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A cross-sectional investigation of acute aerobic exercise intensity on attentional and executive control processing during the Stroop test in healthy aging

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A Cross-Sectional Investigation of Acute Aerobic Exercise Intensity on Attentional and Executive Control Processing during the Stroop Test in Healthy Aging: An ERP Study.

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Contents Page

3.2.1 P3b Amplitudes

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Abstract

Research has argued that effortful cognitive functioning is more susceptible to age-related decline compared to tasks that can be performed with minimal cognitive effort. Aerobic exercise has also been associated with beneficial cognitive effects for tasks implicating higher order executive control processing. Therefore, the current study aims to investigate whether aerobic exercise selectively improves executive control processing which is known to be disproportionately effected by aging, potentially counteracting cognitive deterioration in healthy aging. Although behavioural studies have provided inconsistent findings, EEG/ERP studies investigating the effects of acute exercise intensity on neural activity during executive control tasks are limited in numbers and have mainly focused on younger rather than older populations. Ten healthy participants consisting of five young (mean age = 20±1 years, two male, three female) and five older adults (mean age = 67±4 years, three male, two female) performed a computerised Stroop test with continuous EEG following a 20 minute bout of acute cycling at 40% and 70% heart rate reserve, compared to a no exercise control. Behavioural reaction times showed no significant age effects for exercise condition or congruency, although moderate exercise was associated with the fastest reaction times for congruent trials. The P3b and N450 components also showed no significant higher order effects specific to trial congruency, although significant age effects were observed at the frontal region following acute exercise. The P3b and N450 amplitudes were reduced at the frontal region for the young group following moderate exercise compared to the control, suggesting processing efficiency was enhanced. However, for the older group P3b and N450 amplitudes increased at the frontal region following high intensity exercise compared to moderate, suggesting that high intensity exercise had a negative effect on cognitive processing. Acute exercise does not selectively improve executive control processing during the Stroop test, but rather seems to facilitate a non-specific global activation of neural resources at the frontal region. Acute moderate and high intensity exercise were associated with enhanced frontal processing for young adults, but impaired functioning for older adults. These findings are understood in terms of Compensatory-Related Utilization of Neural Circuits, the Posterior-Anterior Shift in Aging and Scaffolding Theory of Cognitive Aging.

1 - Introduction

A wealth of evidence exists to show that physical activity is associated with positive effects on physical health, mental health and cognitive functioning. Despite the beneficial effects of physical activity, western societies are becoming increasingly inactive with increased prevalence of the negative health consequences associated with sedentary behaviour. The reasons for this growing inactivity are mostly due to advances in technology for occupational and domestic purposes, changing lifestyles, insufficient participation in physical activity, and the over reliance on passive modes of transport. Globally, 23% of adults aged 18 years and over were insufficiently inactive in 2010, with high income countries showing increased inactivity (26% of men, 35% of women) compared to lower income countries (12% of men, 24% of women) (World Health Organization 2015). Additionally, insufficient physical activity is one of the ten leading risk factors for global mortality, with physically inactive people having a 20% to 30% increased risk of death compared to their sufficiently active counterparts (World Health Organization 2015). Although western societies are becoming ever more sedentary, the overall population is also growing increasingly older with a greater proportion of older adults aged 80 years and above. As aging is associated with declines in many cognitive domains essential for daily functioning, an increasingly older population will inevitably have an increased risk of age associated cognitive deterioration impacting their daily activities. In order to meet the cognitive demands of prolonged life expectancy, there is now a growing focus of research exploring strategies in order to reduce the rate of cognitive decline and improve overall brain health and functioning in older adults. As exercise has been associated with positive effects on cognitive functioning, the current research strives to explore whether exercise selectively improves areas of cognitive processing most effected by age-related decline, potentially reducing the rate of cognitive decline in healthy aging.

The aim of the current thesis is to explore whether areas of cognitive functioning susceptible to age-related decline, selectively improve following aerobic exercise at various intensities for both young and older adults. The research also aims to bridge the interdisciplinary gap between Sports Science and Cognitive Psychology by combining neuroscience techniques with experimental exercise to provide a more detailed investigation of exercise-induced effects on higher order cognitive processing in healthy aging. The thesis provides a review of the research exploring exercise effects on cognitive processing, age-related declines in neuronal areas and cognitive functioning, and finally the interaction effects of age and aerobic exercise on cognitive functioning in young and older adults. The evidence reviewed will then be converged to highlight gaps in the current knowledge and inconsistencies in the understanding of how acute exercise at various intensities specifically influences cognitive functioning at behavioural and neuroelectric level during a robust cognitive task with varying demands.

1.1 Exercise Effects & Cognitive Functioning

It has long been established that participation in regular exercise is not only essential for physical health, but is also beneficial for brain health and cognitive functioning (Jennifer et al. 1997; Colcombe et al. 2003; Tomporowski 2003; Hillman, Erickson and Kramer 2008; Hötting and Röder 2013). Physical activity maintained throughout life is now widely associated with reduced risk of many chronic diseases such as cancer, type 2 diabetes, and cardiovascular diseases (Durstine et al. 2013). However, in England only 40% of men and 28% of women meet the government's recommended physical activity guidelines of 30 minutes moderate intensity activity on five days per week, or 75 minutes of vigorous activity per week (Department of Health 2011). Considering the potential applications of physical activity for the prevention of chronic diseases, there is now a growing focus on exploring the effects of physical activity and exercise in order to reduce the risk of cognitive dysfunction and risk of neurodegenerative illnesses (National Institute of Aging 2011; Bherer et al. 2013).

Moderate intensity aerobic physical activity (60% maximum heart rate or VO_2) is associated with a reduced risk of mild cognitive impairment (MCI) and dementia and may slow the rate of dementing illness (Ahlskog et al. 2011). Interestingly, any frequency of moderate intensity exercise (brisk walking, moderate use of exercise machines, swimming, tennis doubles, golfing without a cart, weight lifting) carried out in mid or later life was associated with a reduced risk of MCI, whereas light (leisurely walking, stretching, slow dancing, golfing with a cart) and vigorous intensity exercise (jogging, intense use of exercise machines, cycling up hill, backpacking, tennis singles) were not significantly linked (Geda et al. 2010). High levels of daily physical activity have also been associated with a decreased risk of Alzheimer's disease (Buchman et al. 2012), further supporting the neuro-protective benefits of physical activity.

Research examining the effects of physical activity and exercise on cognitive functioning typically stem from two areas of research activity. The first examines the long term effects of habitual physical activity on cognitive functioning known as chronic effects, whereas the other assesses the short term effects of a single bout of exercise on cognitive processing known as acute effects (McMorris et al. 2009). The effects of acute exercise on psychological and behavioural indices of cognition are rapidly induced during exercise (seconds-minutes), although they also disappear relatively quickly after exercise termination which is usually viewed as a transient modulation of the neural networks (McMorris et al. 2009). On the other hand, the effects of chronic exercise of cognitive processing usually begin gradually after a few weeks of training and result in longer lasting neuroanatomical changes in the brain (McMorris et al. 2009).

A systematic review of the research studying the effects of chronic physical activity concluded that long term habitual physical activity was associated with positive effects on cognitive functioning (Cox et al. 2015). In older adults, baseline cardiorespiratory fitness was positively associated with the preservation of cognitive functioning over a six year period for attention, processing speed, executive functioning and working memory, suggesting fitness may protect against cognitive decline in healthy aging (Barnes et al. 2003).

When examining the effects of acute aerobic exercise on cognitive functioning, individual fitness levels have also been highlighted as a potential moderator of short term exercise effects (Themanson and Hillman 2006; Stroph et al. 2009; Chang et al. 2012; Chang et al. 2014). The effects of fitness training on cognitive functioning usually yield small to moderate effect sizes for spatial-attention, processing speed and memory, with the strongest effect sizes found for executive control abilities (Colcombe et al. 2004; Smith 2010). This is consistent with assumption that tasks which require effortful processing are more sensitive to the effects of fitness than tasks which can be performed with or without minimal attention (Chodzko-Zajko 1991). Executive functioning has been defined as higher level meta-cognitive functioning that regulates attention necessary for planning, decision making, error correction and goal-directed behaviours (Etnier and Chang 2009). It is usually found that individuals' with greater physical fitness demonstrate more efficient executive control abilities compared to their lower fit counterparts (Hillman et al. 2004; Themanson and Hillman 2006; Stroth et al. 2009), supporting the theory that physical fitness may improve top-down attentional processing.

Evidence from a meta-analytic study found that aerobic fitness training had robust but selective benefits on cognitive functioning, with the largest fitness effects observed for executive control processes (Colcombe and Kramer 2003). Individuals of all fitness levels benefit from acute aerobic exercise but interestingly, a moderate level of fitness was associated with the most efficient executive functioning (Chang et al. 2014). This indicates that fitness may influence cognitive processing in an inverted-U fashion, with moderate levels of fitness associated with the greatest cognitive benefits for higher level executive control processing.

Research examining the acute effects of exercise on cognition usually shows an overall positive effect of exercise on cognitive performance, although the effect is generally small (Chang et al. 2012). It has been found that aerobic exercise is associated with modest improvements in attention, processing speed, executive functioning and memory (Smith et al. 2010). However, it has also been argued that physical fitness is associated with enhanced attentional control, but an acute bout of aerobic exercise is not beneficial to neural indices of executive processing (Themanson and Hillman 2006; Stroth et al. 2009). In line with this theoretical argument it has been reported that response inhibition may be impaired during acute exercise (Davranche and McMorris 2009). A meta-analytic study reviewing the effect of acute bouts of exercise on cognition concluded that sub-maximal aerobic exercise performed for periods up to 60 minutes facilitates selective aspects of information processing (Tomporowski 2003). These findings are also consistent with research which found significant increases in processing speed and a reduction in errors immediately after less than 30 minutes of aerobic exercise (stairs climbing until maximum heart rate elevated to 50-70%) (Tam 2013). Additionally, it has been argued that extraneous exercise which leads to dehydration may have a negative effect on information processing (Tomporowski 2003).

