



Cognitive demand of eccentric versus concentric cycling and its effects on post-exercise attention and vigilance

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Received: 7 November 2018 / Accepted: 22 April 2019 / Published online: 25 April 2019
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Abstract

Purpose This study tested the hypotheses that eccentric cycling (ECC) would be more cognitively demanding than concentric cycling (CONC), and attention and vigilance would improve more after ECC than CONC.

Methods Thirty young adults performed CONC and two bouts of ECC (ECC1 and ECC2) for 20 min at a similar workload (227.5 ± 51.5 W) with 1-week apart. Cognitive load during exercise was assessed by the average error from the target torque over 1200 (60 rpm \times 20 min) revolutions, choice reaction time (CRT), the NASA-task load index (NASA-TLX), and prefrontal cortex oxygenation and deoxygenation (HHb) by near-infrared spectroscopy. Attention and vigilance were assessed by a sustained attention to response task (SART) before, immediately, and at every 15 min for 60 min after exercise or sitting (control).

Results Heart rate was lower during ECC1 (115.5 ± 20.3 bpm) and ECC2 (116.7 ± 21.0 bpm) than CONC (156.9 ± 19.4 bpm). The torque error was greater for ECC1 ($26.1 \pm 9.0\%$) and ECC2 ($19.4 \pm 9.0\%$) than CONC ($10.8 \pm 3.7\%$). CRT (CONC: 602.8 ± 69.0 , ECC1: 711.1 ± 113.0 , ECC2: 693.6 ± 122.6 ms) and mental demand in NASA-TLX (46.8 ± 25.8 , 80.0 ± 15.3 , 60.3 ± 17.6) were greater for ECC1 and ECC2 than CONC. Decreases in HHb were greater for ECC1 (-0.41 ± 0.37 μ M) and ECC2 (-0.40 ± 0.40 μ M) than CONC (0.10 ± 0.40 μ M) and control (-0.21 ± 0.28 μ M). Attention and vigilance decreased 2–8% after 20-min sitting, but improved 2–10% immediately after ECC2, and did not decline from the baseline for 30 min after ECC1 or 60 min after CONC and ECC2.

Conclusion Cognitive load was greater during ECC than CONC, but post-exercise attention and vigilance changes were not largely different between ECC and CONC.

Keywords Choice reaction time · NASA-task load index · Sustained attention to response task · Correct detection · False alarms

Introduction

Acute effects of physical activity and/or exercise on cognitive function have been reported in many studies over the last decade. There are several review articles on this topic (e.g., Tomporowski 2003; Brisswalter et al. 2002; Chang

et al. 2012; Ludyga et al. 2016), and the majority of them conclude that aerobic exercise for more than 20 min at a moderate intensity temporarily improves both low-level cognitive functions such as simple reactions, and higher level functions such as memory, processing speed, attention, and executive function. While many of the studies that found acute improvement in cognition after exercise used cycling, it is worth noting that cycling is generally deemed to be lower in cognitive demand in comparison to walking or running (Lambourne and Tomporowski 2010; Schmidt-Kassow et al. 2014). For example, Lambourne and Tomporowski (2010) reported that walking and running had more negative impacts on dual-task performance as compared to cycling.

It is possible that the cognitive demand associated with exercise can play a crucial role in changes in cognitive ability after intervention. Some studies have reported a

Communicated by Toshio Moritani.

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greater improvement in cognition after engaging in more mentally demanding exercise tasks over extended periods of time (e.g., 12 weeks) when compared with less mentally demanding exercise (Anderson-Hanley et al. 2012; Budde et al. 2008; Lennemann et al. 2013). For example, Lennemann et al. (2013) showed that 6-week agility training significantly improved memory and sustained vigilance by ~11% and ~2%, respectively, while no improvement was seen after 6 weeks of running. Likewise, Walker et al. (2011) reported similar benefits of 6-week agility training on selective attention, when compared to running. Anderson-Hanley et al. (2012) found a 29% greater increase in executive function for a virtual reality cycling exercise (exergames) group in comparison to a traditional cycling group. They attributed the greater increase in the exergaming group to the additional cognitive demand induced by the challenging environment. Although training effects of cognitively demanding exercises on cognition function have been reported, little is known about its acute effects on cognition. Budde et al. (2008) found a 5% increase in attention and concentration after 10-min moderate intensity exercises requiring left/right hand/foot coordination, but this was not found after non-coordinative exercise. It seems possible that a cognitively demanding exercise task acutely improves attention and vigilance more than an exercise task requiring less cognitive demand, but this has yet to be investigated.

In eccentric cycling, pedals are rotated backward by a motor, and knee extensor muscles resist against the backward rotations to meet a target torque output (Peñailillo et al. 2013). Peñailillo et al. (2013) reported that when comparing concentric and eccentric cycling for the same work output, oxygen consumption was ~50% lower in eccentric than concentric cycling, and heart rate and perceived exertion were ~20–30% lower during the eccentric than concentric cycling. Practice is required to perform eccentric cycling smoothly, since providing resistance (eccentric contraction) against the backward rotation of the pedals at the right phase with adequate level of intensity requires much coordination and skill (Nosaka et al. 2017). Because of this, it appears that eccentric cycling is more cognitively demanding than concentric cycling, but no previous study has compared cognitive demand between eccentric and concentric cycling. Peñailillo et al. (2013) showed that heart rate during a second bout of eccentric cycling performed 2 weeks after the first bout was 10% lower, and the movements were more coordinated during the second bout. This suggests that the first eccentric cycling bout provided some learning effect on the second bout, and thus, it is possible that cognitive demand is lower during the second than the first eccentric cycling bout, but this has never been investigated and quantified.

Therefore, the present study tested the hypothesis that cognitive demand would be greater during an acute bout of

eccentric than concentric cycling, and this would be more for the first than the second eccentric cycling bout. The present study also tested the hypothesis that attention and vigilance would acutely improve more after eccentric than concentric cycling, and also more after the first than the second bout of eccentric cycling.

Methods

Participants

Thirty healthy young adults including nine women (mean \pm SD age, height and weight: 25.6 ± 4.9 years, 174.6 ± 8.4 cm, 74.8 ± 12.7 kg), participated in the present study. The sample size was based on the effect size shown in the previous studies (Davranche and McMorris 2009; Lambourne and Tomporowski 2010) for the effect of acute exercise on cognition ($d=0.2$). With an α level of 0.05 and a β level of 0.8 using G*Power 3.1 (Faul et al. 2007), the sample size estimation showed that at least 28 participants were required. All participants signed an informed consent form and were required to complete a medical questionnaire which was used to screen for neuromuscular disorders, musculoskeletal disorders or injuries of the lower limbs, and the presence of other medical conditions that are known to affect attention and exercise performance (e.g., chronic fatigue syndrome). Participants were tested for color blindness in disability with red–green colors using an online interactive test (<http://colorvisiontesting.com/ishihara.htm>), as red and green colors were used for one of the cognitive tests. The participants were instructed to refrain from any strenuous exercises for 2–3 days prior to each exercise session. This study was approved by the Human Research Ethics Committee of Edith Cowan University, and was conducted in conformity with the Declaration of Helsinki.

