Clinical Neurophysiology 122 (2011) 1518–1525

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

The effects of single bouts of aerobic exercise, exergaming, and videogame play on cognitive control

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A R T I C L E I N F O

Article history:
Accepted 31 January 2011
Available online 24 February 2011

Keywords:
Cognitive control
Aerobic exercise
Videogames
Exergames
Flanker

H I G H L I G H T S

- The effects of exergames on neurocognition were examined.
- Treadmill-based exercise, in contrast to exergaming, facilitated neurocognition.
- Exergames may not incur the same benefits to brain and cognition as traditional physical activities.

A B S T R A C T

Objective: The effects of single bouts of aerobic exercise, exergaming, and action videogame play on event-related brain potentials (ERPs) and task performance indices of cognitive control were investigated using a modified flanker task that manipulated demands of attentional inhibition.
Methods: Participants completed four counterbalanced sessions of 20 min of activity intervention (i.e., seated rest, seated videogame play, and treadmill-based and exergame-based aerobic exercise at 60% HR_{max}) followed by cognitive testing once heart rate (HR) returned to within 10% of pre-activity levels.
Results: Results indicated decreased RT interference following treadmill exercise relative to seated rest and videogame play. P3 amplitude was increased following treadmill exercise relative to rest, suggesting an increased allocation of attentional resources during stimulus engagement. The seated videogame and exergame conditions did not differ from any other condition.
Conclusions: The findings indicate that single bouts of treadmill exercise may improve cognitive control through an increase in the allocation of attentional resources and greater interference control during cognitively demanding tasks. However, similar benefits may not be derived following short bouts of aerobic exergaming or seated videogame participation.
Significance: Although exergames may increase physical activity participation, they may not exert the same benefits to brain and cognition as more traditional physical activity behaviors.

1. Introduction

Today's industrial and technological societies are becoming increasingly sedentary and unfit, leading to an increased incidence of a number of chronic diseases across the human lifespan (American College of Sports Medicine, 2010). In addition to the physical concerns manifested through a lack of physical activity, concerns for brain health and cognition also exist. That is, a growing body of research has demonstrated a link between physical activity and the health of brain structure and function (Colcombe et al., 2004; Hall et al., 2001), with research indicating that aerobic fitness has a disproportionately greater influence on aspects of cognition requiring greater amounts of cognitive control (Colcombe and Kramer, 2003; Hillman et al., 2008).

Cognitive control describes a subset of operations responsible for adjustments in perceptual selection, response biasing, and the online maintenance of contextual information (Botvinick et al., 2001). These processes describe goal-directed behaviors concerned with the selection, scheduling, and coordination of complex processes underlying perception, memory, and action (Diamond, 2006). The core processes of cognitive control have been categorized along the domains of inhibition (i.e., the ability to ignore distracters and maintain focus), working memory (i.e., the ability to hold information in one's mind and manipulate it), and cognitive flexibility (i.e., the ability to switch perspectives, attention, or response mappings; Diamond, 2006).

Investigations into alterations in cognitive control following a single session of aerobic exercise have primarily used tasks that tap inhibitory control, which relates to the ability to gate task irrel-

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doi:10.1016/j.clinph.2011.01.049

evant information from the environment and inhibit a prepotent response in order to make a correct response. Findings from these investigations have indicated that the transient effects of exercise on cognition may result in improvements in inhibitory control following the cessation of the exercise bout (Hogervorst et al., 1996; Lichtman and Poser, 1983; Tomporowski et al., 2005). Specifically, Hogervorst et al. (1996) and Lichtman and Poser (1983) observed facilitations in cognitive performance during the condition of a Stroop task requiring the greatest amount of inhibitory control immediately following a 20–40 min bout of aerobic exercise. Similarly, Tomporowski et al. (2005) observed performance enhancements on the Paced Auditory Serial Addition Test following a 30 min bout of exercise. Taken together, these results suggest transient benefits to inhibitory aspects of cognitive control following a single bout of exercise.

Beyond behavioral indices of task performance, the examination of neuroelectric activity provides an index of specific cognitive operations, which occur between stimulus encoding and response production that are influenced by some factor. To date, the vast majority of acute exercise research that has incorporated neuroelectric assessment has investigated the P3 (or P300) component of an event-related brain potential (ERP). The P3 is a prominent positive-going component of the stimulus-locked ERP occurring approximately 300–800 ms following the presentation of a stimulus. The amplitude of this component has been related to the amount of attentional resources allocated toward the stimulus environment, while the latency is thought to be a metric of stimulus classification (i.e., stimulus processing) speed (Polich, 2007).

Relative to the exercise literature, increases in P3 amplitude and decreases in P3 latency have been observed following single bouts of aerobic exercise (Hillman et al., 2003; Kamijo et al., 2007, 2009). Specifically, after a single, 30 min bout of exercise, an increase in P3 amplitude was observed across conditions of a flanker, while a reduction in P3 latency was observed only during trials requiring greater amounts of inhibitory control (Hillman et al., 2003). Further, Kamijo et al. (2007) indicated that following three different exercise intensities (e.g., light, moderate, and hard), RT was reduced across conditions of a flanker task, which required variable amounts of inhibitory control. However, after light and moderate exercise intensities, increases in P3 amplitude and decreases in P3 latency were observed selectively for condition requiring greater amounts of inhibitory control. Collectively, these findings suggest that participation in a single bout of aerobic exercise has general benefits to cognition, with selectively greater benefits for task components requiring greater amounts of inhibitory control, as reflected by neuroelectric indices of attentional resource allocation (i.e., P3 amplitude) and cognitive processing speed (i.e., P3 latency).

Despite these improvements in cognition following exercise, a growing portion of industrialized societies are shifting their physical activity behaviors from more traditional "gym based" activities (i.e., running, cycling, etc.) towards computer based "exergames". These exergames (e.g., Dance Dance Revolution® [DDR®], Nintendo Wii™, and Wii Fit™) provide an individual with the ability to physically interact with a virtual environment, with their specific movements being captured or tracked and then depicted on screen via a virtual character. Kinesiological investigations of these "exergames" has observed that participation may serve to increase individuals' energy expenditure during tasks offered by Wii Fit™, eliciting a MET[1] value of 3.4 ± .09 and falling within a moderately intense classification (Miyachi et al., 2010).