Conflicting findings from studies employing varying methodologies makes comparing the effects of exercise on cognition between studies difficult. When reviewing research in relation to the effects of exercise on cognition, there are several important factors to be taken into account which may limit the extent to which the findings can be compared or generalised. Firstly, it is of vital important to consider the timings of when exercise is performed and when cognition is assessed. For example, cognitive functioning is typically impaired during the first 20 minutes of exercise, which is believed to reflect the neurological and metabolic changes occurring in the body during physical activity (Lambourne and Tomporowski 2010). During exercise the body attempts to maintain homeostasis which includes energy utilisation, temperature regulation and the loss of fluids due to sweating (McMorris et al. 2009). For tasks which require effortful processing dependant on prefrontal activation, this homeostatic modulation can sometimes override the positive effects of exercise and impair cognitive performance (Dietrich and Sparling 2004; Dietrich 2006). A meta-analytic study highlighted that small positive exercise effects have been found during exercise, immediately following exercise or after a standardised delay (Chang et al. 2012). Therefore, when assessing the effects of exercise on cognitive functioning it is crucial to consider when exercise was performed in relation to the cognitive assessment.

A second important issue to consider is the type of exercise task conducted with different modes of exercise having differential influences on cognition (Smiley-Oyen et al. 2008; Liu-Ambrose et al. 2010). For example, research has indicated that cycling was associated with enhanced performance during and after exercise, whereas, running on a treadmill impaired performance during exercise and led to small improvements in performance after exercise (Lambourne and Tomporowski 2010). Although acute exercise may improve some aspects of cognition, homeostatic imbalances during acute exercise can also impair cognitive performance, particularly during energy demanding exercise modes such as running. Following exercise, the body rapidly regulates the exercise induced metabolic and neurological changes although exercise effects on cognitive functioning may still be evident, particularly for areas of cognition susceptible to exercise effects such as executive control (Joyce et al. 2009).

Exercise intensity also has a significant influence on the cognitive benefits of acute exercise. For example, research examining the effects of acute exercise on cognition has found that 30 minutes of moderate cycling exercise (40% of maximal aerobic power) can positively influence cognitive performance and this beneficial effect is evident for up to 52 minutes after exercise (Joyce et al. 2009). More importantly, it has been reported that 30 minutes of moderate cycling exercise (40% of maximal aerobic power) can positively influence response execution and response inhibition (Joyce et al. 2009). Information processing has been found to decrease after high intensity cycling exercise (volitional exhaustion according to rating of perceived exertion (RPE)) and increase after medium intensity cycling exercise (12-14 RPE) (Kamijo et al. 2004). This is consistent with research which has found high intensity exercise to be associated with negative effects on information processing (Tomporowski 2003; Kamijo et al. 2004). However, no significant change in information processing was found after low-intensity cycling (7-9 RPE) compared to a control (Kamijo et al. 2004). Therefore, it appears that acute cycling may influence attentional processing in a curvilinear relationship, with moderate intensity exercise yielding the most efficient processing, which has been supported by previous research (Kamijo et al. 2007).

Many cognitive tasks have been used to investigate the effects of acute exercise on attentional and executive functioning such as the go/no-go reaction time test (Kamijo et al. 2004), the auditory and visual oddball tasks (Magnié et al. 2000; Grego et al. 2004; Duzova et al. 2005), the Simon test (Davranche and McMorris 2009), the Eriksen Flanker task (Hillman et al. 2003; Kamijo et al. 2007; Kamijo et al. 2009; Peiffer et al. 2015) and the Stroop Colour-Word test (Barella et al. 2010; Yanagisawa et al. 2010). According to the proposal that exercise effects are largest for tasks which require effortful processing, cognitive paradigms which manipulate the level of executive control required between task trials are essential to explore the selective effects of acute exercise for both automatic stimulus-driven and goal-directed top down attentional processing. Tasks such as the Eriksen flanker task have shown processing effects for executive control in relation to acute exercise (Hillman et al. 2003; Kamijo et al. 2007; Kamijo et al. 2009; Peiffer et al. 2015) and physical activity levels (Hillman et al. 2004). Therefore, it seems reasonable to suggest that if executive control abilities are truly influenced by acute exercise and physical activity levels, this effect should be evident on similar executive control tasks such as the Stroop Colour-Word test.

The Stroop test (Stroop 1935) assesses two types of cognitive functioning (information processing, executive functioning) simultaneously within the same behavioural paradigm with the same instructions and response requirements. The Stroop test consists of both congruent and incongruent trials and requires the participant to name the font colour of the word presented while inhibiting the semantic meaning of the word itself (Stroop 1935). Performance on congruent trials (the word BLUE presented in blue ink) has typically been used as a measure of automatic attentional processing speed, whereas incongruent trials (the word GREEN presented in red ink) have usually been employed as a measure of top-down executive control abilities (Etnier and Chang 2009). The Stroop Interference effect refers to the increase in reaction times (RTs) for incongruent trials compared to congruent trials and is believed to reflect executive control abilities such as inhibition and interference control (MacLeod 1991). Inhibition has been defined as the ability to actively inhibit a proponent response tendency, whereas, interference has been defined as the ability to control interference from task irrelevant information (West 1996). The Stroop test is widely established as an ‘active paradigm’ in the study of inhibitory processes due to the active suppression of task-irrelevant information (the semantic meaning of the word stimuli) required performing the task (Kok 1999).

Research employing the Stroop test to examine the effect of exercise intensity manipulations has found that high intensity cycling exercise (75% of maximal work capacity) improved performance on trials implicating interference and also improved behavioural RTs (Hogervorst et al. 1996). Additionally, in young adults lower fit individuals showed increased Stroop test performance instability in inhibitory processing at a behavioural level during high intensity exercise compared to individuals with a greater physical fitness (Labelle et al. 2013). Research has also indicated that 20 minutes of self-paced moderate treadmill exercise led to improved performance on Stroop trials implicating interference (Sibley et al. 2006). However, it was concluded that exercise facilitates the processing of relevant information rather than increasing inhibition of irrelevant stimuli (Sibley et al. 2006). Consistent with these findings, 20 minutes of acute walking (60% heart rate reserve) was associated with improved processing speed on congruent trials, but no effects were observed for measures of interference or inhibition (Barella et al. 2010). In contrast, research using functional near-infrared spectroscopy (fNIRS) found that acute moderate exercise improved Stroop interference performance and increased activation in brain regions associated with Stroop interference, such as the left dorsolateral prefrontal cortex (Yanagisawa et al. 2010). This enhanced activation was also found to significantly correspond with improved cognitive performance on the Stroop test (Yanagisawa et al. 2010).

1.2 Employing EEG/ERPs to Investigate the Effects of Acute Exercise on Cognitive Functioning

As the Stroop test assesses multiple areas of cognitive processing, this allows for exercise intensity manipulations to be simultaneously assessed across two areas of cognition while also having the capacity to be combined with a continuous record of electroencephalogram (EEG). The processing of task-relevant information (indexed by congruent trials) and executive control functioning (indexed by incongruent trials) can be assessed by two independent data collection methods (behavioural RTs, continuous EEG brain activity) to analyse the effects of differential intensity exercise on information processing and executive control simultaneously. The continuous measure of brain activity obtained allows for electrophysiological neural activity to be time-locked to a specific event (Luck 2005; Woodman 2010), such as trials in the Stroop test. The method of time locking postsynaptic potentials to a sensory or motor response is known as the event-related potential technique (ERP) (Luck 2005; Sur and Sinha 2009). The ERP method is very useful for assessing underlying attentional processing due to the high temporal resolution of ERP measures (ms) which provides a direct and objective measure of the stages of attentional processing influenced by an experimental manipulation (Luck 2005). Furthermore, previous ERP research has found that acute bouts of cardiovascular exercise effects underlying neuroelectric activity associated with executive control processing (Hillman et al. 2003).

The ERP method has considerable benefits compared to the traditional behavioural assessments of cognitive processing measuring speed and accuracy of motor responses in goal-directed attentional paradigms. For example, overt responses made in behavioural paradigms reflect the output of multiple cognitive processes, making it difficult to attribute the differences to a distinct cognitive process (Luck 2005). In behavioural tasks such as the Stroop test, it is difficult to isolate the stages of processing responsible for the increase in reaction times for incongruent trials, as this could possibly reflect the slowing of perceptual processes or the slowing of response processing. By employing the ERP method, it is possible to identify the exact stage or stages of processing effected by an experimental manipulation (Luck 2005). Similarly, behavioural responses are reliant on psychomotor speed processing which is also known to decline with age (Spirduso 1980; Keys and White 2000). Therefore, increased RTs during cognitive tasks may reflect the slowing of motor processing rather than deficiencies in specific attentional processing domains such as executive control. ERP measures overcome this limitation as they provide the capacity to covertly monitor the online processing of information between the stimulus and response, which is arguably the greatest advantage of the method (Luck 2005).

Inconsistent behavioural findings from studies examining moderate and high intensity exercise effects on individual elements of the Stroop test could be resolved by employing EEG as a measure of cognitive processing. This would provide a more detailed insight into whether exercise selectively benefits executive functioning such as the top-down regulation of attentional resources and the evaluative detection of behavioural conflict, or whether acute exercise causes a general global activation and facilitation of the attentional networks. However, using EEG as a measure to examine exercise effects on cognitive functioning is not without methodological problems. EEG measures are very sensitive to movement and require participants to remain still during recording in order to ensure a clear signal which is easily disrupted by bodily movements, making it particularly difficult to record brain activity during exercise.