Study design

The present study consisted of one familiarization and four experimental sessions including one control and three exercise sessions (Fig. 1). Each of the four experimental sessions was conducted 1 week apart in the order of the control session followed by one concentric (CONC) and two eccentric cycling (ECC1 and ECC2) sessions. Considering the uniqueness of eccentric cycling, and to compare the first and second bouts of eccentric cycling for their effects on cognition, the order was not randomized. As shown in Fig. 1, during each experimental session, participants performed cognitive tests before, during, and 0, 15, 30, 45, and 60 min after 20 min of rest (control) or 20-min cycling exercise. The duration of the cycling exercise (20 min) was chosen based on the previous studies showing acute changes in some aspects of cognition

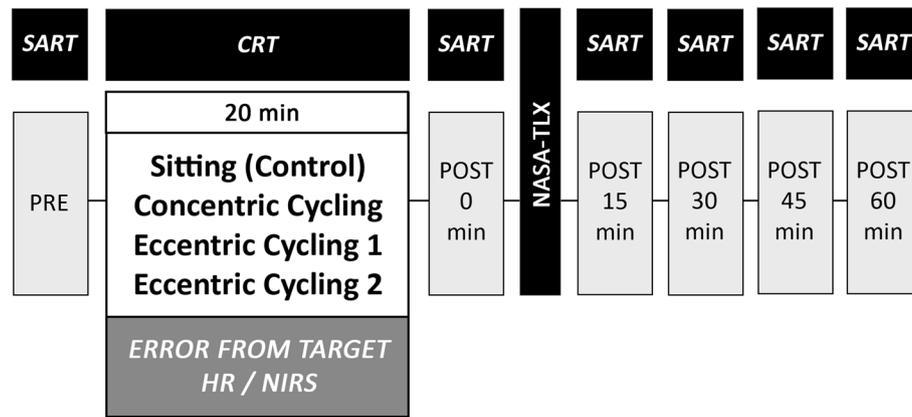


Fig. 1 Study design. Participants performed the sustained attention to response test (SART) before, 0, 15, 30, 45, and 60 min after 20 min of sitting (control) or 20 min of concentric (CONC) or eccentric (ECC) cycling exercise. Physical demand of the 20 min of rest or cycling exercise was monitored by heart rate (HR). Cognitive demand during exercise was assessed by error from the target torque,

such as executive function, memory, and processing speed after aerobic exercise for this duration (Sibley et al. 2006; Hogan et al. 2013).

Familiarization session

Participants were familiarized with the two different computerized cognitive tests used to assess attention and vigilance, and dual-tasking ability. Each of these cognitive tests (as detailed below) was performed twice during the familiarization session to make the participants familiar with the tests. They were also familiarized with producing maximal concentric cycling torque by rotating the pedals maximally for ten revolutions, which was required for determining the intensity of both concentric and eccentric cycling. They performed concentric and eccentric cycling exercise for 5 min each at a low-intensity (approximately 10–15% of peak concentric torque), on a recumbent cycle ergometer (Strength Ergo 240, Mitsubishi Electric Engineering Corp, Nagoya, Japan). To minimize learning effect on cycling especially for the eccentric cycling, the exercise duration was limited to 5 min. Although coordination was not perfect in the familiarization session, the participants clearly understood how to perform eccentric cycling.

Experimental sessions

Control condition

The participants remained seated on the recumbent cycle ergometer and rested for 20 min in an upright position with both feet placed on a floor. They performed computerized cognitive measurements as described below before,

near-infrared spectroscopy (NIRS), and the choice reaction time test (CRT). The perception of physical and cognitive load during the rest/exercise was assessed using the NASA-task load index test (NASA-TLX) upon completion of the SART performed immediately after exercise

immediately, and every 15 min (up to 1 h) after the 20 min of sitting.

Concentric and eccentric cycling sessions

Prior to the 20 min of cycling exercise, participants were required to maximally perform ten revolutions of concentric cycling to assess their peak torque generated by each leg at a fixed cadence (60 revolutions per minute: rpm). Peak torque was determined by averaging the maximal concentric torque produced by the left and right legs. The target torque for both concentric and eccentric cycling sessions was set at 20% of the concentric peak torque. This target was based on a pilot study which showed that participants were able to complete both concentric and eccentric cycling for 20 min while performing a cognitive function test described below during the exercise. As participants were given instantaneous feedback of generated torque for each revolution, they were instructed to match the peak pedaling torque to the target torque as closely as possible. Heart rate (HR) was recorded throughout the 20-min sitting or cycling by a heart rate monitor (Polar, A3, Finland). Based on the HR of each minute, the average HR over the 20 min was calculated for each participant, and the average value of each condition was obtained.

The magnitude of the error was based on the actual torque generated in each revolution against the target torque over ~1200 revolutions. The error per revolution was calculated by the following formula; error per revolution (%) = [(actual torque – target torque)/target torque] × 100. The average error over ~1200 revolutions during CONC, ECC1, and ECC2 of each participant was calculated, and the average error of each cycling exercise was obtained.

Assessment of cognitive load during rest and exercise

Choice reaction time (CRT)

A CRT computerized test was used to assess dual-tasking (DT) ability, which has been shown to reflect cognitive load (Brünken et al. 2002; Zimmermann et al. 1992). The previous studies have suggested that instantaneous cognitive load of a primary task can be measured by performance on a secondary task (Xie and Salvendy 2000; Brünken et al. 2002; Zimmermann et al. 1992). The CRT was programmed using stimulus acquisition software SuperLab (Version 5.0, Cedrus Corporation, San Pedro, California) that displayed the programmed test stimuli and captured participants' responses. Participants were instructed to respond as quickly and accurately as possible to the stimuli presented on a computer screen placed next to the main screen that displayed the pedaling torque, by pressing any of the keys located either on the left side or the right side of a small wireless keyboard that each participant held. The participants were instructed to press any of the character keys located on the left side for red and the right side for green, corresponding to the color that was displayed on the screen. The test was programmed to randomly display either a green or red stimulus on the screen once every 20–30 s, and a total of 36 stimuli were presented over the 20-min duration. It included 36 stimuli as this was considered to be the optimum number that participants could complete without acting as too much of a distraction from the exercise over the 20-min duration. Reaction time (RT) and accuracy of the responses to the 36 stimuli during the 20-min control or exercise session were captured by the software. RT was expressed as the average time (ms) of the responses to the 36 stimuli. Accuracy was indicated by the number of correct responses expressed as a percentage (%) of the 36 stimuli.