[1] MET, or metabolic equivalent of task, provides a practical means of expressing the energetic cost of physical activity participation as a function of resting metabolic rate with one MET corresponding to rest and increasing MET values representing multiples of the resting metabolic rate (Ainsworth et al., 1993).

Since these exergames are relatively new, limited research is available to determine the efficacy of exergames on cognition. However, researchers have explored the effects of single sessions of videogame play on cognitive function. Orosy-Fildes and Allan (1989) indicated that a single bout of videogaming aided in reducing participants' RT by as much as 50 ms on a simple RT task. Additional results indicated that following a single session of both violent and non-violent videogame play, individuals' scored better on a task requiring selective attention, working memory, auditory discrimination, and mathematics (Bartlett et al., 2009), suggesting that a single bout of videogame play may facilitate a number of aspects of cognition, including cognitive control. Given the increased reliance on exergaming for physical activity, additional research is necessary to determine the relationship between videogame play, exercise, and exergaming as well as how participation in these activities influences cognition.

The purpose of the proposed study was to assess the effects of single bouts of videogame play, exergaming, and aerobic exercise on task performance and neuroelectric indices of inhibitory aspects of cognitive control. It was hypothesized that a single bout of moderate aerobic exercise would serve to enhance cognition as measured via task performance and the P3 component, replicating previous research (Hillman et al., 2003, 2009; Davranche et al., 2009; Kamijo et al., 2009; Pontifex et al., 2009). Following treadmill-based aerobic exercise, it was expected that participants would respond more accurately and exhibit shorter RT, suggesting transient improvements in task performance following the cessation of exercise. Additionally, participants were expected to exhibit larger P3 amplitude and shorter P3 latency, indicating greater allocation of attentional resources and faster cognitive processing speed, respectively. Exergaming was expected to exhibit a similar effect given that the exercise elicited by the games was similar in intensity and duration. Lastly, based on previous research, seated videogame play was predicted to show similar facilitations in cognition.

2. Method

2.1. Participants

Thirty-six college-aged young adults (18 females; age range: 18–25 years) were recruited from the undergraduate population at the University of Illinois at Urbana-Champaign. All participants provided written informed consent, which was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign. Participants completed the Physical Activity Readiness Questionnaire (PAR-Q), the Edinburgh handedness inventory (Thomas et al., 1992; Oldfield, 1971), and reported normal or corrected to normal vision. Participants were instructed to abstain from physical activity on the days they visited the laboratory. Demographic and fitness data for all participants are provided in Table 1.

Table 1
Mean (SD) values for participant demographic and fitness data.

Variable	All participants (*M* ± *SD*)	Females (*M* ± *SD*)	Males (*M* ± *SD*)
Sample size (*n*)	36	18	18
Age (years)	21.2 ± 1.5	20.6 ± 1.3	21.8 ± 1.6
BMI	23.3 ± 3.0	22.7 ± 2.6	24.3 ± 3.2
IQ (K-BIT composite)	106.8 ± 7.3	106.6 ± 7.7	107.1 ± 7.1
VO_{2max} (mL/kg/min)	45.2 ± 5.9	41.5 ± 4.2	48.9 ± 5.0
Max HR (bpm)	195.1 ± 7.9	193.8 ± 8.1	196.3 ± 7.8
Max RPE	17.9 ± 1.5	17.9 ± 1.4	17.9 ± 1.5

Note: BMI = Body Mass Index; K-BIT = Kaufman Brief Intelligence Test; PA = Physical Activity; RPE = Ratings of perceived exertion (Borg, 1970).

2.2. Task

Participants completed a modified flanker task (Pontifex and Hillman, 2007; Pontifex et al., 2010) in which they were instructed to respond as quickly and as accurately as possible to a centrally presented target arrow amid lateral flanking arrows and press a button using their left thumb when the target arrow faced to the left (e.g., '<') and their right thumb when the target arrow faced to the right (e.g., '>'). Congruent trials consisted of the target arrow flanked by arrows facing the same direction (e.g., <<<<< or >>>>>), resulting in faster and more accurate responses relative to incongruent trials in which the target arrow was flanked by arrows facing the opposite direction (e.g., <<><< or >><>>). The incongruent, relative to the congruent, condition necessitates the concurrent activation of both the correct response (elicited by the target) and the incorrect response (elicited by the flanking stimuli) before stimulus evaluation is complete; thus, requiring greater amounts of interference control to inhibit the flanking stimuli and execute the correct response (Spencer and Coles, 1999). Following the provision of task instructions, participants were afforded the opportunity to ask questions and 20 practice trials were administered prior to the start of testing. One block of 200 trials was given during each session with equiprobable congruency and directionality. The stimuli were 3 cm tall white arrows comprising a 16.5 cm wide array with a vertical visual angle of 1.32° and a horizontal visual angle of 7.26°, presented focally on a black background for 100 ms, with a counterbalanced inter-trial interval of 1000, 1200, and 1400 ms. Multiple task performance indices were assessed including response speed (RT) and accuracy (% correct), in addition to interference score measures, which require simple subtractions across task conditions to yield changes in the speed and accuracy of information processing between congruent and incongruent trials (Fan et al., 2002).

2.3. ERP recording

Electroencephalographic (EEG) activity was recorded from 64 electrode sites of the International 10-10 system (Chatrian et al., 1985) using a Neuroscan Quik-cap (Neuro, Inc., Charlotte, NC, USA). The data were referenced to the left mastoid (and later rereferenced to the average of both mastoids) with AFz serving as the ground electrode and impedances <10 kΩ. Electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor bipolar electro-oculographic (EOG) activity. Continuous data were sampled at 500 Hz and amplified 500× with a Neuroscan Synamps amplifier (Neuro, Inc., Charlotte, NC, USA).