Neuroimaging studies have reported the effects of exercise on cognition after a delay, but neural activation associated with a cognitive task sometimes rapidly returns to baseline after the cessation of exercise (Dietrich 2006). This contributes to the difficulty of interpreting the neural activity recorded after acute exercise as this may not be a true representation of neural activity during acute exercise (Dietrich 2006). Nevertheless, research has explored neuroelectric indices of cognitive processing during (Grego et al. 2004; Pontifex and Hillman 2007) and following acute exercise (Magnié et al. 2000; Hillman et al. 2003; Kamijo et al. 2004, Duzova et al. 2005; Themanson and Hillman 2006; Kamijo et al. 2009). In order to examine how acute exercise specifically influences stages of cognitive processing in young and older adults, the combination of behavioural and ERP measures provides a deeper investigation of exercise-induced effects on cognitive processing and attempts to resolve theoretical inconsistencies in the research area.

1.3 Age and Cognitive Functioning

In order to explore whether exercise is selectively beneficial for aging cognition in older adults, it is important to understand how aging typically effects cognitive functioning and the context in which cognitive decline occurs. Increased life expectancy, population growth and a long term decline in the average number of children being born has resulted in an aging population. More importantly, despite the older population having an extended life expectancy, this is not necessarily accompanied by prolonged good health or extended productivity (National Institute of Aging 2011). For example, aging is often associated with an increased risk factor for many major chronic and degenerative diseases, so a growing aging population will inevitably become more reliant on health and social care services in the future.

Considering the challenges of an aging population, there is now growing interest in ways to maintain healthy cognitive functioning, delay the onset of age-related decline, or reduce the rate of age-associated cognitive deterioration in order to meet the demands of prolonged life expectancy.

Declines in cognitive functioning with increased age are inevitable and many areas of cognition such as processing speed, reasoning, memory and executive functions deteriorate over the life span (Deary et al. 2009). In healthy adults some aspects of cognition begin to show age-related decline as early as the second and third decades of life, although age-related effects rapidly accelerate from the sixth decade of life (Salthouse 2009; Verhaeghen and Salthouse 1997). Research has showed that older adults exhibit greater reductions in psychomotor speed responses (Spirduso 1980; Keys and White 2000), working memory and processing speed (Salthouse 1991; Verhaeghen and Salthouse 1997), episodic memory (Verhaeghen and Salthouse 1997), and executive functioning (Keys and White 2000; Wecker et al. 2000). However, a common misconception is that age-related decline only begins after 50 years of age or later, with research indicating that some aspects of cognition can slowly degrade from early adulthood onwards (18-50 years) (Verhaeghen and Salthouse 1997).

Cognitive deterioration in normal aging does not impact all neuronal areas and cognitive processes at a standardised rate (Kramer et al. 1999). It is theorised that the frontal lobes are the last region of the brain to develop, but are also the first region to show signs of age-related deterioration (Dempster 1992). According to the frontal lobe deterioration theory, executive functions associated with these regions are impacted disproportionately by age-related decline (West 1996; Kramer et al. 1999).

Theories of cognitive aging have argued that an underlying decline in the function of the dopamine system projection to the prefrontal cortex results in impaired performance across multiple domains including attention, inhibition and working memory (Braver et al. 2001; Braver and Barch 2002). Executive functions associated with attention, such as inhibition and interference, are both susceptible to age-related decline (West 1996). If theories of cognitive aging are accurate, it is reasonable to assume that age-related declines in attentional control will be evident on tasks implicating interference suppression and response inhibition.

The Inhibitory Deficit Hypothesis proposed by Hasher and Zacks (1988), suggests that in normal aging older adults typically exhibit a breakdown in inhibitory processes which results in a reduced efficiency to inhibit the processing of task-irrelevant information (Dempster 1992; West 1996). According to the Inhibitory Deficit Hypothesis (Hasher and Zacks 1988), older adults should perform more poorly than younger adults on executive control paradigms such as the Stroop test (Stroop 1935). Research employing the Stroop test has found that older adults show a disproportionate increase in Stroop interference compared to younger adults, which supports the hypothesis of an inhibitory breakdown in healthy aging (Cohn et al. 1984; Spieler et al. 1996; West and Alain 2000a; Van der Elst et al. 2006). Research employing fMRI found that older adults showed a decreased responsiveness in brain regions associated with attentional control during the Stroop test, such as the dorsolateral prefrontal cortex (Milham et al. 2002). This may suggest that older adults exhibit limitations in flexibly recruiting the attentional network in response to increasing attentional demands, possibly reflecting a reduced efficiency of cortical regions responsible for implementing attentional control (Milham et al 2002; Prakash et al. 2009).

ERP research examining attentional control processing found that older adults execute selective attention less efficiently than younger adults and also perform more poorly on conditions which require suppression (Haring et al. 2013). Interestingly, older adults also exhibited enhanced neural processing on task relevant conditions, which is believed to reflect compensatory brain mechanisms (Haring et al. 2013). Further supporting these findings, fMRI research has shown that healthy older adults demonstrate impairments in the suppression of cortical activity associated with task-irrelevant stimuli, whereas enhanced processing of task-relevant stimuli was preserved (Gazzaley et al. 2005). According to the Compensation-Related Utilisation of Neural Circuits Hypothesis (CRUNCH), the aging brain recruits compensatory neural resources in order to combat the effects age-related declines in processing efficiency (Dinteren et al. 2014). This compensatory recruitment often results in an increase in neural activity in the prefrontal regions and increases bilateral hemispheric processing, which may be associated with enhanced cognitive performance in older adults (Dinteren et al. 2014; Cabeza 2001; Cabeza et al. 2004). Taken together, these findings strongly support the Inhibitory Deficit Hypothesis (Hasher and Zacks 1988; West 1996) and also suggest that the processing of task-relevant stimuli may sometimes be enhanced in normal aging due to compensatory mechanisms. As exercise has been associated with improved cognitive processing, research is now exploring whether exercise may be used as an intervention to counteract cognitive aging and potentially reduce the rate of cognitive decline in healthy older adults.

1.4 Exercise, Age and Cognitive Functioning

It has been argued that exercise may have selective benefits for cognitive functioning in older adults, with the greatest benefits for tasks which involve the frontal and prefrontal brain regions, such as executive control processing (Kramer et al. 1999; Colcombe and Kramer 2003). Research conducted over a six month period found that aerobic training (walking) significantly improved interference control, whereas anaerobic training (stretching, toning) did not (Kramer et al. 1999). Interestingly, no differences in cognitive performance were found between the two groups for congruent trials, suggesting that aerobic exercise only benefitted executive control processing (Kramer et al. 1999). These findings are consistent with the Selective Improvement Hypothesis (Kramer et al. 1999) as aerobic exercise selectively improved executive functioning in normal aging. Similarly, research investigating the effects of physical activity levels on three executive processes (shifting, inhibition and updating) in older adults found that physical activity scores were significant for inhibition, but not for updating and shifting (Boucard et al. 2012). This partially supports the Selective Improvement Hypothesis but also suggests that physical activity levels may specifically benefit executive control and not all types of executive functioning.

In relation to ERP components employed to assess attentional and executive control processing, there are multiple early and late components associated with different stages of attentional processing and the nature of the cognitive task. ERP components are normally defined by their polarity (positive or negative going voltage), timings (latency window), scalp distribution, and sensitivity to task manipulations (Woodman 2010). Early stage ERP components which have been used to investigate visual attention include the sensory and perception-related P1 component, the N1 associated with spatial attention and visual discrimination, the target-related P2, and the N2 associated with object recognition and categorisation (Luck 2005; Woodman 2010). Later stage ERP components such as the P3 is associated with cognitive load and the N450 implicated in conflict monitoring, reflect higher order meaningful cognitive processing such as stimulus evaluation, working memory processing, context updating and goal-directed behaviour (Luck 2005; Woodman 2010). ERP research examining age-related differences during the Attention Network Test (ANT) found that earlier ERP components related to alerting and orienting aspects of attention were similar for both young and old age groups, whereas, later components associated with information processing and executive control processing showed age differences (Williams et al. 2016).

The P3 component, also known as the P300, is the largest ERP component in the ERP waveform although timings can vary widely from 250-900ms (Patel & Azzam 2005). The P3 component consists of two distinct sub-components, the P3a sub-component which is associated with frontal activity and stimulus-driven attentional processing, and the P3b related to temporal-parietal activity associated with attention and memory processing (Polich 2007). However, it should be noted that many studies do not make the distinction between the P3a and P3b sub-components and the majority of studies referring to the P3 component are usually examining the P3b (Luck 2005).

The P3b amplitude is sensitive to the amount of attentional resources engaged during attentional tasks and is therefore useful for examining information processing in relation to tasks with varying cognitive demands (Polich 2007). As the Stroop test includes both congruent (indexing general information processing) and incongruent (indexing executive control) trials with the same set of instructions and responses, the P3 was selected as a measure of resource allocation in the current study. Additionally, the P3 is also thought to be related to stimulus evaluation, probability sequences, and the processing of target stimulus events in attentional tasks (Patel & Azzam 2005; Polich 2007). Research employing ERPs has indicated that the Stroop interference effect occurs within the latency window of the P3a and P3b, approximately 300-450ms post-stimulus, and suggested that semantic conflict delays the response process explaining the longer RT for incongruent trials (Zurron et al. 2009).