NASA-task load index (NASA-TLX)

The perception of cognitive load during the exercise was assessed immediately after each cycling session by the computerized NASA-TLX (Cao et al. 2009; Hart and Staveland 1988). The NASA-TLX has been shown to be a valid indicator of both physical and mental demand (Hart and Staveland 1988). The validity and reliability of the NASA-TLX were confirmed by several studies (Smit et al. 2005; Tomporowski and Ganio 2006), and NASA-TLX was reported to be a valid tool to assess mental workload even in a multitasking scenario (DiDomenico and Nussbaum 2011). This assessment consisted of six dimensions; mental demand, physical demand, temporal demand, frustration, effort, and performance. A 20-step bipolar scale of 100 was used to quantify for each of the six dimensions. Overall score was determined

by the average of the total score of the six dimensions (Cao et al. 2009).

Near-infrared spectroscopy (NIRS)

Using an NIRO-200 oximeter (Hamamatsu Photonics K.K., Hamamatsu, Japan), changes in prefrontal cortex oxygenation (HbO₂) and deoxygenation (HHb) before and during exercise were assessed. A probe unit had two silicon photodiodes as photodetectors on one side and three laser emitting diodes (775, 810, and 850 nm) on the other, separated by a distance of 4 cm enclosed by a rubber shall. The probe unit was attached firmly over the skin of the forehead region in accordance to Fp 1 and Fp 2 of the 10–20 International EEG system, respectively, using a double-sided adhesive tape and covered by a black elastic band to block out any external light. After initialization, the zero-set procedure was applied to reset HbO₂ and HHb values to an arbitrary zero value. The oximeter sampling rate was set at 6 Hz and the data were collected using data acquisition software (Powerlab 16/30; Ad Instruments, Bella Vista, Australia). The data were grouped into 15-s blocks over 20 min to reduce undesired noise (Rinnan et al. 2009). Changes in HbO₂ and HHb (Δ HbO₂ and Δ HHb) from the baseline of zero over 20 min were expressed as $\Delta\mu$ M, which was obtained by including an age-dependent constant differential path length factor ($5.13 + 0.07 \times \text{age}^{0.81}$) (Duncan et al. 1995). The average Δ HbO₂ and Δ HHb for each session was derived by the average of all the 15-s blocks throughout the 20-min duration of either rest or each exercise session, taken from the left and right forehead. An increase in Δ HbO₂ with a decrease in Δ HHb have been reported to be indicative of an increasing cognitive load imposed by a task (Kikukawa et al. 2008).

Assessment of attention and vigilance before and after sitting or exercise

Attention and vigilance were assessed by a 3-min sustained attention to response task (SART) that quantifies the ability to sustain attention with an element of inhibitory/suppression response (Robertson et al. 1997). This test was designed to be a brief, reliable and valid measure for sustained attention and vigilance, and has been reported to have good test–retest reliability ($r=0.76$) over time (Robertson et al. 1997), and to be ecologically valid (Smilek et al. 2010). SART was performed, while each participant was seated comfortably on a chair before, immediately after, and 15, 30, 45, and 60 min after sitting (control) or cycling (CONC, ECC1, and ECC2). The SART was programmed by the stimulus acquisition software Superlab (Version 5.0, San Pedro, California: Cedrus Corporation) to display test stimuli, and capture participants' responses. In the 3-min SART, a total of 120 stimuli that were made up of single numerical digits

between 1 and 9 were displayed for 500 ms each, with an inter-stimulus interval (letter “X”) displayed after each number for 1150 ms. The numbers and inter-stimulus X were presented in a size 48 Arial black font on the center of the screen with a white background. Participants were required to respond quickly and accurately to every number displayed on the screen except for when a predetermined number (the number “4”) was displayed. Reaction time (RT) as well as accuracy of response to each presented stimulus was assessed and recorded throughout the duration of the 3-min test. RT for each time point was based on the average response time across the 120 stimuli, which included 24 stimuli requiring an inhibitory response.

Attention and vigilance scores included correct detections and false alarms indicating participant’s inhibitory and suppression responses. The correct detections represent correct responses to both reaction (correct commission to a response) and suppression/inhibitory task (correct omission of a response). False alarms reflect the inability to react to the stimulus by correctly omitting a response or having responded incorrectly by commissioning a response (Helton et al. 2005; Robertson et al. 1997). Thus, correct detections were defined as the correct key responses (either rightly withholding or responding) to target stimuli, while false alarms were the incorrect responses. The scores of both correct detections and false alarms scores were expressed as a percentage of the total number of presented commission and omission stimuli, respectively (Helton et al. 2005).

Statistical analysis

The normality of the data was assessed by a Kolmogorov–Smirnov normality test. The average heart rate, error from the target torque, choice reaction time and accuracy, NASA-TLX scores, and the average change in the NIRS parameters during the 20-min sitting or cycling were compared between the conditions (control, CONC, ECC1 and ECC2, or CONC, ECC1 and ECC2) by a one-way analysis of variance (ANOVA). The baseline values of SART variables (reaction time, correct detection, and false alarms), and the magnitude of change in the values from baseline to immediately after the sitting or cycling for 20 min, were compared among the four conditions using a one-way ANOVA. A two-way repeated-measures ANOVA was used to compare among the four conditions (control, CONC, ECC1, and ECC2) for changes in the SART variables before, immediately after, and 15, 30, 45, and 60 min after the 20-min sitting or 20-min cycling. This was also performed for the changes from before to immediately after the 20-min sitting/cycling, since the largest difference between the conditions was evident at this time point. If the ANOVA indicated a significant effect, a least significant difference (LSD) post hoc test was performed. The significance level was set at

$p < 0.05$. All results presented as mean \pm SD. Effect size for the change in SART accuracy and false alarms from before to immediately after the 20-min sitting or cycling was calculated using Hedges g (Hedges et al. 1985).

Results

During rest or exercise

Heart rate (HR)

The average HR during the exercise was significantly different among CONC, ECC1, and ECC2 ($F_{(2, 87)} = 40.761$, $p < 0.001$). The post hoc test revealed that the HR was 27% lower ($p = 0.001$) during ECC1 (115.5 ± 20.3 bpm) and ECC2 (116.7 ± 21.0 bpm) when compared with CONC (156.9 ± 19.4 bpm) without a significant difference ($p = 0.809$) between ECC1 and ECC2.