Data were corrected offline for EOG activity using a spatial filter (Compumedics Neuroscan, 2003). Epochs were created from −100 to 1000 ms around the stimuli, and baseline corrected using the 100 ms pre-stimulus period. Data were filtered using a zero phase shift 30 Hz (24 dB/octave) low pass filter. A linear detrend was applied across the entire epoch to control for DC drift. Trial epochs with artifacts exceeding ±75 μV or response errors were rejected. The P3 was defined as the largest positive-going peak within a 300–520 ms latency window from stimulus onset. Amplitude was measured from the average stimulus-locked ERP as the difference between the mean pre-stimulus baseline and maximum peak amplitude; peak latency was defined as the time point corresponding to the maximum amplitude.

2.4. Cardiorespiratory fitness assessment

Maximal oxygen consumption (VO_{2max}) was assessed using a computerized indirect calorimetry system (ParvoMedics True Max 2400) with averages for oxygen uptake (VO_2) and respiratory exchange ratio (RER) assessed every 20 s. A modified Balke protocol (ACSM, 2010) was employed using a Life Fitness motor-driven treadmill (Brunswick Corporation, Schiller Park, IL, USA) at a constant speed with grade increments of 3% every 2 mins until volitional exhaustion. A Polar Heart Rate monitor (Model A1, Polar Electro, Finland) was used to measure HR throughout the entire test and ratings of perceived exertion (RPE; Borg, 1970) were assessed every 2 mins. Relative peak oxygen consumption was expressed in ml/kg/min and was based on a maximal effort when the participant achieved at least two of the four following criteria: (1) Plateau in oxygen consumption resulting in an increase of less than 2 ml/kg/min with an increase in workload, (2) a peak heart rate at or above 95% of age-predicted HR_{max} (220–age), (3) RPE > 17, (4) RER ⩾ 1.10.

2.5. Procedure

2.5.1. Day 1

On the first visit, participants completed an informed consent, and were fitted with a Polar Heart Rate monitor (Model A1, Polar Electro, Finland). Participants then completed the PAR-Q to screen for previous health issues that may be exacerbated by aerobic exercise, the Edinburgh Handedness Inventory, a health history and demographic questionnaire, and completed the Video Game Usage Questionnaire (Gentile, 2009). A trained experimenter then administered the Kaufman Brief Intelligence Test (K-BIT; Kaufman and Kaufman, 1990). Participants received 10 min of practice on both the Wii Fit™ and MarioKart® games. An experimenter then led the participant to a sound attenuated room and read aloud the flanker task instructions. Participants were given 20 practice trials with the experimenter in the room, and then received a block of 200 trials as a learning session. Following the flanker task, the participant's height and weight were measured using a stadiometer and a Tanita BWB-600 digital scale, respectively and completed a maximal exercise test to assess their VO_{2max}.

2.5.2. Days 2–5: Experimental sessions

Using a within-participants design, the order of the experimental conditions (seated rest, MarioKart®, treadmill walking, or Wii Fit™) were counterbalanced across participants to reduce the possibility of learning or habituation effects. Prior to each session, participants were fitted with a Polar Heart Rate Monitor (Model A1, Polar Electro, Finland). Each experimental condition lasted 20 min during which time Heart Rate and RPE were assessed every 2 mins.

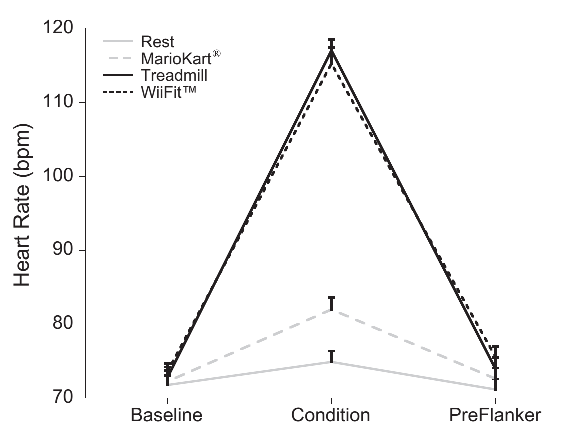

Fig. 1. Mean HR (bpm; ±1 S.E.) at baseline, across the entire activity protocols, and immediately prior to the flanker task.

Fig. 1 provides intensity data for each experimental condition. During the Wii Fit™ session participants completed six-minute versions of three aerobic games, including Aerobic Step, Rhythm Boxing, and Hula-Hoop®, which place the participant in a virtual world in order to complete certain tasks. The Aerobic Step (4.0 ± 0.6 METs; Miyachi et al., 2010) game requires the individual to step on and off the balance board at a particular time in different combinations. The game provides feedback for perfect timing, good timing, or a missed step. Rhythm boxing (3.9 ± 0.7 METs; Miyachi et al., 2010) is similar to the Aerobic Step game, but has the addition of using a remote control for each hand to monitor the participants' punching. The Hula Hoop® task (4.2 ± 1.2 METs; Miyachi et al., 2010) asks the individual to shift their center of gravity in a circle in one direction for 3 mins and then the other direction for another 3 mins. Across all games participants were instructed to try to achieve the best score possible. During the MarioKart® session participants raced around a track in a vehicle with the objective of besting computerized drivers in a three lap race. The game responds to the driver using the Wiimote™ placed in a small steering wheel. The participants were instructed to try to achieve the best finishing spot for each race. During the treadmill session, participants walked on a motor-driven treadmill at 60% HR_{max}. Finally, during the quiet reading session, participants sat on a chair and were instructed to read a campus newspaper. Following each experimental condition, participants were prepared for neuroelectric measurement, provided with task instructions, and completed a series of 20 practice trials. Once participants' HR returned to within 10% of pre-exercise levels (M = 22.2 ± 0.6 min) the flanker task was performed.

2.6. Statistical analysis

Preliminary analyses were conducted to examine the order in which the sessions occurred to ensure that the observed effects were not due to the order in which participants completed their sessions. These analyses employed an additional between-subjects variable that accounted for the order of the four experimental sessions for each participant for each of the analyses described below.