ERP research examining executive control found that moderate and high physically active older adults (indexed by the Yale Physical Activity Survey) exhibited increased P3 amplitude at the frontal region on interference trials compared to younger adults (Hillman et al. 2004). Similarly, P3 latencies were significantly longer for low and moderately active older adults, but were not significantly different for the high active older adults compared to the younger group (Hillman et al. 2004). This suggests that high physical activity levels are associated with increased frontal P3 amplitudes and reduced P3 latencies, possibly reflecting enhanced attentional processing in healthy aging. In addition, research investigating the effects of acute cycling on executive processing found that regardless of age group, reaction times improved following moderate exercise (50% VO_2 max) (Kamijo et al. 2009). Corresponding ERP data also revealed that P3 latencies were also shorter for both age groups following light (30% VO_2 max) and moderate exercise, whereas, P3 amplitude only increased for younger adults following moderate exercise (Kamijo et al. 2009).

Research examining the effects of physical activity levels in relation to age found that long term physically active (approximately 50 years) older adults exhibited enhanced executive control processing on the Stroop test at both a behavioural and neuroelectric level, compared to their low physically active counterparts (Gajewski and Falkenstein 2015). It has been reported that low physically active older adults showed lower activation in the anterior cingulate cortex, a region associated with attentional control and conflict processing (Colcombe et al. 2004). This is further supported by higher fitness levels being associated with enhanced behavioural performance and increased activation in the prefrontal and parietal cortices for the most challenging Stroop condition (Prakash et al. 2011). These results suggest that physical fitness is associated with enhanced cognitive functioning and increased activation in brain areas involved in neural processing during the Stroop test. However, a hierarchal regression study found that physical activity scores indexed by the Yale Physical Activity Survey explained a small, but significant amount of variance on Stroop performance after accounting for intelligence and age (Bixby et al. 2007). This suggests that chronic physical activity is associated with enhanced cognitive performance and brain activation for trials implicating executive control during the Stroop test, although the effect may be small.

Research conducted over a three month period (three 60 minute sessions per week) found that aerobic exercise training, consisting of stretching and cardiorespiratory exercises (fast walking, aerobic dancing) significantly improved Stroop test performance in older adults, but only for the inhibition/switching condition and not the interference condition (Predovan et al. 2012). Similarly, longitudinal research examining the effects of 10 months of aerobic or strength and flexibility training (three sessions per week for 25-30 minutes) in older adults found that cognitive performance in tasks requiring minimal executive control were unaffected by aerobic training, whereas Stroop interference selectively improved only for the aerobic fitness group (Smiley-Oyen et al. 2008). A 12 month controlled trial assessing executive functioning in older adults also found that once-weekly or twice-weekly resistance training (40 minutes), significantly improved executive control and conflict resolution during the Stroop test compared to a twice-weekly (40 minutes) balancing and toning group (Liu-Ambrose et al. 2010). This suggests that aerobic fitness training has selective benefits for older adults, specifically for executive control processing which is consistent with the Selective Improvement Hypothesis (Kramer et al. 1999).

Research employing fNIRS found that 10 minutes of moderate cycling (50% VO_2 max) significantly improved Stroop performance in older adults and revealed that this improvement was associated with compensatory contralateral activation (Hyodo et al. 2012). This is further supported by research examining cerebral blood flow during the Stroop test which found regardless of age, executive control is improved during acute cycling at 30% and 70% heart rate reserve (Lucas et al. 2012). In younger adults, the effects of 20 minutes acute moderate cycling (65% VO_2 max) were found to significantly enhance Stoop test performance for all fitness groups (low, moderate, high), compared to the pre-exercise baseline measures (Chang et al. 2014). Interestingly, for congruent trials no significant differences were found based on fitness grouping, whereas for incongruent trials the low (average VO_2 peak = 35.25) and moderate (average VO_2 peak = 45.52) fitness groups performed significantly quicker than the high group (average VO_2 peak = 56.21) (Chang et al. 2014).

ERP research examining acute exercise effects on executive control have typically selected the P3 ERP component to examine cognitive processing (Hillman et al. 2003; Kamijo et al. 2007; Kamijo et al. 2009). The P3 is usually employed as a measure of attentional allocation and stimulus evaluation in goal-directed attentional paradigms (Patel & Azzam 2005; Polich 2007). However, as to date no research has examined the effects of differential intensity aerobic exercise (cycling) on Stroop test performance indexed by the P3 component for both young and older adults.

A second important ERP component related to executive control processing is the N450 which has previously been attributed to conflict processing with an enhanced N450 amplitude produced for trials implicating higher conflict (Lansbergen et al. 2007). As the Stroop test varies the degree of attentional control required during the task with incongruent trials requiring increased attentional control, the N450 was selected as a measure of evaluative conflict processing. FMRI studies have pointed to several brain areas implicated in conflict processing, with the anterior cingulate cortex being the most prominent and active in nearly all studies examining conflict processing (Szucs and Soltesz 2012). However, within the N400 component group (ranging from 200-600ms post stimulus onset), evidence supports multiple distinct components related to conflict processing. The N450 component is thought to be associated with conflict detection whereas the later conflict sustained potential (SP) is believed to be associated with the resolution of conflict (Kray et al. 2005).

Recently, the N450 has been examined in relation to long term physical activity and age during the Stroop test, showing that high physically active older adults exhibited more negative amplitudes of the fronto-central N450 (Gajewski & Falkenstein 2015).

It was concluded that long term physical activity was associated with enhanced activity in the frontal cortex possibly enabling more efficient interference resolution in the Stroop test (Gajewski & Falkenstein 2015). However, as to date no research has examined the effects of acute aerobic exercise and age in relation to the N450 component, previously implicated in conflict and executive control processing (Lansbergen et al. 2007; Tillman & Wiens 2011; Szucs and Soltesz 2012). Therefore, it is currently unclear how acute aerobic exercise intensity influences both P3b and N450 amplitudes during the Stroop test for young and older adults.

1.5 Aims, Objectives and Hypotheses

Aims

The aims of the current study were to investigate the effects of acute bout of aerobic exercise (cycling) at both a moderate and high intensity compared to a no exercise control, on behavioural RTs and neural indices of information processing (P3b) and executive control functioning (N450) during the Stroop test in relation to age. The study also aimed to examine the interaction between physical activity levels (low, moderate, high), cognitive functioning and acute aerobic exercise effects.

Objectives

The present study had a number of objectives which are outlined bellow:

1) To measure the effects of an acute bout of aerobic exercise at different intensities (40% heart rate reserve, 70% heart rate reserve) compared to a no exercise control on information processing and executive control functioning indexed by the Stroop test.

2) To measure habitual physical activity levels using the International Physical Activity Questionnaire.
3) To measure heart rate during an acute bout of cycling.
4) To measure behavioural RTs during Stroop congruent and incongruent trials after an acute bout of aerobic exercise.
5) To measure neural correlates of information processing and stimulus evaluation, namely the P3b ERP component amplitude during Stroop congruent and incongruent trials after an acute bout of exercise.
6) To measure neural correlates involved in executive control processing and conflict monitoring, namely the N450 ERP component amplitude during Stroop congruent and incongruent trials after an acute bout of exercise.

Hypotheses (H)

The present study formulated a series of hypotheses relating to the behavioural and EEG elements of the study design which are listed below:

Behavioural Element:

H1 – There will be no significant main effects of congruency, exercise condition, or physical activity group.

H2 – There will be a significant main effect of age group with the younger group performing faster than the older group.

H3 – There will be a significant interaction effect of age group and congruency, with the younger group performing faster than the older group on incongruent compared to congruent trials.

H4 – Moderate intensity exercise compared to the control, will significantly decrease RTs for congruent and incongruent trials for both age groups.

H5 – High intensity exercise compared to the control condition, will significantly increase RTs for congruent and incongruent trials for both age groups.

H6 – High intensity compared to moderate intensity exercise will significantly increase RTs for congruent and incongruent trials for both age groups.

EEG Element:

H7 – There will be no significant main effect of electrode position, congruency, exercise condition, physical activity group, and age group.

H8 – Relative to the control, moderate intensity exercise will significantly reduce P3b and N450 amplitudes for incongruent compared to congruent trials for both the young and older age groups.

H9 – Relative to the control, high intensity exercise will significantly increase P3b and N450 amplitudes for incongruent compared to congruent trials for both the young and older age groups.

H10 – Relative to moderate intensity, high intensity exercise will significantly increase P3b and N450 amplitudes for incongruent compared to congruent trials for both the young and older age groups.

2 – Method Section

2.1 Design

2.1.1 Behavioural Element

A 2 (congruency; congruent, incongruent) x 3 (exercise task; control, moderate intensity, high intensity) x 2 (age group; young, old) multifactorial mixed method design was employed to examine the effects of age and cycling intensity on cognitive functioning during Stroop congruent and incongruent trials. Age group was the between groups factor, whereas, congruency and exercise intensity were the repeated factors. The dependent variable was the behavioural RTs (ms) for congruent and incongruent trials recorded during a computerised Stroop task completed after the exercise task was performed.

2.1.2 EEG Element

A 3 (electrode position; FZ, CZ, PZ) x 2 (congruency; congruent, incongruent) x 3 (exercise task; control, moderate, high) x 2 (age group: young, old) multifactorial mixed method design was employed to examine the effects of age and cycling intensity on cognitive functioning during Stroop congruent and incongruent trials. Age group was the between groups factor, whereas, electrode position, congruency and exercise condition were the repeated factors. EEG was continuously recorded during the Stroop task to allow experimentally induced changes in event related potentials (ERPs) associated with information processing and executive functioning to be examined. The dependent variable was the mean amplitude (μV) for the P3b and N450 ERP components during Stroop congruent and incongruent trials.

2.2 Participants

Following ethical approval by Coventry University Human Research Ethics Committee, participants were opportunity sampled from two independent sources based upon the participants' age. Participants recruited for the young age group (defined as those below the age of 25 years), consisted of undergraduate Psychology and Sports Science students from Coventry University. Participants for the older age group (defined as those above the age of 60 years), were recruited from a community group via a member of University staff. Participants were included if they were free from neurological damage or cognitive impairment, with normal or corrected-to-normal vision, and were physically and medically able to perform the two 20 minute experimental exercise tasks. All participants were right handed as indexed by the Edinburgh Handedness Inventory-revised (Oldfield 1971; Williams 1986). All older participants and undergraduate students from Sports Science volunteered to participate in the research and received no payment for participation, whereas undergraduate Psychology students received 720 research participation credits via Coventry University's SONA system.