Error from the target torque

The target torque was similar between exercise sessions (CONC: 36.6 ± 7.7 Nm; ECC1: 37.1 ± 7.8 Nm; and ECC2: 38.3 ± 8.1 Nm). The percentage error from the target torque was significantly different among the three exercise sessions ($F_{(2, 87)} = 30.81$, $p < 0.001$), as shown in Fig. 2. The post hoc test revealed that the magnitude of the error was greater ($p < 0.001$) during ECC1 ($26.1 \pm 9.0\%$) and ECC2 ($19.4 \pm 9.0\%$) as compared to CONC ($10.8 \pm 3.2\%$), with a significant difference between ECC1 and ECC2 ($p < 0.001$).

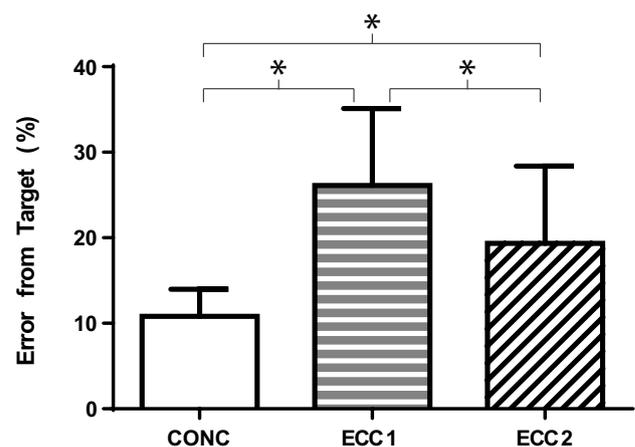


Fig. 2 Average (\pm SD, $n=30$) error from the target torque (%) over ~1200 revolutions during 20 min of concentric (CONC) and the first (ECC1) and second bout of 20-min eccentric cycling (ECC2). *Significantly ($p < 0.01$) different between sessions

Crt

The average reaction time during the CRT was significantly different among control, CONC, ECC1, and ECC2 sessions ($F_{(3, 116)}=21.04$, $p<0.001$), and the post hoc test revealed that the reaction time was slower ($p<0.001$) during the cycling sessions (CONC, ECC1, and ECC2) than the control session (537.0 ± 119.2 ms), as shown in Fig. 3A. The reaction time during ECC1 (711.1 ± 111.1 ms) and ECC2 (693.6 ± 120.4 ms) was ~15% slower ($p<0.001$) than CONC (602.8 ± 79.6 ms), without a significant difference ($p=0.486$) between ECC1 and ECC2 sessions.

Similarly, the accuracy score of the CRT was significantly different among control, CONC, ECC1, and ECC2 sessions ($F_{(3, 116)}=11.35$, $p<0.001$), and the post hoc test showed that the accuracy score was lower ($p<0.001$) during the exercise (CONC: $87.6\pm 8.1\%$, ECC1: $80.3\pm 13.7\%$, ECC2: $81.6\pm 14.3\%$) when compared to the control session ($95.0\pm 4.5\%$). The score was significantly lower for ECC1 ($p=0.011$) and ECC2 ($p=0.035$) than CONC, without a significant difference ($p=0.654$) between ECC1 and ECC2 (Fig. 3b).

NASA-TLX

Some of the NASA-TLX results are shown in Table 1. There was a significant difference in overall perception between the exercise sessions ($F_{(2, 87)}=22.60$, $p<0.001$), and the post hoc test revealed that ECC1 was scored higher ($p<0.001$) than CONC and ECC2, without a significant difference between CONC and ECC2 ($p=0.289$). The ratings for physical demand were also significantly different between the exercise sessions ($F_{(2, 87)}=4.49$, $p=0.014$), and the post hoc test showed that ratings were significantly lower during ECC1 ($p=0.009$) and ECC2 ($p=0.014$) than CONC, without a significant difference ($p=0.874$) between ECC1 and ECC2. Similarly, ratings for mental

Table 1 NASA-task load index (0–100) for overall, physical demand (PD), mental demand (MD), and frustration (FR) ratings (mean \pm SD, $n=31$) after 20 min of concentric cycling (CONC) and the first (ECC1) and second (ECC2) bout of eccentric cycling sessions

	CONC	ECC1	ECC2
Overall	43.6 \pm 9.8	61.3 \pm 10.2*	46.6 \pm 13.0
PD	58.8 \pm 24.4	44.3 \pm 21.5*	45.2 \pm 17.8*
MD	46.8 \pm 25.8	80.0 \pm 15.3*	60.3 \pm 17.6*#
FR	37.1 \pm 20.7	72.1 \pm 15.1*	51.6 \pm 25.3*#

*Significantly different ($p<0.05$) from the value of CONC. #Significantly different ($p<0.05$) from the value of ECC1

demand were significantly different between the exercise sessions ($F_{(2, 87)}=21.57$, $p<0.001$), and it was also higher ($p<0.001$) for ECC1 and ECC2 than CONC, with a significant ($p<0.001$) difference between ECC1 and ECC2. A significant difference was evident for the frustration score too ($F_{(2, 87)}=22.11$, $p<0.001$), and ECC1 showed a higher score ($p<0.001$) when compared to both with ECC2 and CONC sessions that were not significantly different ($p=0.062$).

Near-infrared spectroscopy parameters

The average ΔHbO_2 was significantly different between sessions ($F_{(3, 116)}=37.89$, $p<0.001$), and the post hoc test revealed that it was higher ($p<0.01$) for ECC1 (2.33 ± 1.13 μM), ECC2 (2.06 ± 1.02 μM), and CONC (2.99 ± 1.19 μM) when compared to the control (0.38 ± 0.40 μM). The values were significantly lower for both ECC1 ($p=0.012$) and ECC2 ($p<0.001$) than CONC without a significant difference ($p=0.284$) between ECC1 and ECC2 (Fig. 4A).