HR and RPE data were analyzed using a 4 (Condition: Rest, MarioKart®, Treadmill, Wii Fit™) × 3 (Time: Pre-, During-, Post-session) repeated measures ANOVA. Additional one factor repeated measure ANOVAs and follow up paired samples *t*-tests with Tukey's HSD procedure were used to determine significant differences between conditions at each time point. Analyses were conducted separately for task performance measures (RT and response accuracy) using a 4 (Condition: Rest, MarioKart®, Treadmill, Wii Fit™) × 2 (Congruency: Congruent, Incongruent) repeated measures ANOVA. Additional analyses examining interference scores (i.e., the difference between congruent and incongruent trails for both accuracy and RT) were conducted using a one factor (Condition: Rest, MarioKart®, Treadmill, Wii Fit™) repeated measures ANOVA and paired-samples *t*-tests with Tukey's HSD procedure to determine specific differences between conditions.

P3 analyses were conducted using 25 electrode sites (five coronal sites within each of five regions). P3 values (amplitude, latency) were submitted to a 4 (Condition: Rest, MarioKart®, Treadmill, Wii Fit™) × 2 (Congruency: Congruent, Incongruent) × 5 (Region: Frontal-, Fronto-Central, Central, Centro-Parietal, Parietal) × 5 (Site: 3, 1, z, 2, 4) repeated measures ANOVA. The reported significances for the *F* values were those obtained using the Greenhouse–Geisser correction. When appropriate, follow up analyses were conducted using additional repeated measures ANOVAs and paired-samples *t*-tests with Tukey's HSD correction. Means and standard errors are reported for all measures. The family-wise alpha level was set at 0.05.

3. Results

3.1. Session order

Preliminary analyses were conducted to test whether the order of the activity sessions, which was counterbalanced across participants, had a relationship with any of the dependent variables. Findings revealed no significant main effects or interaction involving Session Order for response accuracy, $F(69, 36) = .763$, $p = .840$, $\eta^2 = .585$, or RT, $F(69, 36) = 1.519$, $p = .166$, $\eta^2 = .744$. Additionally, findings revealed no significant main effect involving Session Order for P3 Amplitude, $F(69, 36) = 1.344$, $p = .191$, $\eta^2 = .720$. However, a Condition × Site × Session Order interaction was found, $F(276, 144) = 6.412$, $p = .002$, $\eta^2 = .348$. Decomposition of this interaction by examining each of the five Sites within the four Conditions revealed no significant differences. Thus, all further analyses were collapsed across Session Order.

3.2. Session intensity

3.2.1. Heart rate

The omnibus analysis revealed main effects of Condition, $F(3, 105) = 151.162$, $p < .001$, $\eta^2 = .812$, and Time, $F(2, 70) = 737.102$, $p < .001$, $\eta^2 = .955$, which were superseded by a Condition × Time interaction, $F(6, 210) = 257.132$, $p < .001$, $\eta^2 = .880$. Decomposition of this interaction by examining Condition within Time revealed increased mean HR for Treadmill Walking ($M = 117.1 \pm 1.5$ bpm), Wii Fit™ ($M = 115.3 \pm 2.2$ bpm), and MarioKart® ($M = 82.0 \pm 1.6$ bpm) relative to Seated Rest ($M = 74.9 \pm 1.5$ bpm), $t's\ (35) \geqslant 5.780$, $p \leqslant .001$. Additionally, an increase in mean HR was revealed during the experimental manipulation for Treadmill Walking and Wii Fit™ relative to the MarioKart® session, $t's\ (35) \geqslant 19.297$, $p \leqslant .001$, whereas no significant differences were observed between the Treadmill and Wii Fit™ sessions (see Fig. 1).

3.3. Task performance

Mean task performance values for accuracy and response time are provided in Table 2 for each experimental condition.

3.3.1. Accuracy

Analysis of response accuracy revealed a main effect of Congruency, $F(1, 35) = 34.1$, $p < .001$, $\eta^2 = .51$, with more accurate responses for congruent trials ($M = 97.1 \pm 0.4\%$) relative to the incongruent ($M = 89.1 \pm 1.2\%$) trials. No main effect or interaction was observed involving Condition, $F's\ (3105) \leqslant 1.6$, $p \geqslant .2$, $\eta^2 \geqslant .03$. Analyses of the interference effect (congruent ACC–incongruent ACC) revealed no significant main effects, $F(3, 105) = 1.6$, $p = .2$, $\eta^2 = .04$.

3.3.2. Response time

RT analyses revealed a main effect for Congruency, $F(1, 35) = 329.4$, $p < .001$, $\eta^2 = .9$, with incongruent trials ($M = 395.3$, S.E. = 6.4 ms) yielding longer RT compared to congruent trials ($M = 346.2 \pm 5.0$ ms). No main effect of Condition was observed, $F(3, 105) = 1.0$, $p = .39$, $\eta^2 = .03$. An interaction of Condition × Congruency was observed, $F(3, 105) = 3.4$, $p < .05$, $\eta^2 = .09$, however, decomposition of this interaction revealed no significant differences ($p \geqslant .2$). Analyses of the interference effect (incongruent RT–congruent RT) revealed a significant effect for Condition, $F(3, 105) = 3.3$, $p < .05$, $\eta^2 = .09$. Paired samples *t*-tests revealed a decrease in RT interference for Treadmill Walking ($M = 43.9 \pm 2.6$ ms) as compared to both Seated Rest ($M = 49.0 \pm 2.3$ ms) and MarioKart® ($M = 49.4 \pm 2.3$ ms), $t's\ (35) \geqslant 2.5$, $p \leqslant .05$ (see Fig. 2).

Table 2
Mean (SD) values for flanker behavior across experimental conditions.

	Congruent		Incongruent	
	Accuracy (% ± SD)	RT (ms ± SD)	Accuracy (% ± SD)	RT (ms ± SD)
Seated rest	96.3 ± 4.3	347.7 ± 32.9	88.1 ± 8.4	398.1 ± 41.4
MarioKart®	97.8 ± 2.4	346.2 ± 29.8	88.9 ± 7.4	397.9 ± 37.6
Treadmill	97.2 ± 3.1	348.3 ± 39.4	89.6 ± 7.6	393.9 ± 49.2
Wii Fit™	96.9 ± 3.3	342.6 ± 27.2	89.8 ± 8.0	391.2 ± 35.9

3.4. Neuroelectric measures

Preliminary analyses were conducted on the number of trials to ensure that differences in the P3-ERP component were not the result of different numbers of trials included in the ERP averages. Analyses revealed no significant differences in the number of trials for any of the experimental conditions, t's $(35) \leqslant 1.9$, $p \geqslant .07$.