The study consisted of 10 healthy participants who were categorised into either the young or older age group. The young age group consisted of five participants (two male, three female) with a mean age of 20±1 years. The older age group also consisted of five participants (three male, two female) with a mean age of 67±4 years.

2.3 Measures

2.3.1 Physical Activity Levels

Physical activity levels were measured using the International Physical Activity Questionnaire (IPAQ) which is a standardised inventory used to assess physical activity (IPAQ 2015). The IPAQ long version consists of 27 questions across four sub-questionnaires relating to 'Job-Related Physical Activity', 'Transportation Physical Activity', 'Housework, House Maintenance and Caring for Family', and 'Recreation, Sport, and Leisure-Time Physical Activity'. Research assessing the reliability and validity of the IPAQ has concluded that the instrument is a suitable tool for research assessing physical activity with both young and elderly participants (Tomioka, Iwamoto, Saeki and Okamoto 2011).

2.3.2 Heart Rate (HR) & Acute Exercise Intensity

A Polar HR Monitor belt and receiver watch was used to monitor participants' HR during the exercise conditions and determine the exercise condition HR frequency. The Karvonen formula was used to determine a participant's target HR, using the participant's maximum HR and their resting HR (Karvonen et al. 1957). The maximum HR was calculated by subtracting the participant's age from 220. This allowed an individual's heart rate reserve (HRR) to be calculated and a target heart rate to be established depending on the exercise intensity required. The moderate exercise condition was operationalised as 40% of a participant's HRR, whereas, the high condition was operationalised as 70% of a participant's HRR. The control condition required no exercise task to be performed so HR was not measured during this condition.

2.3.3 The Stroop Colour-Word Task

A computerised Stroop Colour-Word task (Stroop 1935) was performed to assess cognitive function. The modified Stroop task consisted of a practice Stroop block, followed by the main experiment block. The practice block contained 40 trials, consisting of 20 congruent trials and 20 incongruent trials. EEG was not recorded for the practice block and the behavioural reaction times were not analysed. The sole purpose of the practice block was for participants to familiarise themselves with the Stroop task and the responses required. All participants completed a practice Stroop block before beginning the main Stroop block for all three conditions of the study.

The main Stroop block consisted of 160 trials, containing 80 congruent trials (20 of each of the four font colour stimuli), 80 incongruent trials (20 of each of the four font colour stimuli). To ensure no order effects occurred, the Stroop trial congruency was randomised for all participants. Congruent trials were when the font colour of the word presented, is the same as the semantic meaning of the word, whereas, incongruent trials were when the font colour of the word presented, is semantically different from the meaning of the word. For example, a congruent trial would display the word ‘Blue’ presented in a blue font, whereas, a incongruent trial would display the word ‘Green’ presented in a red font. Behavioural reaction times and continuous EEG were both recorded and analysed for the main Stroop block.

The word stimuli used in the Stroop task consisted of the colour names ‘Red’, ‘Blue’, ‘Green’ and White’. Each Stroop trial was 3700-4200ms long, consisting of a white fixation cross presented in the centre of the screen, followed by a 2000ms presentation of the word stimuli. The word stimuli and the fixation cross were presented in size 42

Arial font on a black background. During each individual trial, the word stimuli were presented immediately after the fixation cross disappeared, in the same position on the screen. Presentation timings of the fixation cross varied from 1700-2200ms. Once a response had been made, the next trial began. Participants were required to respond as quickly and as accurately as possible by pressing one of four buttons (red, blue, green, white) on a RB-530 Cedrus response box. The time required to complete the main Stroop block was between 11.59-13.16 minutes.

Participants' received standardised verbal instructions about the Stroop task and a demonstration of the responses required. Written instructions for the Stroop task were also displayed on the screen, presented in size 32 white Arial font positioned on a black background (see Appendix 1 for instructions presented). In total, all participants completed the main Stroop block with continuous EEG after each of the exercise conditions (moderate, high, control). Taking the three conditions together, each participant completed 480 trials (240 congruent, 240 incongruent).

2.3.4 EEG Data Acquisition

EEG was continuously recorded during the Stroop task using silver-silver chloride active electrodes from 26 scalp sites (FP1, FP2, F3, Fz, F4, FC3, FC4, FC7, FC8, C3, Cz, C4, CP3, CPz, CP4, CP5, CP6, T3, T4, T5, T6, P3, Pz, P4, PO3, PO4). EEG data was obtained using a stretch lycra cap with electrodes positioned in accordance to the international 10/20 system (Jasper 1958). Vertical and horizontal electrooculography (EOG) were recorded from above and below the left eye and at the right and left outer canthi, respectively. All electrode impedances were kept below 5 kΩ. Processing and analysis of the EEG signal was performed offline using Megis BESA 5 (version 5.1.8) software. All EEG procedures employed the use of Biosemi Active two measurement system. EEG signals were filtered between 0.16-100 Hz and had a sampling rate of 2048 Hz.

2.3.5 ERP Measures and Waveform Scoring

The ERP variables were measured using mean amplitude. Latency time windows were defined for each waveform measured and the mean voltage was calculated within the specific time window for both amplitude and latency measures (Luck 2005). Latency time windows were derived after examining the relevant grand mean ERPs and inspection of previous reports in the literature. Once the latency time windows were selected, they were the same for all participants and conditions.

2.3.5.1 P3b ERP Component

Based on a review of the literature and inspection of the grand average data, the P3b ERP component (the major positive deflection typically appearing 300-600ms post stimulus onset) was selected for analyses over electrode position PZ. The P3 amplitude is sensitive to the amount of attentional resources engaged during attentional tasks and is therefore useful for examining information processing in relation to tasks with varying cognitive demands (Polich 2007). The component was time locked to the participants response and was analysed within the latency window 280-530ms at midline recording sites FZ (frontal), CZ (central), PZ (parietal).

2.3.5.2 N450 ERP Component

Based on a review of the literature and inspection of the grand average data, the second ERP component to be examined is the N450 (the major negative deflection typically appearing 250-550ms post stimulus onset) and was selected for analyses over electrode position FZ. The N450 has previously been attributed to conflict processing and attentional control with an enhanced N450 component produced for trials implicating higher conflict (Lansbergen et al. 2007). The fronto-central N450 was time locked to the participants' response and was analysed within the latency window 350-500ms at midline electrodes FZ (frontal), CZ (central) and PZ (parietal). Research has previously indicated this as an appropriate latency window to examine the Stroop interference effect (West and Alain 2000a; Larson et al. 2009; Zurron et al. 2009; Tillman & Wiens 2011).

2.4 Procedure

During the first of the three testing session, participants were instructed to read the Participant Information Form which outlined the aims of the present study and provided a detailed explanation of the study requirements. The Participant Information Form also provided a detailed overview of the current research, how the data would be used and analysed, and contact details of the researcher. Secondly, participants were required to sign a Consent Form reiterating their ethical rights and to confirm their informed written consent to participate in the current research. A health screen questionnaire was administered at the beginning of each testing session consisting of three sections relating to the participant's general physical fitness, the participant's general health, and the participant's health on the day of the exercise task. All participants completed the Health Screen Questionnaire independently and on completion the information provided was discussed in collaboration with the researcher. If the information provided highlighted any significant risks to the participant or had implications for the tasks planned, all further testing was terminated and the participant was excluded from the study.

All participants completed three two hour sessions, one session per week at the same time of day. To ensure no order effects occurred, the exercise intensity conditions were counterbalanced for all participants using a Latin square design. Next, depending on the exercise task condition (control, moderate, high), participants were either taken to the sports laboratory to complete the moderate or high intensity exercise task, or the participant remained in the EEG laboratory to complete the control condition. For the moderate and high intensity cycling tasks, the procedure was identical for both exercise tasks.

Once at the sports laboratory, a Polar HR monitor was strapped securely around the participant's chest, with the Polar logo in the central position just below the chest muscles. Water was applied to the electrode sensors on the belt to improve the conduction from the skin. The receiver watch was then attached to the participant's wrist to display the HR reading. The participant's resting HR was then measured following a five minute period of sitting. Once the target HR was calculated, participants were then required to complete a two minute warm up cycle (60 RPM non-weighted) on the exercise bike. A Monark Weight Ergometer was used for participants to perform the cycling tasks and resistance weights (0.1 kg, 0.5 kg, 1 kg) were used to manipulate the participant's HR accordingly during the cycling tasks. After the warm up session, weights were slowly added to the bike in order to increase the participants' HR to the optimal level. Once the target HR was achieved, a timer was set for 20 minutes. Participants were instructed to cycle at 60 RPM throughout both exercise tasks and were allowed to consume only water during the sessions. In cases where a participant's HR was above the optimal level for the condition despite there being no weight on the bike, the RPM was reduced accordingly. The participant's HR was continuously monitored until the exercise task was completed.

At the end of the 20 minute cycling exercise, participants were informed to keep the HR monitor attached until they returned to the EEG laboratory. Participants were then seated on a chair in the centre of the laboratory to start preparing the participant for their EEG recording session. When necessary, participants were asked to remove any hair accessories and leave all electrical devices in a separate room to ensure a clear EEG signal. To begin with, the participant's head was measured using a tape measure to ensure the appropriate sized lycra EEG cap was used (small, medium, large). The distance from the participant's nasion to their inion was measured and this distance divided by two to determine the correct position of the vertex electrode (CZ). The distance from the participant's left preauricular point to their right preauricular point was also measured and divided by two to determine the left-right position of electrode CZ. The location of CZ was positioned at the half-way point between the nasion and inion, and half-way between the left and right preauricular points. Once the correct position of CZ was achieved, the EEG cap straps were secured.