Similarly, the average ΔHHb was different between the sessions ($F_{(3, 116)}=12.44$, $p<0.001$), and it was shown by the post hoc test that ΔHHb was significantly lower for ECC1 (-0.41 ± 0.37 μM), $p=0.023$

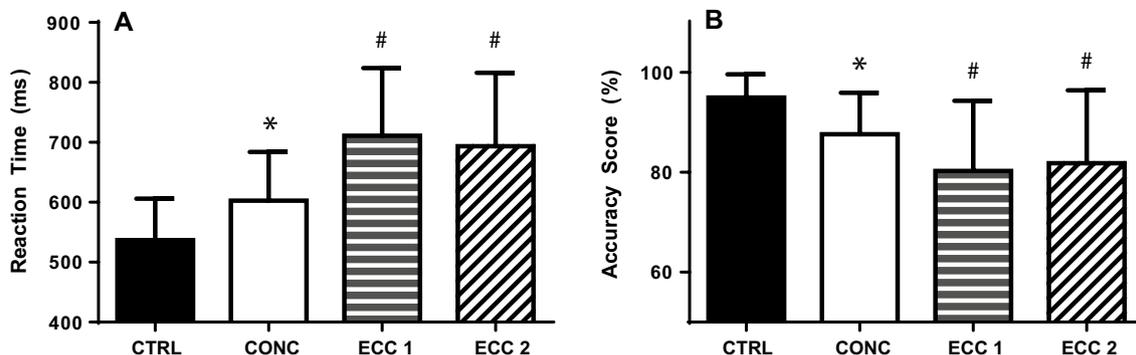


Fig. 3 Average (\pm SD, $n=30$) reaction time (a) and accuracy score (b) derived from a choice reaction time test administered during 20 min of rest (CTRL), and 20 min of concentric (CONC) and the

first and second 20-min eccentric cycling (ECC1 and ECC2). *Significantly different ($p<0.05$) from CTRL. #Significantly different ($p<0.05$) from CTRL and CONC

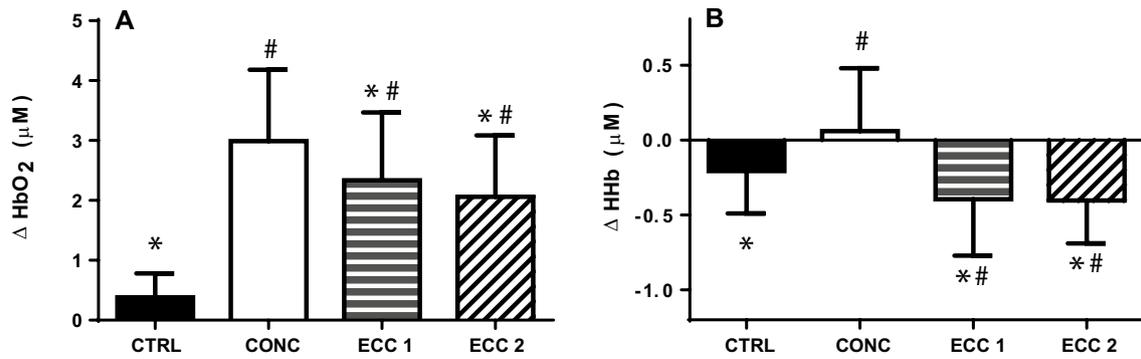


Fig. 4 Average (mean ± SD, *n* = 30) change in oxygenated (ΔHbO₂: **a**) and deoxygenated hemoglobin concentration (ΔHHb: **b**) during the 20 min of sitting (control: CTRL), concentric cycling (CONC),

and the first (ECC1) and second (ECC2) eccentric cycling. *Significantly different (*p* < 0.05) from CONC. #significantly different (*p* < 0.05) from CTRL

and ECC2 (− 0.40 ± 0.40 μM, *p* = 0.029) than control (− 0.21 ± 0.28 μM) and CONC (0.10 ± 0.40 μM), without a significant difference (*p* = 0.926) between the ECC1 and ECC2 (Fig. 4B).

Post-exercise effects on attention and vigilance

Reaction time

No significant interaction effect (*F*_(15, 435) = 1.47, *p* = 0.114) was evident for the changes in the reaction time over time (before, immediately after, and 15, 30, 45, and 60 min after sitting or cycling) among the four conditions (control, CONC, ECC1, and ECC2). Reaction time did not change significantly (*p* = 0.215 – 0.545) from the baseline (control: 347.1 ± 31.9 ms, CONC: 340.1 ± 31.6 ms, ECC1: 330.7 ± 24.9 ms, ECC2: 322.0 ± 28.7 ms) to 60 min after sitting (342.7 ± 37.1 ms) or after CONC (340.2 ± 34.1 ms), ECC1 (333.6 ± 32.6 ms), or ECC2 (333.3 ± 34.7.0 ms).

Correct detections

Table 2 shows changes in correct detection and false alarm scores of the SART before, and for up to 60 min after 20-min sitting or 20-min cycling (CONC, ECC1, ECC2). The baseline values of correct detection were similar among the four conditions (*F*_(3, 116) = 0.45, *p* = 0.716). A significant interaction effect was evident for the changes in the correct detection from baseline to 60-min post-intervention (*F*_(15, 435) = 2.63, *p* < 0.001). Post hoc analysis showed that correct detection immediately after 20-min sitting was significantly lower (*p* < 0.001) than the baseline, up to 60-min post-sitting. The baseline value was maintained after CONC for 60 min, but ECC1 resulted in a significant decrease at 30-min post-cycling (*p* = 0.05), which remained significantly lower than the baseline (*p* = 0.001) for up to 60-min post-cycling. In contrast, the correct detection value improved significantly at immediately after ECC2 (*p* = 0.01), and did not return to the baseline for 60 min. The largest difference between conditions was evident immediately post-intervention, and the analysis for the two time points (before and immediately post-intervention) showed

Table 2 Changes in correct detection and false alarm scores of the sustained attention to response test (mean ± SD, *n* = 30) performed before (pre), immediately after (post), and 15, 30, 45, and 60 min after either sitting for 20 min (Control) or 20 min of concentric cycling (CONC), or the first (ECC1) and second bout of eccentric cycling (ECC2)

	Pre	Post	15 min	30 min	45 min	60 min
Correct detection (%)						
Control	89.5 ± 3.4	87.9 ± 3.3*	86.4 ± 4.8*	86.0 ± 4.8*	87.1 ± 3.7*	86.7 ± 4.7*
CONC	90.3 ± 7.1	91.8 ± 4.9	91.4 ± 5.0	90.1 ± 5.7	90.0 ± 4.9	88.9 ± 5.0
ECC1	91.0 ± 3.9	91.6 ± 5.1	90.3 ± 4.9	89.4 ± 5.3*	89.9 ± 5.7*	87.9 ± 6.1*
ECC2	90.2 ± 5.0	92.2 ± 5.3*	90.0 ± 5.3	89.7 ± 4.4	88.5 ± 5.3	88.5 ± 4.9
False alarms (%)						
Control	43.8 ± 17.2	48.9 ± 18.3*	54.8 ± 20.9*	54.3 ± 21.4*	53.4 ± 18.0*	53.9 ± 20.0*
CONC	34.9 ± 19.2	31.0 ± 22.0	33.0 ± 22.4	37.5 ± 22.8	42.2 ± 21.5*	45.7 ± 23.7*
ECC1	37.7 ± 18.3	32.4 ± 21.3	40.8 ± 23.2	44.0 ± 21.6*	45.8 ± 21.8*	48.2 ± 23.4*
ECC2	41.6 ± 22.7	32.0 ± 24.7*	42.9 ± 24.2	46.6 ± 23.2	49.9 ± 24.4*	49.0 ± 23.7*