3.4.1. P3. Amplitude

Fig. 3 illustrates the grand average ERP waveform averaged across congruency for all midline sites and topographic maps of P3 amplitude for each experimental condition. The omnibus analysis revealed a main effect for Condition, $F\ (3,\ 105) = 2.8$, $p < .05$, $\eta^2 = .08$, with increased P3 amplitude following Treadmill Walking ($M = 7.6 \pm .6$ μV) relative to Rest ($M = 6.0 \pm .6$ μV), $t\ (35) \geqslant 2.5$, $p \leqslant .05$ (see Fig. 4). No significant differences in P3 amplitude were observed for either Wii Fit™ ($M = 6.9 \pm .6$ μV) or MarioKart® ($M = 7.0 \pm .5$ μV) relative to any other Condition, (Tukey's $HSD_{critical} = 1.6$), t's $(35) \leqslant 2.0$, $p \geqslant .05$. Additional main effects were found for Congruency, $F\ (1, 355) = 10.5$, $p < .01$, $\eta^2 = .2$, Region, $F\ (4, 140) = 34.7$, $p < .001$, $\eta^2 = .5$, and Site, $F\ (4,\ 140) = 16.9$, $p < .001$, $\eta^2 = .3$. These effects were superseded by an interaction of Congruency × Region, $F\ (4,\ 140) = 6.0$, $p < .01$, $\eta^2 = .1$, Congruency × Site, $F\ (4, 140) = 8.2$, $p < .001$, $\eta^2 = .2$, and Region × Site, $F\ (16,\ 560) = 2.9$, $p = .01$, $\eta^2 = .08$. Decomposition of the Congruency × Region interaction examined Congruency within each Region and revealed that incongruent trials exhibited larger P3 amplitude compared to congruent trials at the fronto-central, $t\ (35) = 4.3$, $p \leqslant .001$, central, $t\ (35) \geqslant 4.1$, $p \leqslant .001$, and centro-parietal, $t\ (35) \geqslant 2.8$, $p \leqslant .01$, regions. Decomposition of the Congruency × Site interaction examined Congruency within each Site and revealed that incongruent trials exhibited larger P3 amplitude compared to congruent trials at electrode sites 1, z, 2, and 4, t's $(35) \geqslant 2.3$, $p \leqslant .05$, while no effects were observed at the 3 Site, $t\ (35) = 1.8$, $p = .08$. Decomposition of the Region × Site interaction examined the five Sites within each Region and revealed significant effects at each Region, F's $(4, 140) \geqslant 5.2$, $p \leqslant .003$, $\eta^2 \geqslant .1$, with midline electrode sites demonstrating larger amplitude relative to lateral electrode sites, t's $(35) \geqslant 2.7$, $p \leqslant .01$.

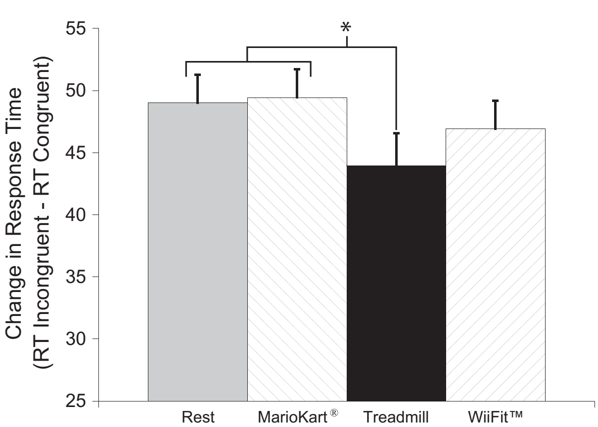

Fig. 2. Mean RT interference (Incongruent RT–Congruent RT; ms ± 1 S.E.) score as a function of experimental condition.

3.4.2. P3. Latency

The omnibus analysis revealed main effects for Congruency, $F\ (1,\ 35) = 80.3$, $p < .001$, $\eta^2 = .7$, and Region, $F\ (4,\ 140) = 16.4$, $p < .001$, $\eta^2 = .3$, which were superseded by a Congruency × Region interaction, $F\ (5, 175) = 3.4$, $p < .05$, $\eta^2 = .09$. Decomposition of this interaction revealed that across all Regions, incongruent trials ($M = 407.2 \pm 3.8$ ms) yielded longer latency compared to congruent trials ($M = 374.9 \pm 4.5$ ms). In addition, a Region × Site interaction was observed, $F\ (16, 560) = 4.7$, $p < .001$, $\eta^2 = .1$. Follow-up analyses indicated significant Region effects for each of the five sites, Fs $(4, 140) \geqslant 4.2$, $p \leqslant .02$, $\eta^2 \geqslant .1$, with faster P3 latency for parietal electrode sites relative to frontal sites, t's $(35) \geqslant 3.6$, $p \leqslant .01$. No effects of Condition were observed for P3 latency $F\ (3,\ 105) = .4$, $p = .8$, $\eta^2 = .01$.

4. Discussion

In the present study, the effects of single bouts of treadmill-based exercise, videogame play, and exergaming on cognition were investigated using neuroelectric and behavioral indices of task performance. The current findings revealed that a single session of moderately-intense, treadmill-based aerobic exercise facilitated task performance and enhanced neuroelectric indices underlying the allocation of attentional resources during a task requiring variable amounts of cognitive control. No such changes were observed following a single session of videogame or exergame play. Specifically, individuals exhibited reduced RT interference and larger P3 amplitude following treadmill-based aerobic exercise, whereas no facilitative or debilitative effects of single bouts of videogame or exergame play were revealed. The current findings indicate that neither exergaming nor seated videogame play served to modulate neuroelectric or behavioral indices of cognition in a manner similar to that of traditional exercise involvement.