The EOG electrode sites were cleaned using a cotton wool pad and an EEG abrasive skin prepping gel. Once the area was cleaned, EOG electrodes EXG 1 and 2 were applied directly above and below the participants' left eye. The EOG electrodes EXG 3 and 4 were then applied at the participant's right and left outer canthi. All EOG electrodes were secured in position using surgical tape. Once the EOG electrodes were applied, the EEG electrodes were then applied to the cap. Each electrode position of the lycra cap was injected with a highly conductive electrode gel forming a conductive column between the participant's scalp and the electrode. Once the gel had been inserted into the electrode site, the corresponding electrode was applied. This procedure was repeated for each individual electrode.

Once all of the electrodes were correctly applied, the participants HR was then monitored to ensure their HR frequency was within 10% of their original resting HR before starting the EEG recording. The HR monitor and receiver watch were then removed from the participant and then the participant was escorted into an isolated recording room and seated in a comfortable chair 80cm from the computer screen. Both the EEG and EOG electrodes were then connected to the EEG battery pack to begin reading the participant's signal. All electrode offsets were then checked to ensure a clear signal and when necessary problematic electrodes were adjusted.

For the control condition, participants were seated in the EEG laboratory for 20 minutes and completed the IPAQ long version. Once completed, participants were then prepared for the EEG recording session following the same procedure as previously outlined. As the control condition did not require exercise to be performed, HR readings were not needed for the control session.

In relation to the cognitive task, a computerised Stroop colour-word test was employed. Participants received a standardised verbal instruction of what the Stroop task required them to do and the responses required. Participants were informed that they would be presented with a number of colour name words and that they were required to read the word and indicate the colour of the font the word was presented, and not the semantic meaning of the word. Examples of each trial congruency (congruent; incongruent) were provided and the correct response demonstrated using the Cedrus response box. In addition, written instructions were also presented on the screen before the practice Stroop block began. Once the instructions were understood, participants performed a practice Stroop block to familiarise themselves with the task and mapping the response buttons on the Cedrus response box. After the practice block was completed, participants were asked if they needed any further explanations regarding the Stroop task. Once fully understood, participants performed the main Stroop block while their behavioural data and continuous EEG was recorded. At the end of their final testing session, all participants received a Debrief Form.

2.5 Data Analyses

The data analyses were performed using IBM SPSS Statistics v.22 by conducting a series of Analysis of Covariance (ANCOVA) and Analysis of Variance (ANOVA) to test the study hypotheses. Significant results were further explored using multiple contrasts for interactions which only included repeated factors. For significant interactions including both within and between subject factors, a series of post hoc independent and paired samples t tests were conducted. Statistical analyses employed a two-tail alpha level of .05 and Bonferroni corrections were applied for multiple comparisons. Effect sizes (partial eta squared np^2) for significant results are presented to indicate the proportion of explained variance.

Adhering to ANOVA parametric assumptions, the data was normally distributed and variances between the conditions were equal. However, ERP analyses which include electrode position with three levels as a within-subjects factor, violates the assumption of homogeneity of covariance (Luck 2005). This is due to the correlation between nearby electrodes being stronger than data between distant electrodes. For example, the EEG noise at electrode FZ will spread more strongly to CZ than PZ, and the correlation of data between PZ and CZ will be stronger than the correlation between PZ and FZ. In order to protect against this parametric violation, the Greenhouse-Geisser epsilon adjustment is reported for all results with electrode position as a repeated factor (Luck 2005).

2.5.1 Behavioural RTs Data Preparation

Behavioural RTs for trials with incorrect responses were excluded from statistical analyses. Trials with responses below 200ms or above 1500ms were also excluded. Z scores for the RTs were then computed and Z scores higher than 2 standard deviations were removed from the analyses.

2.5.2 Behavioural RTs Analyses

A 2 (congruency; congruent, incongruent) x 3 (exercise task; control, moderate intensity, high intensity) x 2 (age group; young, old) mixed method ANCOVA was conducted on the behavioural RTs. Congruency and exercise condition were the within-groups factors and age group (young, old) was the between-groups factor. Physical activity group (low, moderate, high) as indexed by the IPAQ, was added to the analyses as a covariate factor as fitness level has previously been found to be a significant moderator of exercise effects (Chang et al. 2012; Kamijo and Takeda 2010).

2.5.3 ERP Data Preparation

As EEG files are often large, the files were down sampled to 512hz using BioSemi Decimator 82.vi. All EEG data preparation was conducted using BESA software (version 5.1.8, MEGIS software GmbH, Gräfelfing, Germany). All data was averaged to a common reference and was filtered between 0.01Hz and 30Hz before averaging. The raw data was then inspection for eye blinks with a monophasic deflection (50-100µV) and an artefact correction procedure that used principle component analysis was performed (SAW) to remove eye blinks from the data. Average epochs were defined as prestimuli start position of -200ms to 700ms post stimulus. Finally, separate grand average ERPs were then computed for correct responses on congruent and incongruent trials for each exercise condition. This produced 6 grand averages which were: control congruent, control incongruent, moderate congruent, moderate incongruent, high congruent, high incongruent. Prior to data analyses, artifactual EEG (±100 µV) was automatically removed from the EEG data and eye blinks that appeared in the EOG data were also removed. Trials containing horizontal eye movements and trials with incorrect responses were excluded from the analyses. Prior to data analyses, all ERP waveforms were passed through a low filter ranging from 0.01 to 30Hz.

2.5.4 ERP Component Analyses

Both the P3b and N450 mean amplitude data was subjected to a 3 (electrode position; FZ, CZ, PZ) x 2 (congruency; congruent, incongruent) x 3 (exercise task; control, moderate intensity, high intensity) x 2 (age group; young, old) mixed method ANCOVA with electrode position, congruency and exercise task as the within-subjects factors and age group as the between-subjects factor. Physical activity group was also added to the analyses as a covariate factor.

3 – Results Section

3.1 Behavioural Reaction Times

Congruent trial RTs were faster following moderate intensity exercise, but were slower following high intensity exercise regardless of age group. However, incongruent trial RTs did not benefit from moderate intensity exercise and were slower with increased exercise intensity compared to the control. These results are shown in Table 1.

Table 1: Mean behavioural RTs (ms) and standard deviations by Stroop trial congruency, exercise condition and age group.

Stroop Trial	***Exercise Condition***	***Young Age Group (N = 5)***	***Older Age Group (N = 5)***
		Mean (Std Dev)	***Mean (Std Dev)***
Congruent	Control	626.91 (68.43)	796.81 (172.04)
	Moderate	599.03 (59.52)	783.07 (96.10)
	High	639.08 (42.88)	811.15 (81.65)
Incongruent	Control	675.83 (95.91)	871.04 (157.23)
	Moderate	682.88 (118.80)	877.24 (62.07)
	High	710.67 (63.91)	903.11 (73.87)

In line with H1, the ANCOVA showed no significant main effects for congruency (*F* (1, 7) = 0.36, $p > .05$), exercise task (*F* (2, 14) = 0.84, $p > .05$) or physical activity group (*F* (1, 7) = 0.50, $p > .05$). However, consistent with H2 a significant main effect of age group was observed (*F* (1, 7) = 9.08, $p = .020$, $np^2 = .56$), showing that RTs for the younger group were significantly faster than RTs for the older group regardless of trial congruency and exercise condition.

In relation to H3, the ANCOVA showed no significant interaction effect for congruency and age group (*F* (1, 7) = 0.12, *p* > .05), which did not support predictions. Inconsistent with H4, H5, and H6, the ANCOVA found no significant interaction effect between age group, exercise condition and congruency (*F* (2, 14) = 0.03, *p* > .05).

Finally, the ANCOVA showed no significant interaction effects for congruency and exercise task (*F* (1, 7) = 3.36, *p* > .05, congruency and physical activity group (*F* (1, 7) = 0.52, *p* > .05), exercise task and physical activity group (*F* (2, 14) = 0.66, *p* > .05), exercise task and age group (*F* (2, 14) = 0.09, *p* > .05), exercise task, congruency and physical activity group *F* (2, 14) = 2.49, *p* > .05).

3.2 ERP Amplitudes

3.2.1 P3b Amplitudes

3.2.1.1 P3b Amplitude Descriptive Data

Table 2: Mean P3b amplitudes (µV) and standard deviations at midline frontal, central and parietal regions for congruent and incongruent trials in relation to exercise condition and age group.

Region (Electrode Site)	***Stroop Trial***	***Exercise Condition***	***Young Age Group (N = 5)***	***Older Age Group (N = 5)***
			Mean (Std Dev)	***Mean (Std Dev)***
Frontal (FZ)	Congruent	Control	8.71 (6.32)	7.95 (11.99)
		Moderate	1.67 (4.96)	8.10 (13.82)
		High	2.78 (5.13)	22.01 (20.99)
	Incongruent	Control	8.29 (7.50)	10.03 (15.41)
		Moderate	1.53 (6.54)	11.42 (20.57)
		High	5.13 (5.76)	24.97 (22.78)
Central (CZ)	Congruent	Control	-0.29 (3.72)	4.20 (5.23)
		Moderate	0.89 (2.97)	3.55 (8.39)
		High	-0.69 (6.85)	3.17 (5.43)
	Incongruent	Control	0.03 (3.55)	6.02 (7.34)
		Moderate	0.51 (2.05)	4.40 (13.19)
		High	1.26 (9.68)	4.90 (4.95)
Parietal (PZ)	Congruent	Control	-5.06 (5.13)	5.80 (9.27)
		Moderate	-2.28 (6.48)	-0.97 (4.03)
		High	-2.77 (4.19)	-8.07 (6.54)
	Incongruent	Control	-4.85 (5.17)	5.75 (10.87)
		Moderate	-1.36 (5.47)	-0.87 (5.91)
		High	-2.78 (5.26)	-9.60 (7.42)

3.2.1.2 P3b Amplitude Analyses

In line with H7, the ANCOVA revealed no significant main effects of electrode position (*F* (1.04, 7.28) = 0.29, $p > .05$), exercise condition (*F* (1.38, 9.66) = 3.16, $p > .05$), congruency (*F* (1, 7) = 1.34, $p > .05$), physical activity group (*F* (1, 7) = .26, $p > .05$), and age group (*F* (1, 7) = 2.33, $p > .05$).