*Significantly different (*p* < 0.05) from the pre value

a significant interaction effect ($F_{(3, 87)}=5.48, p=0.002$), but when comparing CONC, ECC1, and ECC2, no significant interaction effect was found ($F_{(2, 58)}=0.95, p=0.393$). As shown in Fig. 5A, the correct detection score decreased ($p<0.001$) from pre- to post-sitting in the control condition ($-1.7\pm 2.2\%$, $g=-0.48$), but was maintained or slightly increased after CONC ($1.4\pm 4.5\%$, $g=0.22$), ECC1 ($0.6\pm 3.6\%$, $g=0.14$), and ECC2 ($2.0\pm 4.2\%$, $g=0.38$). Further analysis showed that the magnitude of changes in correct detection values from the baseline to immediately after sitting or cycling was significantly different among the sessions ($F_{(3, 116)}=5.68, p=0.001$). The post hoc test revealed that the magnitude of change in the correct detection was significantly greater for ECC1 ($p=0.016$), ECC2 ($p=0.001$), and CONC ($p=0.002$) when compared to control.

False alarms

No significant difference in the baseline values was observed between sessions ($F_{(3, 116)}=1.18, p=0.320$), as shown in Table 2. A significant interaction effect for the changes in false alarms was found between sessions from baseline to 60-min post-intervention ($F_{(15, 435)}=1.93, p=0.019$). The false alarms increased immediately after 20 min of sitting ($p<0.001$) from the baseline (Pre) and remained higher than Pre for 60 min ($p=0.004$). However, no such increase was observed immediately after CONC ($p=0.132$), but increased from the baseline at 45 min ($p=0.014$) and 60 min after CONC ($p=0.003$). After ECC1, the baseline values did not change at immediately ($p=0.065$) to 15 min ($p=0.329$) post-exercise, but increased at 30 min ($p=0.041$) to 60 min ($p=0.006$) from the baseline. In contrast, the false alarms decreased immediately after ECC2 ($p=0.009$) and returned to the baseline at 15 min and 30 min ($p=0.157$),

then increased at 45–60 min post-exercise ($p=0.019$). When focusing on the changes from the baseline to immediately after sitting or cycling, a significant interaction effect ($F_{(3, 87)}=5.51, p=0.002$) was found, but when comparing the three exercise sessions, no significant difference was evident ($F_{(2, 58)}=1.20, p=0.310$). As shown in Fig. 5B, the false alarms increased ($p<0.01$) at immediately after 20-min sitting from the baseline ($5.2\pm 10.8\%$, $g=-0.27$), but did not change or slightly improved after CONC ($-3.7\pm 13.6\%$, $g=0.18$), ECC1 ($-5.3\pm 15.1\%$, $g=0.26$), and ECC2 ($-9.7\pm 18.7\%$, $g=0.40$), as shown in Fig. 5B. The percentage changes were significantly different among the four sessions ($F_{(3, 116)}=5.318, p=0.002$), and the post hoc test revealed that percentage changes were significantly smaller for ECC1 ($p=0.007$), ECC2 ($p=0.001$), and CONC ($p=0.021$) when compared to the control condition.

Discussion

The present study tested two hypotheses; (1) cognitive load would be greater during ECC than CONC, and ECC1 than ECC2; and (2) attention and vigilance would be improved to a greater extent after ECC than CONC, and ECC1 than ECC2. Regarding the first hypothesis, the torque error (Fig. 2), CRT (Fig. 3), and NASA-TLX scores for mental demand and frustration (Table 1) were greater for ECC than CONC. In addition, ΔHbO_2 and ΔHHb were found to be smaller during ECC than CONC (Fig. 4). Significant differences between ECC1 and ECC2 were evident for the torque error as well as NASA-TLX scores for mental demand and frustration. These findings appear to suggest that cognitive demand was greater for ECC than CONC, but not much reduction in cognitive demand occurred from ECC1 to ECC2. Regarding the second hypothesis, both

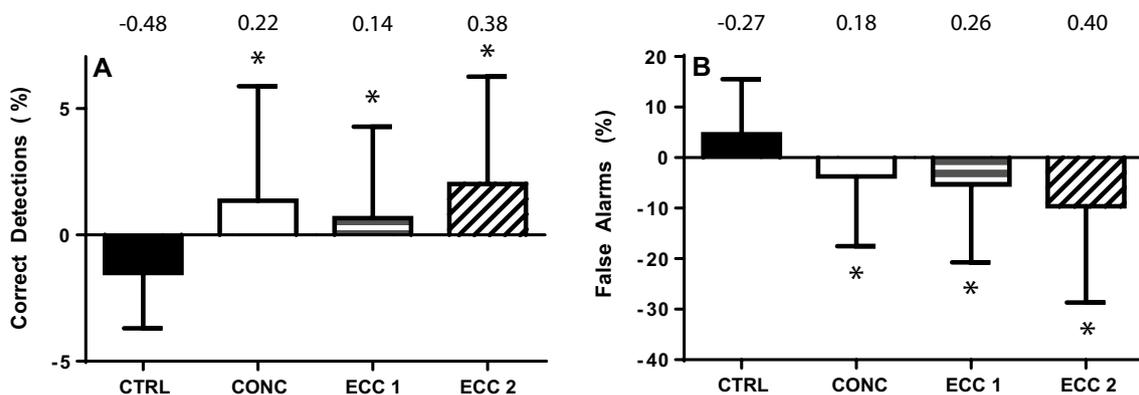


Fig. 5 The magnitude of changes (mean \pm SD, $n=30$) in accuracy score (%) of correct detection (a) and false alarm scores (b) during the sustained attention to response test from baseline to immediately after 20-min sitting (control: CTRL) and 20-min concentric (CONC)

or the first (ECC1) and second (ECC2) 20-min eccentric cycling. Effect sizes (g) of the changes from before to immediately after the 20-min sitting or exercise are also shown. *Significantly ($p<0.05$) different from CTRL

correct detection and false alarms scores did not change immediately after CONC and ECC1 from the baseline, while the correct detection scores decreased and the false alarm scores increased after 20-min sitting (control condition) (Table 2, Fig. 5). Interestingly, the correct detection and false alarm scores were slightly improved immediately after ECC2 (Fig. 5). Thus, the second hypothesis was not fully supported by the results, but it appears that both CONC and ECC cycling similarly prevented a decline in vigilance and attention that was evident in the control condition, at immediately after exercise.