The study was designed to hold exercise duration and intensity constant between the two active interventions (i.e., treadmill walking and exergaming). The study protocol was successful in this respect, as HR did not differ across the two conditions, indicating that the overall intensity of the exercise conditions were approximately 60% of HR_{max} during the 20 min period, similar to previous reports of moderate aerobic activity in young adults (Kamijo et al., 2007). Additionally, increased HR was observed during the seated videogame play relative to seated rest, indicating that there was a general increase in arousal during this condition as compared to resting quietly. Such a finding is not unexpected given the engaging nature of videogames relative to less-engaging activities such as reading a newspaper.

Unlike previous research (Orosy-Fildes and Allan, 1989; Bartlett et al., 2009), no changes in RT or accuracy following a single bout of videogame play were evidenced. Orosy-Fildes and Allan (1989) indicated that a single session of videogame play elicited a 50 ms reduction in RT on a visual discrimination task, whereas Bartlett

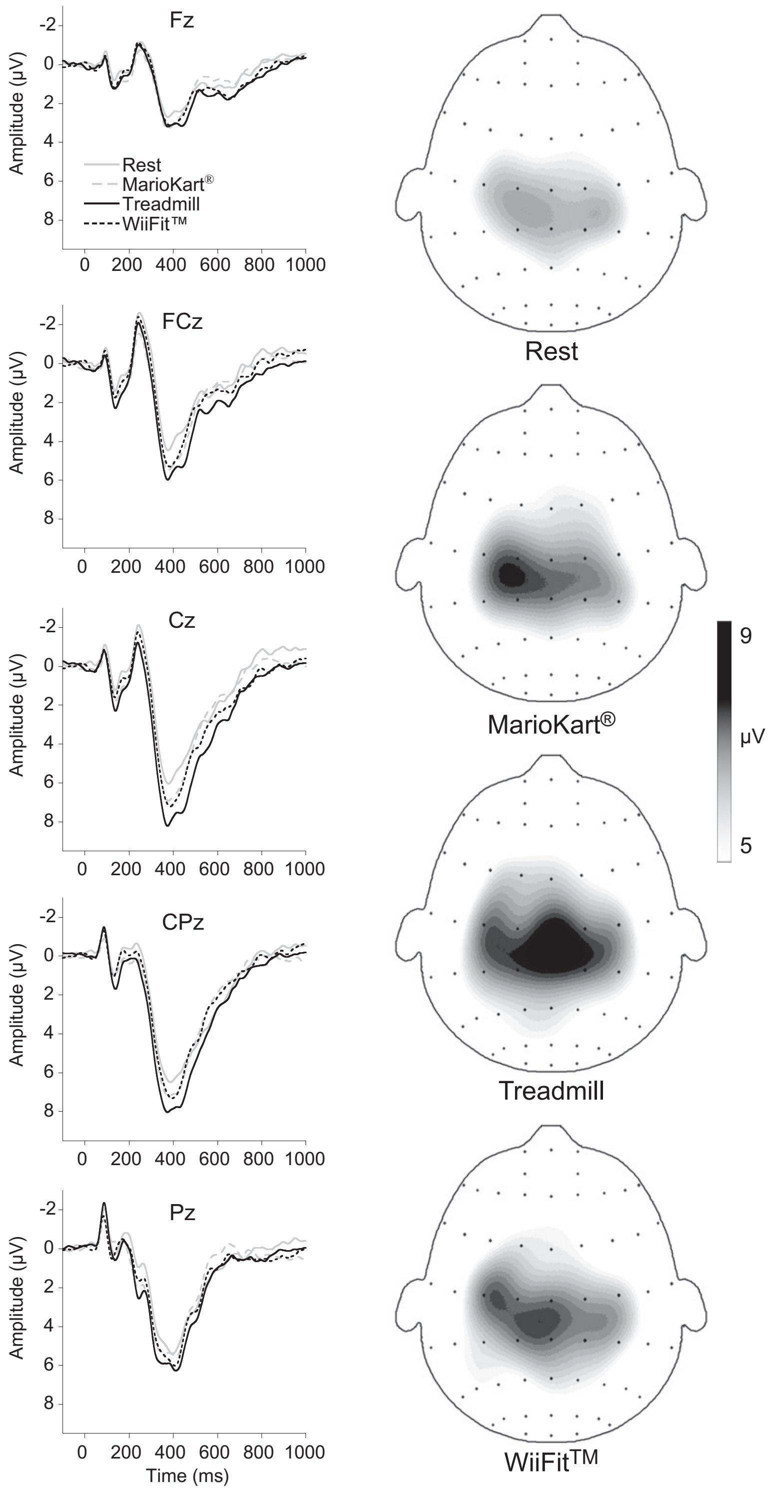

Fig. 3. Stimulus-locked grand-averaged waveforms for each experimental condition at midline sites, collapsed across congruency and topographic maps of P3 amplitude for each experimental condition.

et al., (2009) found that a single session of videogame play increased performance on a task that required cognitive flexibility. Differences between the current study and those reported previously may be due to task parameters and the aspect of cognition examined, as the relationship between a single videogame session and inhibitory control has not been reported previously. Therefore, observed changes in cognition due to single bouts of videogame play may be selective to certain aspects of cognition (i.e., cognitive flexibility). Additionally, this is the first study to assess the P3 component following a single bout of videogaming or exergaming. The present study indicates that a single 20 min bout of active and passive videogame play elicited no changes in this covert measure of cognition, suggesting that videogames do not alter the allocation of attentional resources or stimulus classification speed during a task requiring variable amounts of cognitive control.