Inconsistent with H8, H9 and H10, for P3b amplitudes the ANCOVA showed no significant interaction effects between electrode position, exercise condition, congruency and age group (1.60, 11.20) = 0.36, $p > .05$). However, when exploring higher order interactions the ANCOVA did reveal a significant interaction effect between age group, electrode position and exercise task (*F* (1.76, 12.31) = 5.44, $p = .023$, $np^2 = .44$).

At the parietal region post hoc tests showed no significant age group differences in P3b amplitudes for the control condition, (*t* (8) = -2.13, $p > .05$), the moderate intensity condition (*t* (8) = -0.26, $p > .05$), and the high intensity condition (*t* (8) = 1.64, $p > .05$). For the young group, post hoc tests found no significant differences at the parietal region for the moderate versus control condition (*t* (4) = -1.22, $p > .05$), the moderate versus high intensity condition (*t* (4) = 0.43, $p > .05$), nor the high intensity versus the control condition (*t* (4) = -2.06, $p > .05$). Similarly, the older group also showed no significant differences in P3b amplitudes at the parietal region for the moderate versus control condition (*t* (4) = 1.67, $p > .05$), the moderate versus high intensity condition, (*t* (4) = 2.03, $p > .05$), and the high intensity versus control condition (*t* (4) = -2.05, $p > .05$).

At the frontal region, P3b amplitudes showed no significant age group differences for the control condition (t (8) = -0.07, $p > .05$), the moderate condition (t (8) = -1.03, $p > .05$), and the high intensity condition (t (8) = -1.94, $p > .05$). However, post hoc tests revealed that P3b amplitudes were significantly reduced at the frontal region following moderate intensity exercise (1.60μV ± 5.56) compared to the control (8.50μV ± 6.79) for the younger group (t (4) = 3.53, $p = .024$). However, after applying Bonferroni corrections this pattern failed to reach significance. The young group showed no other significant differences in P3b amplitudes between the moderate versus high intensity condition (t (4) = -1.06, $p > .05$) and the high intensity versus control condition (t (4) = -1.25, $p > .05$). For the older group, no significant differences were found at the frontal region for the control versus moderate intensity condition, (t (4) = -0.25, $p > .05$), nor the high intensity versus control condition (t (4) = 2.49, $p > .05$). However, post hoc tests revealed that P3b amplitudes were significantly increased at the frontal region following high intensity (23.49μV ± 21.83) compared to moderate intensity exercise (9.76μV ± 16.68) for the older group (t (4) = -3.63, $p = .022$). Although after applying Bonferroni corrections, this effect also failed to reach significance.

At the central region, no significant age group differences in P3b amplitudes were observed for the control condition (t (8) = -1.66, $p > .05$), the moderate intensity condition (t (8) = -0.67, $p > .05$), and the high intensity condition (t (8) = -0.86, $p > .05$). The young group also showed no significant differences in P3b amplitudes between the moderate and control condition (t (4) = -0.36, $p > .05$), the moderate and high intensity condition (t (4) = 0.10, $p > .05$), and the high intensity and control condition (*t* (4) = 0.20, *p* > .05). Similarly, the older group showed no significant differences in P3b amplitudes at the central region for the moderate versus control condition (*t* (4) = 0.36, *p* > .05), the moderate versus high intensity condition (*t* (4) = -0.02, *p* > .05), nor the high intensity versus control condition (*t* (4) = -0.79, *p* > .05).

For P3b amplitudes, the ANCOVA showed no significant interaction effects for congruency and electrode position *(F* (1.04, 7.25) = 1.03, *p* > .05), congruency and age group (*F* (1, 7) = 0.72, *p* > .05), congruency and physical activity group (*F* (1, 7) = 0.14, *p* > .05), congruency and exercise condition (*F* (1.09, 7.64) = 1.03, *p* > .05), age group and exercise task (*F* (1.38, 9.66) = 0.84, *p* > .05), age group and electrode position (*F* (1.04, 7.28) = 0.41, *p* > .05), electrode position and exercise task (*F* (1.76, 12.31) = 0.46, *p* > .05), exercise task and physical activity group (*F* (1.38, 9.66) = 3.29, *p* > .05, physical activity group and electrode position (*F* (1.04, 7.28) = .29, *p* > .05), physical activity group, electrode position and exercise task (*F* (1.76, 12.31) = 0.14, *p* > .05), electrode position, exercise condition, and congruency (*F* (1.60, 11.20) = 0.94, *p* > .05), electrode position, exercise condition, congruency and physical activity group (1.60, 11.20) = 0.75, *p* > .05).

3.2.2 N450 Amplitudes

3.2.2.1 N450 Amplitude Descriptive Data

Table 8: Mean N450 amplitudes (μV) and standard deviations at midline frontal, central and parietal regions for congruent and incongruent trials in relation to exercise condition and age group.

Region (Electrode Site)	***Stroop Trial***	***Exercise Condition***	***Young Age Group (N = 5)***	***Older Age Group (N = 5)***
			Mean (Std Dev)	***Mean (Std Dev)***
Frontal (FZ)	Congruent	Control	9.32 (7.57)	7.47 (11.39)
		Moderate	1.79 (5.03)	7.33 (14.73)
		High	2.65 (4.79)	22.85 (21.06)
	Incongruent	Control	8.97 (8.54)	9.74 (15.01)
		Moderate	1.64 (6.24)	10.66 (21.32)
		High	4.94 (5.32)	26.11 (23.16)
Central (CZ)	Congruent	Control	-0.27 (3.82)	4.09 (5.56)
		Moderate	1.11 (3.46)	2.69 (10.52)
		High	-0.95 (7.18)	2.84 (6.40)
	Incongruent	Control	-0.01 (3.77)	5.88 (7.50)
		Moderate	0.89 (2.51)	3.39 (15.45)
		High	1.01 (9.96)	4.39 (5.80)
Parietal (PZ)	Congruent	Control	-5.28 (5.47)	5.92 (9.06)
		Moderate	-2.26 (6.52)	-0.81 (3.97)
		High	-2.88 (4.22)	-8.61 (6.61)
	Incongruent	Control	-5.04 (5.60)	5.85 (10.72)
		Moderate	-1.18 (5.34)	-0.78 (5.83)
		High	-2.89 (5.23)	-10.37 (7.58)

3.2.2.2 N450 Amplitude Analyses

Consistent with H7, the ANCOVA revealed no significant main effects of electrode (*F* (1.04, 7.30) = 0.34, $p > .05$), exercise condition (*F* (1.29, 8.95) = 2.75, $p > .05$), congruency (*F* (1, 7) = 1.31, $p > .05$), physical activity group (*F* (1, 7) = 0.29, $p > .05$), and age group (*F* (1, 7) = 1.95, $p > .05$).

Contrary to H8, H9, and H10, N450 amplitudes showed no significant interaction effects between electrode position, exercise condition, congruency and age group (1.74, 12.18) = 0.30, $p > .05$). However, the ANCOVA did reveal a significant interaction effect between age group, electrode position and exercise task (*F* (1.74, 12.18) = 5.92, $p = .019$, $np^2 = .46$).

Post hoc tests found no significant age group differences in N450 amplitudes at the frontal region for the control condition (*t* (8) = -0.08, $p > .05$), the moderate intensity condition (*t* (8) = -0.89, $p > .05$), and the high intensity condition (*t* (8) = -2.04, $p > .05$). However, for the young group post hoc tests revealed that N450 amplitudes were significantly reduced after moderate intensity exercise (1.71μV ± 5.40) compared to the control (9.15μV ± 7.93) at the frontal region (*t* (4) = 3.33, $p = .029$). However, after applying Bonferroni corrections this pattern failed to reach significance. The young group showed no other significant differences in N450 amplitudes at the frontal region between the moderate and high intensity condition (*t* (4) = -0.88, $p > .05$) and the high intensity and control condition (*t* (4) = -1.28, $p > .05$). For the older group no significant differences in N450 amplitudes were found between the control and moderate conditions (*t* (4) = -0.11, $p > .05$) and the high intensity and control condition (t (4) = 2.57, $p > .05$). However, N450 amplitudes were significantly increased for the older group following high intensity (24.88.71μV ± 22.04) compared to moderate intensity exercise (9.00μV ± 17.51) at the frontal region (t (4) = -3.70, $p = .021$). Following Bonferroni corrections, this effect also failed to reach significance.

At the central region no significant age group differences were observed for the control condition, (t (8) = -1.56, $p > .05$), the moderate intensity condition (t (8) = -0.35, $p > .05$), and the high intensity condition (t (8) = -0.76, $p > .05$). For the young group, N450 amplitudes showed no significant differences at the central region between the moderate intensity and control condition (t (4) = -0.46, $p > .05$), the moderate and high intensity conditions (t (4) = 0.22, $p > .05$), and the high intensity and control condition (t (4) = 0.08, $p > .05$). By the same token, the older group also showed no significant differences in N450 amplitudes at the central region between the moderate versus the control condition (t (4) = 0.49, $p > .05$), the moderate versus the high intensity condition (t (4) = -0.13, $p > .05$), and the high intensity versus the control condition (t (4) = -1.06, $p > .05$).

