figure 1. The magnitude (Hedges' g effect) of the performance improvement between Baseline and all other time points (15EX, 45EX and Exhaustion) on the CRT and Stroop tests for (A) global RT; and (B) the μ-component of ex-Gaussian RT distribution (pooled data).

not differ between 15EX, 45EX and Exhaustion (p's>0.05). No other differences were observed in these analyses (p's>0.05). Analysis of CRT and Stroop Accuracy failed to identify any significant effects (p's>0.05); participants demonstrated a high degree of accuracy in response to CRT (97 ±1%), Congruent (97 ±2%) and Incongruent (97 ±2%) stimuli at all stages of cognitive testing.

3.3.4. Ex-Gaussian modelling of CRT and Stroop performance

Components of the CRT, Congruent RT and Incongruent RT distributions are reported in Table 2; Hedges' g effect sizes are summarised in Figure 1. The μ-component of CRT, Congruent RT and Incongruent RT distributions differed significantly across Time. Pairwise comparisons identified a reduction in the μ-component of CRT at 15EX (p= 0.047), 45EX (p<0.001) and Exhaustion (p<0.001), compared to Baseline; μ was also reduced at 45EX (p= 0.041) and Exhaustion (p= 0.004), compared to 15EX. On the Stroop test, the μ-component of Congruent and Incongruent RT was reduced at 45EX (p's<0.020) and Exhaustion (p's<0.005), compared Baseline; but did not differ between Baseline and 15EX (p's>0.05); or across 15EX, 45EX and Exhaustion (p's>0.05). No other differences were observed (p's>0.05). Analysis of the σ- and τ- parameters failed to indicate any significant effects (p's>0.05).

3.3.5. Subjective feelings

Participants' alertness, $F_{[1.7,32.6]} = 5.02$, $p= 0.016$, $\eta_p^2 = 0.21$; and concentration, $F_{[2.1,40.9]} = 5.07$, $p= 0.009$, $\eta_p^2 = 0.21$; ratings differed significantly by Time. On average, individuals reported feeling more alert at 15EX (71 ±15 mm, p= 0.001) and 45EX (71 ±15 mm, p= 0.018) than at Baseline (60 ±15 mm); and better able to concentrate at 15EX (69 ±13 mm, p= 0.036) and 45EX (67 ±19 mm, p= 0.032), than at Exhaustion (57 ±22 mm). No other significant differences were observed in these analyses (p's>0.05).

3.4. Participant expectations

The majority of participants believed acute exercise could enhance (81% "Yes"), and that dehydration could impair (81% "Yes"), cognitive performance. Most individuals (n= 12) stated they were "unsure" what the supplement contained; others guessed it was caffeine (n= 3), sodium (n= 2), CoQ10 (n= 1), citicoline (n= 1), or a placebo (n= 2). Participants generally indicated that the supplement "Probably" (n= 7) or "Possibly" (n= 7) improved their cognitive performance; few believed that it "Probably Did Not" or "or Definitely Did Not" improve their performance (n= 3); the remainder (n = 4) were "unsure" if they were affected by the supplement.

4. Discussion

This study explored the effect of acute exercise on cognitive performance in endurance-trained athletes. Specifically, it investigated the impact of different exercise durations (completed at a fixed moderate intensity) and a subsequent bout of HI/EE on simple and complex cognitive functions. Overall, results indicate: (1) a greater benefit of 45 min than 15 min MIE on lower-order cognitive abilities (i.e. CRT, Congruent RT) with no clear effect of exercise duration on higher-order cognitive abilities (i.e. Incongruent RT); and (2) a positive effect of HI/EE (performed following a sustained bout of dehydrating activity) on both lower- and higher-order cognitive abilities.