Similar to previous research on acute aerobic exercise (Davranche et al., 2009; Hillman et al., 2003; Kamijo et al., 2007), no changes in response accuracy were elicited by any experimen-

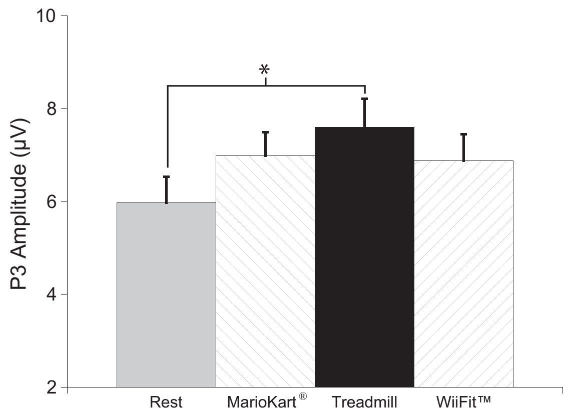

Fig. 4. Mean P3 amplitude (μV; ±1 S.E.) as a function of experimental condition collapsed across all congruencies, regions, and sites.

tal condition. The present study also corroborates previous research that incorporated moderately intensity aerobic exercise (Kamijo et al., 2009), indicating that RT may not be altered following treadmill exercise at 60% of HR_{max}. Novel to this report, a single session of treadmill-based aerobic exercise resulted in a reduction in RT interference compared to both rest and seated videogame play, indicating greater inhibitory control following aerobic exercise. Specifically, the interference effect is an index that examines the cost of managing conflict produced by the presence of irrelevant stimuli in the perceptual field. As such, the present results indicate that a single bout of treadmill-based aerobic exercise may attenuate interference by approximately 10%, suggesting that acute exercise may enhance cognitive control through the management of conflict in the stimulus environment.

The present study also indicates that following the cessation of a single bout of treadmill exercise, P3 amplitude is increased relative to seated rest. This result corroborates numerous studies using similar tasks (Hillman et al., 2003; Kamijo et al., 2007, 2009), and suggests that acute exercise may serve to increase the allocation of attentional resources, as evidenced by an increase in P3 component amplitude. Recent reports (Hillman et al., 2003; Kamijo et al., 2007, 2009) have suggested a general increase in P3 amplitude following a single session of aerobic exercise, with greater amplitude observed across task conditions that manipulated inhibitory requirements. However, P3 latency was unchanged following all experimental conditions. Previous reports have indicated that P3 latency is reduced following a single session of aerobic exercise (Hillman et al., 2003; Kamijo et al., 2007, 2009). However, the present study incorporated a task design where the stimulus duration was shorter than that used in previous research (Hillman et al., 2003; Kamijo et al., 2007, 2009). Such a change in task design may have accounted for the lack of modulation in P3 latency, with increased task difficulty diminishing the effect of exercise on cognitive processing speed. Future research should systematically manipulate stimulus duration to examine the variable exercise-induced changes in P3 latency.

Even though the exercise intensity in the aerobic exercise and exergaming conditions was titrated, cognitive changes were not observed following exergaming. Hockey (1997) proposed a compensatory control model, accounting for the effects on performance observed during stressful conditions or under high workload. This model proposed two adjoining negative feedback loops, where the lower loop controls automatic processes, for maintenance of well learned skills that require little effort. The upper loop manages the regulation of effort during stressful conditions. Relative to the current dataset, treadmill walking may be controlled by the lower loop, as it is an automated skill, where little effort is needed to perform the exercise task. Alternatively, the tasks which comprised the exergaming condition may be cognitively more difficult due to their changing nature and variable attentional control demands for successful task completion. Although practice was afforded to the participants, the dynamic nature of the exergaming environment placed greater demands on cognitive control. Hockey (1997) suggested that during the upper loop, cognitive resources are managed through mobilizing increases in effort to complete the task. Therefore, the potentially beneficial changes that may have been elicited by the aerobic nature of the exergames may have been negated by the constant regulation of effort in a more demanding environment caused by the increased demands of simultaneous exercise and videogame play, resulting in a lack of change along our outcome measures of cognitive control.

In this study, a modified flanker task was used to measure cognitive control. Therefore, only one aspect of cognitive control (i.e., inhibitory control) was investigated in order to understand the relationship between videogame and exergame play on cognition. Future research should examine other aspects of cognitive control to determine the breadth and variability of the observed effects. A second limitation is that the videogame used herein differed from the games employed in previous study. Previous cognitive research on videogames has examined first person shooter, strategy, and other action videogames (Clark et al., 1987; Dustman et al., 1992; Goldstein et al., 1997; Green and Bavelier, 2003; Boot et al., 2008). Therefore, it is difficult to generalize the results of this study to other categories of videogames. Lastly, further research is necessary to elucidate the duration which these exercise induced enhancements in cognition may persist.

The present findings extend previous research indicating alterations in cognitive control following single bouts of aerobic exercise (Hillman et al., 2003, 2009; Kamijo et al., 2007, 2009; Davranche et al., 2009). Specifically, a single bout of treadmill-based aerobic activity was found to facilitate neurocognition by increasing the ability to successfully manage interference and increase the allocation of attentional resources during performance of a task requiring variable amounts of cognitive control. Novel to this study, exergaming, as a form of aerobic exercise, did not successfully alter cognition, and suggests that this type of exercise may differ considerably relative to more traditional means of exercise. Additionally, even though previous research has suggested that long term use of videogames may cause social and/or cognitive impairments (Anderson and Bushman, 2001; Bailey et al., 2009), the present study indicates that a single session of seated videogame play does not enhance or impair cognitive control. Accordingly, although the use of active videogame play has been shown to increase metabolic expenditure (Miyachi et al., 2010) and may be a viable option to increase physical activity, cognitive benefits similar to those derived via traditional forms of exercise may not accrue.

5. Author disclosure statement

The authors declare no competing or conflicting interests.

References

Ainsworth BE, Haskell WL, Leon AS, Jacobs Jr DR, Montoye HJ, Sallis JF, et al. Compendium of physical activities: classification of energy costs of human physical activities. Med Sci Sports Exerc 1993;25:71–80.

American College of Sports Medicine (ACSM). 8th ed. ACSM's guidelines for exercise testing and prescription. New York: Lippincott, Williams, and Wilkins; 2010.

Anderson CA, Bushman BJ. Effects of violent video games on aggressive behavior, aggressive cognition, aggressive, affect, physiological arousal, and prosocial behavior: a meta-analytic review of the scientific literature. Psychol Sci 2001;12:353–9.

Bailey K, West R, Anderson CA. A negative association between video game experience and proactive cognitive control. Psychophysiology 2009;47:34–42.