Cognitive load of exercise

The average heart rate during ECC1 and ECC2 was 25% lower than that of CONC, despite performing the cycling at a similar workload. This was consistent with the previous study that showed that heart rate was ~30% lower for ECC than CONC for the same workload (Peñailillo et al. 2013). Abbott et al. (1952) reported 41–67% lower oxygen consumption during eccentric than concentric cycling for the same work. These suggest that ECC in the present study was comparable to that of the previous studies, and ECC is less metabolically demanding than CONC.

As shown in Fig. 2, the error from the given target torque was ~10–15% greater during the two ECC sessions as compared to CONC, and the error became smaller for ECC2 than ECC1. This improvement seems to indicate that participants were more familiarized with the eccentric cycling and coordinated their leg movements better in the second bout. The previous studies (Mueller et al. 2009; Hoppeler 2014) suggested that complexity of eccentric cycling requires a sustained conscious concentration to maintain a given target output. In the present study, one familiarization session was performed before ECC1, but many participants still struggled to cycle smoothly during ECC1, and some learning effect was evident during ECC2. Although a learning effect was evident, the variability of torque error was similar between the two ECC sessions (Fig. 2). However, it should be noted that the error during ECC2 was still greater than during CONC. It is also worth mentioning that the CRT, which was used only as a tool to assess cognitive load in the present study, would not have adversely affected that successful coordination of ECC (Brünken et al. 2002). It is possible that ECC coordination could be further improved in subsequent sessions (Peñailillo et al. 2013), suggesting that it would be worthwhile to investigate the number of sessions required for the error from the target torque to be reduced to the level seen in CONC.

Reaction time was slower and accuracy was lower during all exercise conditions as compared to the control condition (Fig. 3). Moreover, the dual-task reaction time and accuracy during ECC1 and ECC2 were ~15% slower, and the errors

were ~20% greater than those of CONC without a significant difference between ECC1 and ECC2. Importantly, the use of a dual task to assess cognitive load has been well supported by research, and has been deemed to be a useful and promising tool in measuring cognitive load in a resting condition (Brünken et al. 2002; Xie and Salvendy 2000). To the best of our knowledge, this was the first study to compare reaction time and accuracy parameters during eccentric and concentric cycling exercises, but a delay in reaction time during prolonged cycling exercise was reported previously (Brisswalter et al. 1997; Delignières et al. 1994; Kashihara and Nakahara 2005). For example, Kashihara et al. (2005) showed a 8% decrease in reaction time during a 20-min conventional cycling session at ~120 bpm, but the accuracy of the CRT was not affected. Likewise, Delignieres et al. (1994) and Brisswalter et al. (1997) reported 8–10% reductions in dual-tasking reaction time when cycling at 40–80% of maximal aerobic power, but found no changes in accuracy. It has been reported that dual-task performance is affected when performance involves a mentally demanding task, but automatic tasks do not impair dual-task performance (Brünken et al. 2002; Xie and Salvendy 2000). McMorris et al. (1999) reported that, unlike automatic tasks, challenging tasks induced a high arousal which impaired decision-making and accuracy. In the present study, participants were required to match the peak pedaling torque to the target torque as closely as possible during CONC and ECC. Thus, both CONC and ECC were not “automatic” tasks. This may explain why the reaction time was delayed and accuracy scores were reduced during CONC and ECC when compared with the control condition (sitting). It seems likely that the slower reaction time and lower accuracy score in ECC than CONC indicate that ECC was more difficult than CONC. Therefore, it is plausible that a higher cognitive demand was required to perform ECC than CONC. No significant differences in the reaction time and accuracy score between ECC1 and ECC2 may suggest that arousal was similarly high for both ECC sessions, although participants performed better for ECC2 than ECC1 in terms of the target error as previously discussed.

NASA-TLX has been shown to be a valid even when assessing multitasking scenarios (DiDomenico and Nussbaum 2011). Smit et al. (2005) reported that the NASA-TLX was sensitive enough to detect mental effort during 40-min moderate exercise (130–150 bpm) shown by increased MD and FR scores. Tomporowski et al. (2006) reported similar MD (~47) and FR scores (~38) during 40-min moderate cycling exercise (60% VO₂max) to those of the present study for CONC. Compared to these values, the MD and FR scores of ECC1 were more than twice as large, suggesting that ECC1 was more mentally demanding and frustrating than CONC, despite ~25% lower physical demand (Table 1). Although ECC2 required the same physical demand as

ECC1, it was less mentally demanding and frustrating than ECC2. This may reflect that ECC2 was subjectively less cognitively demanding than ECC1 with a trend also seen towards it being more demanding than CONC.

Changes in ΔHbO_2 and ΔHHb have been found to be indicative of the cognitive load imposed by a task (Kikukawa et al. 2008). In the present study, ΔHbO_2 was higher during cycling than sitting, but was lower during ECC1 and ECC2 similarly when compared with CONC (Fig. 4). Increases in ΔHbO_2 in the present study were consistent with a previous study (Rooks et al. 2010) showing a linear relationship between aerobic exercise intensity and cerebral NIRS parameters. For example, Chang et al. (2013) found similar changes in HbO_2 in healthy young adults when cycling for 10 min at intensity of 70% VO_2max ($\sim 3\text{--}4\ \mu\text{M}$). Giles et al. (Giles et al. 2014) also found that 20-min high-intensity (85% heart rate max) and low-intensity cycling increased ΔHbO_2 by 3–4 μM and 2 μM , respectively, and similar increases in ΔHHb ($\sim 0.5\ \mu\text{M}$) for both intensities. These studies indicated that the increases in ΔHbO_2 and ΔHHb resulted from an enhanced blood flow to the brain. In the present study, ΔHHb decreased in ECC1 and ECC2 (Fig. 3). It has been documented that an increase in ΔHbO_2 accompanied by a decrease in ΔHHb is indicative of an increased level of cognitive demand (Kikukawa et al. 2008). Thus, the lower ΔHHb in ECC than CONC may indicate that ECC was more cognitively demanding than CONC.