This study identified a small but significant improvement (i.e. from Baseline) in CRT (Hedges' g= 0.36), Congruent RT (g= 0.28) and Incongruent RT (g= 0.22) after 15 min MIE (74 ±6% HR_{max}; RPE: 13 ±1). After 45 min MIE (79 ±8% HR_{max}; RPE: 14 ±2), these improvements (i.e. from Baseline) were still apparent, however, the magnitude of effect differed for each of the variables assessed. Specifically, while Congruent RT (g= 0.44; small effect) and CRT (g= 0.70; moderate effect) were significantly faster at 45EX than 15EX, Incongruent RT (g= 0.37) did not differ significantly across time. The Ex-Gaussian distributional analyses did not reveal any additional (masked) effects and the percentage of correct responses to reaction stimuli was unchanged throughout trials. Collectively, these findings suggest a positive relationship between exercise duration and lower-order cognitive functions (i.e. CRT and, to a lesser extent, Congruent RT), and no effect of exercise duration (beyond 15 min) on higher-order cognitive functions (i.e. Incongruent RT). Stated differently, it appears that the relationship between exercise duration and cognitive performance differs as a function of task complexity, or the amount of executive control required in responding to stimuli (Kramer et al., 1994; Kramer & Jacobson, 1991). Of course, longer exercise durations (i.e. >45 min) may elicit different cognitive effects (Cian et al., 2001, 2000; Grego et al., 2005; Williams et al., 2017). It is also important to acknowledge that although the initial 45 min bout of submaximal cycling exercise was intended to be of a moderate intensity (~65–75%HR_{max}), the task elicited average HRs of between 76–83% HR_{max} within the male subgroup, indicating that some individuals were exercising above a moderate intensity (particularly during the latter stages of the ride).

In contrast to the current findings, Chang et al. (2015) recently proposed a generalized curvilinear relationship between exercise duration and cognitive performance after demonstrating that 20 min of MIE (~75% HR_{max}; RPE: ~13–15), but not 10 or 45 min, improved all aspects of performance on the Stroop task (i.e. decreased RT and increased response accuracy to Congruent and Incongruent stimuli). Given that this study was conducted in untrained individuals (VO_{2max}: 42.5 ±6.5 $mL·kg^{-1}·min^{-1}$), differences in training-status/fitness may partly explain the inconsistency (Brisswalter et al., 1997; Labelle et al., 2013; Llorens et al., 2015). Indeed, earlier investigations involving endurance-trained participants and longer exercise interventions (i.e. >45 min) have reported cognitive improvements consistent with the current study (Irwin et al., 2018; McCartney et al., 2019a). However, other methodological differences also exist. For instance, Chang et al. (2015) randomized the administration of the different exercise durations (i.e. thereby controlling for trial order effects); but also utilized a longer cognitive testing protocol (i.e. 6 × ~3 min blocks) that concluded ~35 min post-exercise, discarded correct Stroop responses >1000 ms, and did not appear to standardise pre-trial conditions (e.g., time of day, diet, exercise, caffeine/alcohol use, hydration state). Given the paucity of data and inconsistent findings, further research examining the relationship between exercise duration and cognitive performance is required.

Participants in the current study repeated Baseline and 15EX cognitive assessments during two standardised trials (i.e. where time of day, diet and exercise, caffeine/alcohol use and hydration state were controlled) to evaluate the reproducibility of the cognitive performance measures. In general, CRT indicated "good" reliability and consistency across trials at Baseline and 15EX (i.e. ICCs>0.75; CVs≤3.8%); while "moderate" reliability was observed for Congruent and Incongruent RT. These data are in agreement with previous reports, e.g., Irwin et al. (2018) CRT (CV = 5.0%); McCartney et al. (2019a) CRT (CV = 4.1%; ICC = 0.96); Hedge et al. (2018) (Stroop RT ICC = ~0.65). Clearly, it is imperative that studies of this nature employ reliable neuropsychological tests, under controlled conditions. Tests with low reliability may lack the necessary sensitivity to detect small, but potentially meaningful, cognitive changes (Hedge et al., 2018; Pontifex et al., 2019).