Bartlett CP, Vowels CL, Shanteau J, Crow J, Miller T. The effect of violent and non-violent computer games on cognitive performance. Comput Hum Behav 2009;25:96–102.

Boot WR, Kramer AF, Simons DJ, Fabiani M, Gratton G. The effects of video game playing on attention, memory, and executive control. Acta Psychol 2008;129:387–98.

Borg G. Perceived exertion as an indicator of somatic stress. Scand J Rehabil Med 1970;2:92–8.

Botvinick MM, Braver TS, Barch DM, Carter CS, Cohen JD. Conflict monitoring and cognitive control. Psychol Rev 2001;108:624–52.

Chatrian GE, Lettich E, Nelson PL. Ten percent electrode system for topographic studies of spontaneous and evoked EEG activity. Am J EEG Technol 1985;25:83–92.

Clark JE, Lanphear AK, Riddick CC. The effects of videogame playing on the response selection processing of elderly adults. J Gerontol 1987;42:82–5.

Colcombe SJ, Kramer AF. Fitness effects on the cognitive function of older adults: a meta-analytic study. Psychol Sci 2003;14:125–30.

Colcombe SJ, Kramer AF, Erickson KI, Scalf P, McAuley E, Cohen NJ, et al. Cardiovascular fitness, cortical plasticity, and aging. Proc Natl Acad Sci USA 2004;101:3316–21.

Compumedics Neuroscan. Offline analysis of acquired data (SCAN 4.3–vol. II, EDIT 4.3) [Software manual]. TX: El Paso; 2003.

Davranche K, Hall B, McMorris T. Effect of acute exercise on cognitive control required during an Eriksen flanker task. J Sport Exerc Psychol 2009;31:628–39.

Diamond A. The early development of executive functions. In: Bialystok E, Craik FIM, editors. Lifespan Cognition: Mecahnism of Change. New York: Oxford University Press; 2006. p. 70–95.

Dustman RE, Emmerson RY, Steinhaus LA, Shearer DE, Dustman TJ. The effects of videogame playing on neuropsychological performance of elderly. J Gerontol 1992;47:168–71.

Fan J, McCandliss BD, Sommer T, Raz A, Posner MI. Testing the efficiency and independence of attentional networks. J Cog Neurosci 2002;14:340–7.

Gentile D. Pathological video-game use among youth ages 8 to 18: a national study. Psychol Sci 2009;20:594–602.

Goldstein J, Cajko L, Oosterbroek M, Michielsen M, van Houten O, Salverda F. Video games and the elderly. Soc Behav Pers 1997;25:345–52.

Green CS, Bavelier D. Action video game modifies visual selective attention. Nature 2003;423:534–7.

Hall CD, Smith AL, Keele SW. The impact of aerobic activity on cognitive function in older adults: a new synthesis based on the concept of executive control. Eur J Cog Psychol 2001;13:279–300.

Hillman CH, Erickson KI, Kramer AF. Be smart, exercise your heart: exercise effects on brain and cognition. Nat Rev Neurosci 2008;9:58–65.

Hillman CH, Pontifex MB, Raine LB, Castelli DM, Hall EE, Kramer AF. The Effect of acute treadmill walking on cognitive control and academic achievement in preadolescent children. Neuroscience 2009;159:1044–54.

Hillman CH, Snook EM, Jerome GJ. Acute cardiovascular exercise and executive control function. Int J Psychophysiol 2003;48:307–14.

Hockey GRJ. Compensatory control in the regulation of human performance under stress and high workload: a cognitive-energetical framework. Biol Psychol 1997;45:73–93.

Hogervorst E, Riedel W, Jeukendrup A, Jolles J. Cognitive performance after strenuous physical exercise. Percept Mot Skills 1996;83:479–88.

Kamijo K, Nishihira Y, Higashiura T, Kuroiwa K. The interactive effect of exercise intensity and task difficulty on human cognitive processing. Int J Psychophysiol 2007;65:114–21.

Kamijo K, Hayashi Y, Sakai T, Yahiro T, Tanaka K, Nishihira Y. Acute effects of aerobic exercise on cognitive function in older adults. J Gerontol B Psychol Sci 2009;64:356–63.

Kaufman AS, Kaufman NL. Kaufman Brief Intelligence Test manual. Circle Pines: American Guidance Service; 1990.

Lichtman S, Poser EG. The effects of exercise on mood and cognitive functioning. J Psychosom Res 1983;27:43–52.

Miyachi M, Yamamoto K, Ohkawara K, Tanaka S. METs in adults while playing active video games: a metabolic chamber study. Med Sci Sports Exerc 2010;46:1149–53.

Oldfield RC. The assessment and analysis of handedness: the edinburgh inventory. Neuropsychologia 1971;9:97–113.

Orosy-Fildes C, Allan RW. Psychology of computer use: XII. Videogame, play: human reaction time to visual stimuli. Percept Mot Skills 1989;69:243–7.

Polich J. Updating P300: an integrative theory of P3a and P3b. Clin Neurophysiol 2007;118:2128–48.

Pontifex MB, Hillman CH. Neuroelectric and behavioral indices of interference control during acute cycling. Clin Neurophysiol 2007;118:570–80.

Pontifex MB, Hillman CH, Fernhall B, Thompson KM, Valentini TA. The Effect of acute aerobic and resistance exercise on working memory. Med Sci Sports Exerc 2009;41:927–34.

Pontifex MB, Scudder MR, Brown ML, O'Leary KC, Wu C, Themanson JR, et al. On the number of trials for stabilization of error-related brain activity across the lifespan. Psychophysiology 2010;47:767–73.

Spencer KM, Coles MGH. The lateralized readiness potential: relationship between human data and response activation in a connectionist model. Psychophysiology 1999;36:364–70.

Thomas S, Reading J, Shephard RJ. Revision of the physical activity readiness questionnaire. PAR-Q. Can J Sport Sci 1992;17:338–45.

Tomporowski PD, Cureton K, Armstrong LE, Kane GM, Sparling PB, Millard-Stafford M. Short-term effects of aerobic exercise on executive processes and emotional reactivity. Int J Sport Exerc Psychol 2005;3:131–46.