Collectively, it appears that ECC in the present study was more cognitively demanding than CONC. Based on the differences between ECC and CONC in some of the variables such as CRT, it is assumed that ECC was 10–15% more cognitively demanding than CONC. Duchateau and Baudry (2014) stated in their review article about the differences in neural control between eccentric and concentric contractions, such that cortical excitability is enhanced in the motor cortex and a greater brain area is involved when controlling eccentric contractions. This may support the notion that the cognitive demand associated with ECC is greater than CONC, found in the present study. When comparing between ECC1 and ECC2, although the participants felt that ECC2 was easier to perform based on NASA-TLX ratings, CRT and NIRS parameters suggest that cognitive demand was similar between the two. It is interesting to investigate further when ECC is repeated more than three times, its cognitive demand would become similar to that of CONC, or the difference in the cognitive demand between CONC and ECC still exists. It should be noted that the concentric cycling performed in the present study differs from normal bicycle pedaling with a classic bicycle or a cycling ergometer that does not provide a target torque in each revolution. Thus, it seems possible that normal concentric cycling is much less cognitively demanding than the concentric cycling performed in the present study, and the difference in cognitive

demand between general concentric cycling and eccentric cycling could be much greater than that found in the present study.

Post-exercise changes in vigilance and attention

The second aim of the present study was to compare the effects of concentric versus eccentric cycling exercise on post-exercise attention and vigilance. Attention and vigilance are the basis for various basic tasks important for everyday function. It is crucial to investigate whether attentional function can be improved by exercise as has been shown with other domains of cognitive function. The SART was designed to be a brief, reliable, and valid measure for sustained attention and vigilance by detecting a person's ability to sustain attention with an element of inhibitory/suppression response (Robertson et al. 1997). It was reported that SART had a good test–retest reliability ($r = 0.76$) over time (Robertson et al. 1997), and was ecologically valid (Smilek et al. 2010).

The baseline reaction time found in the present study (347.1 ± 31.9 ms) was similar to that of a previous study by Robertson et al. (1997) who reported that the reaction time in a group of healthy young adults was 305–397 ms. The present study showed no significant changes in the reaction time after sitting or cycling for 20 min (Table 2). This was in line with the finding of Brisswalter et al. (1997) who reported no changes in reaction time after cycling for 10 min at 20, 40, 60, and 80% of maximal power performed by healthy young men. Improvement in cognitive processing following exercise was more evident in clinical and elderly individuals (Hillman et al. 2008), but little changes have been found in healthy young adults (Voss et al. 2011). This may be due to a ceiling effect, such that no further improvement is observed in reaction time following exercise, since young adults have a relatively stable cognitive performance which leaves no room for improvement (Voss et al. 2011).

After sitting for 20 min, vigilance and attention decreased as shown by reductions in correct detection scores and increases in false alarm scores (Table 2). It seems likely that the decreased attention and vigilance after sitting were due to boredom and under-stimulation (Jackson et al. 2014), or a depletion of attentional resources (Young et al. 2009) resulting from staring at a blank screen for 20 min. In contrast, attention and vigilance were maintained after cycling for 20 min (CONC and ECC1), and transiently improved after ECC2 (Table 2). It should be noted that despite the disparity in exercise intensity between CONC and ECC as indicated by the heart rate, both sessions similarly prevented a decline in attention and vigilance scores after exercise. The previous studies (Brisswalter et al. 2002; Chang et al. 2012; Tomporowski 2003) have shown that exercise intensity is important for determining changes in cognition

post-exercise, whereby exercise at low and high intensities is detrimental to cognitive performance, but exercise at a moderate intensity induces positive effects. However, the present study found that both CONC and ECC1 maintained attention and vigilance scores similarly, although the exercise intensity was largely different. It should be noted that a slight but significant improvement was seen immediately after ECC2. It seems that better coordination, while performing ECC2 might have led to a transient improvement in attention and vigilance. This suggests that it is important to investigate whether further improve attention and vigilance will be found when ECC is repeated more times.

Little is known about the benefits of exercise on attention and vigilance, but the effect sizes found in the present study for CONC and ECC1 (Fig. 5) were similar to those reported in a review article of the influence of aerobic exercise, such as cycling, on other aspects of cognition with young adults (Chang et al. 2012). Although the positive effect found in the present study was small, it was similar to that reported by Budde et al. (2008) who showed a 5% improvement in selective attention assessed by a d2 test after 10-min moderate intensity complex exercise requiring left and right hand and foot coordination, but this was not found after non-coordinative exercise. It seems that ECC2 induced more beneficial effects for correct detections and false alarms than CONC and ECC1, as shown by a significant increase in both parameters of the SART immediately after cycling. It may be that participants were more engaged in ECC2 than ECC1, and ECC2 might have been less frustrating and more enjoyable, as shown in lower frustration scores in NASA-TLX (Table 1). The findings of the present study suggest that parameters other than intensity, such as the cognitive load associated with being constantly engaged in the exercise task by trying to achieve the target torque output for every revolution, also influence the effects of exercise on cognitive function. Although the mechanisms underpinning the improvement of cognitive function after exercise still remain to be investigated, it is possible that being engaged in such cognitively demanding exercise for extended periods of time would further alter the post-exercise cognitive changes (Anderson-Hanley et al. 2012). In fact, Anderson-Hanley et al. (2012) reported a 29% greater increase in executive function after 3 months of virtual reality cycling exercise (exergames) in comparison to a traditional cycling group, and they attributed the greater increase in the exergaming group to the additional cognitive demand induced by the challenging environment. Currently, it is not known whether extended periods of eccentric cycling training would further improve cognition, but the results of the current study warrant follow-up in further studies.

In conclusion, 20 min of either concentric or eccentric cycling used in the present study were able to contribute to the maintenance of attention and vigilance for no longer

than 30 min after exercise. A limitation of this study was that the order of the experimental sessions was not randomized. Notwithstanding this limitation, the study suggests that exercise intensity is not a key factor in modulating cognition, but exercise that requires participants to be constantly engaged (high cognitive load) is an important factor in improving cognitive function. Future studies should investigate whether prolonged exposure to eccentric cycling will elicit a long-term benefit to cognition, and whether the effects of eccentric cycling on cognition can prevent a decline in attention for more than 1 h. It would also be interesting to investigate the effects of eccentric versus concentric cycling training on cognitive function of children and older adults.

Acknowledgements This study was supported by an International Postgraduate Research Scholarship at Edith Cowan University that was awarded to the author. Authors thank all participants who volunteered for this study. There is no conflict of interest.

Author contributions Kan: designed the study, collected and analysed the data, wrote up the manuscript draft. Speelman: designed the study, checked the final draft of the manuscript. Nosaka: designed the study, analysed the data, checked final draft of the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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