In line with our hypothesis, the current study identified a moderate (g= 0.69) improvement in CRT at volitional exhaustion (93 ±7% HR_{max}). While research investigating the impact of high intensity exercise on CRT in trained individuals is limited (Browne et al., 2017), these results concur with previous reports indicating an improvement in CRT during ~6 min cycling at 80% PPO (Guizani et al., 2006) and ~3 min cycling at a "severe" intensity (Draper et al., 2010). The current study also detected a small improvement in Congruent (g= 0.32) and Incongruent (g= 0.45) RT at volitional exhaustion. In contrast, we hypothesized that HI/EE would impair executive function. Indeed, studies investigating the effect of high intensity exercise on executive function in trained individuals typically report negligible or negative effects (Browne et al., 2017). For instance, Smith et al. (2016) observed a decrement in Go/No Go performance (i.e. speed, omission errors and decision errors) during ~4 min of running at 90% HR reserve; Whyte et al. (2015) identified a reduction in Stroop accuracy following ~6 min of intermittent running and jumping at an RPE≥18; and Labelle et al. (2013) found no change in Stroop RT or accuracy during ~6.5 min of cycling at 80% PPO. While one study did observe a significant improvement in overall Stroop RT following a ride to exhaustion at 90% VO2max, the participants cycled for an average of 62.8 ±11.1 min, suggesting that unlike the studies described above (which had much shorter duration), the task was predominantly aerobic (i.e. performed below lactate threshold) (Pollow et al., 2016). Considering the evidence, one might have even anticipated a more pronounced negative effect in the present study given the added duration of the exercise intervention (i.e. ~55 min) and large fluid losses incurred (M: – 2.3 ±0.3% BM; F: – 1.7 ±0.3% BM); although some evidence does suggest that the cognitive-enhancing effect of acute exercise is sufficient to offset any adverse effects imposed by dehydration (Irwin et al., 2018; McCartney et al., 2019a). Our unexpected result could relate to the time (i.e. relative to the completion of exercise) at which cognitive testing occurred. While it was our intention to evaluate executive function at "exhaustion", there was a short delay (i.e. ~2 min) between the cessation of exercise and the administration of the Stroop task during which participants completed the CRT task. In this time, arousal could have decreased to a level that facilitated cognitive performance (Chang et al., 2012). Hence, further research is required to clarify the cognitive effects of HI/EE. Future studies could consider using longer exercise durations and frequent episodes of high intensity exercise to better simulate the demands of sporting events. Additionally, as some (albeit limited) evidence suggests that the cognitive enhancing effect of acute exercise may be attenuated during cognitively demanding sporting activities (i.e. where a greater proportion of neural resources are required to regulate exercise behaviour (Kamijo & Abe, 2019)), it is worthwhile noting that cycling undertaken in an urban environment, along a complex route (e.g., down-hill mountain biking), or in a race event could potentially elicit different responses than stationary cycling in a laboratory.

The administration of a "placebo treatment" (i.e. positive expectancy) did not affect cognitive responses to HI/EE in the current study. Given that HI/EE had an unexpected effect to enhance executive function, and the purpose of the placebo was to counteract cognitive impairment, this result is not surprising. Future studies should consider utilising untrained participants, who may be less capable of maintaining cognitive function during HI/EE than endurance-trained cyclists/triathletes (Brisswalter et al., 1997; Labelle et al., 2013; Llorens et al., 2015), and administering a stronger expectation (e.g., positive rather than partial-positive information) to determine whether cognitive impairment sometimes observed following HI/EE is related to a negative expectation (i.e. "nocebo effect") (Oberste et al., 2017).

The ex-Gaussian distributional analyses performed in the present study localised the exercise-induced improvements in CRT to the μ-component of the RT curve. To the authors' knowledge, only two studies have previously characterized the effect of acute exercise on a RT distribution (Davranche et al., 2006; McCartney et al., 2019a) and these also identified reductions in μ with no significant effects on σ or τ. Some of the observed improvements in Congruent RT and Incongruent RT were also localized to the μ-component of the RT curve. However, others could not be localized (i.e. neither σ, τ nor μ were significantly altered, despite a change in global RT performance), suggesting that they might have resulted from an accumulation of small, non-significant changes in two or more parameters. Nonetheless, the observed changes in μ suggest that acute aerobic exercise improves overall response speed, without affecting the variability or accuracy of participants' RT responses (i.e. the spread and the skew of the RT distribution) (Whelan, 2008).

Overall, the results of the present study suggest that, in well-trained individuals, acute MIE improves lower-order cognitive abilities (i.e. CRT, Congruent RT), with the magnitude of improvement increasing with increasing exercise duration (i.e. 45 min > 15 min > Baseline). While MIE also appears to improve higher-order cognitive abilities (i.e. Incongruent RT), the magnitude of this improvement does not appear to be influenced by exercise duration. Furthermore, a bout of HI/EE (following a period of sustained MIE) does not appear to impair cognitive function, even in the presence of considerable fluid losses (~2% BM loss).

Disclosure statement

The authors have no potential conflicts of interest to report.

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