At the parietal region there were no significant age group differences observed between the control condition (t (8) = -2.19, $p > .05$), the moderate intensity condition (t (8) = -0.28, $p > .05$), and the high intensity condition (t (8) = 1.77, $p > .05$). At the parietal region, the young group showed no significant differences in N450 amplitudes for the moderate intensity versus the control condition (t (4) = -1.19, $p > .05$), the moderate intensity versus the high intensity condition (t (4) = 0.51, $p > .05$), and the high intensity versus the control condition (t (4) = 2.06, $p > .05$). Similarly, the older group also showed no significant differences at the parietal region for the moderate intensity versus the control condition (*t* (4) = 1.66, *p* > .05), the moderate intensity versus the high intensity condition (*t* (4) = 2.17, *p* > .05), and the high intensity versus the control condition (*t* (4) = -2.15, *p* > .05).

For N450 amplitudes, the ANCOVA showed no significant interaction effects for congruency and electrode position *(F* (1.03, 7.19) = 0.69, *p* > .05), congruency and age group (*F* (1, 7) = 0.62, *p* > .05), congruency and physical activity group (*F* (1, 7) = 0.64, *p* > .05), congruency and exercise condition (*F* (1.09, 7.60) = 0.88, *p* > .05), age group and exercise task (*F* (1.28, 8.95) = 1.04, *p* > .05), age group and electrode position (*F* (1.04, 7.30) = 0.36, *p* > .05), electrode position and exercise task (*F* (1.74, 12.18) = 0.49, *p* > .05), exercise task and physical activity group (*F* (1.28, 8.95) = 2.91, *p* > .05, electrode position and physical activity group (*F* (1.04, 7.30) = 0.48, *p* > .05), electrode position, physical activity group and exercise task (*F* (1.74, 12.18) = 0.20, *p* > .05), electrode position, exercise condition, and congruency (*F* (1.74, 12.18) = 0.74, *p* > .05), electrode position, exercise condition, congruency and physical activity group (1.74, 12.18) = 0.56, *p* > .05).

4 – Discussion Section

The present study investigated how acute cycling at a moderate and high intensity compared to a no exercise control, effects behavioural and neural indices of information processing and executive control during the Stroop test in both young and older healthy adults. The ERP technique was employed to explore whether moderate intensity exercise selectively enhances attentional resource allocation (P3b amplitudes) and conflict processing (N450 amplitudes) following an acute bout of aerobic exercise. The study also examined whether physical activity levels were specifically related to executive control processing at a behavioural or neuroelectric level. The study provides evidence that following acute bout of aerobic exercise at various intensities, both P3b and N450 amplitudes are modulated at the frontal region for young and older adults, although this exercise-induced effect was not specific to Stroop trial congruency.

4.1 Summary of Behavioural RT Findings

Consistent with H1, RTs showed no significant main effects for congruency, exercise condition or physical activity group. The lack of significance for the main effect of congruency (the classic Stroop Interference effect) is inconsistent with previous research which typically shows that incongruent RTs are significantly longer than congruent RTs (Chen et al. 2011; Mayas et al. 2012; Zurron et al. 2014). The lack of a significant main effect of congruency may be due to the acute exercise focus of the current study. However, partially in line with H1 behavioural RTs were increased for incongruent compared to congruent trials. Consistent with H2, RTs for the younger group were significantly faster than the older group regardless of trial congruency and exercise condition. This result confirms the well established finding of psychomotor speed responses declining with increased age (Spirduso 1980; Keys and White 2000, West and Alain 2000a, Zurron et al. 2014).

Contrary to H3, there was no significant behavioural interaction between age group and trial congruency, although RTs were increased for incongruent compared to congruent trials regardless of age group. This finding is inconsistent with previous research which has found the Stroop interference effect to be significantly greater for older compared to young adults (West and Alain 2000a; Prakash et al. 2009; Mayas et al. 2012; Zurron et al. 2014). In addition the lack of significant effects between age group and congruency are also inconsistent with the inhibitory breakdown in normal aging theory (Hasher and Zacks 1988; Dempster 1992; West 1996), which argues that older adults should perform more poorly on tasks requiring executive functioning. Partially supportive of H3, RTs for the young group were faster than the older group for both incongruent and congruent trials.

Inconsistent with H4, acute moderate exercise compared to the control did not significantly reduce RTs for incongruent versus congruent trials for both age groups, suggesting that moderate exercise did not selectively enhance executive control at a behavioural level. This contradicts previous research which found acute moderate exercise was associated with a small but significant improvement in interference control during the Stroop test at a behavioural level (Sibley et al. 2006). However, the findings are in line with research which also failed to show a selective improvement in executive control during the Stroop test following moderate intensity exercise (60% HRR) for older adults (Barella et al. 2010). In addition, acute mild cycling (30% VO2 peak) has previously been shown to improve executive functioning during the Stroop test in young adults and this enhancement was mediated by the exercise-induced arousal system intensifying task-related neural activation in the prefrontal sub-regions (Byun et al. 2014). The current study did not employ a mild exercise intensity condition, but failed to show a significant decrease in RTs for incongruent trials following moderate intensity cycling. This indicates that mild intensity exercise is associated with positive effects on executive control, whereas moderate intensity exercise did not improve incongruent RTs during the Stroop test. The current results are consistent with previous research which has failed to show any significant effects of acute moderate exercise on executive control at a behavioural level following the cessation of exercise (Soga et al. 2015; Barella et al. 2010).

Inconsistent with H5, both age groups showed no significant increase in RTs following high intensity exercise compared to the control for incongruent or congruent trials. However, for both age groups congruent and incongruent RTs increased following high intensity exercise compared to the control, suggesting that high intensity exercise had a general negative effect on cognitive processing at a behavioural level. Contrary to H6, high intensity compared to moderate intensity exercise did not significantly increase RTs for incongruent versus congruent trials for both age groups. Results showed that RTs were increased following high intensity compared to moderate intensity exercise regardless of age group or congruency, which is supportive of the view that acute exercise intensity effects cognitive processing in a curvilinear relationship (Brisswalter et al. 2002).

Interestingly, the Stroop interference effect (incongruent – congruent RTs) was most pronounced for both age groups following moderate intensity (young 83.85ms, older

94.17ms) and high intensity exercise (young 71.59ms, older 91.96ms), compared to the control (young 48.92ms, older 74.23ms). Despite there being no significant difference, this suggests that following acute moderate exercise the processing of task-relevant stimuli was enhanced whereas the processing of task-irrelevant information was impaired. This finding is consistent with research employing the Simon task which also found that the Simon effect was increased during moderate intensity cycling compared to at rest (Davranche and McMorris 2009).

No significant interaction effects were observed for RTs between congruency and exercise condition, which indicates that regardless of age group acute exercise did not significantly influence behavioural performance for incongruent or congruent trials. This is inconsistent with research in young adults which found that RTs for incongruent trials were significantly reduced immediately after moderate intensity continuous cycling (60% VO_2 peak) and high intensity interval cycling (90% VO_2 peak) compared to a no exercise control, suggesting executive control was enhanced at a behavioural level (Tsukamoto et al. 2016). As the present study failed to show a significant reduction in RTs for incongruent trials following moderate (40% HRR) and high intensity exercise (70% HRR) in young adults, this may indicate the effect of acute exercise on executive control was relatively transitory and potentially returned to baseline during the standardised delay. However, the current findings were consistent with previous research which also failed to show significant effects of acute exercise intensity on congruent and incongruent RTs during the Stroop test (Labelle et al. 2013). In addition, no significant age group differences in RTs were found between the exercise conditions regardless of trial congruency, suggesting that acute exercise intensity did not significantly effect behavioural performance for both young and older adults during the Stroop test.

In relation to physical activity levels, no significant interaction effects were found between congruency and physical activity group, physical activity group and exercise condition, exercise task congruency and physical activity group. These results are inconsistent with findings that have linked greater physical fitness with more efficient executive control processing (Hillman et al. 2004; Themanson and Hillman 2006; Stroth et al. 2009; Labelle et al. 2013). The discrepancies between the literature and the current results may be due to the reliance on self-reported physical activity levels to infer individual physical fitness, which may have been problematic due to social desirability bias. Nevertheless, the current results failed to show that physical activity levels are a significant moderator of acute exercise effects at a behavioural level during the Stroop test.

4.2 Summary of ERP Findings

As the human brain has finite cognitive resources and a limited cognitive processing capacity, activation cannot be maintained in all neuronal networks at any given time (Broadbent 1958; Dietrich 2006). The activation of one neural network requires resources to be diverted from other cognitive domains not required to successful executive task demands. In line with the processing efficiency assumption, increased amplitudes suggest more cognitive effort was employed which may be interpreted as a positive effect due to more attentional processes engaged in the task. However, when considered in terms of limited attentional resources and processing efficiency, this modulation may also be interpreted as a negative effect as more cognitive resources were required to successfully execute task demands. The current study discusses amplitude modulations from a neural efficiency understanding, with increased amplitudes reflecting a negative exercise-induced effect as limited cognitive resources were allocated less efficiently.

P3b and N450 Amplitudes

In line with H7, no significant main effects were observed for P3b and N450 amplitudes. This indicates that P3b and N450 amplitudes were not significantly modulated by electrode position, exercise condition, congruency, physical activity group, or age group. In relation to the N450, the lack of significant main effects of congruency and electrode position are consistent with previous research which also failed to show these main effects during the Stroop test (Chen et al. 2011). N450 amplitudes reversed in polarity between the parietal and frontal regions, with both age groups showing increased positivity at the frontal region which is also consistent with previous research employing the Stroop test (West 2003; West 2004).

Contrary to H8, H9, and H10, P3b and N450 amplitudes showed no significant interaction effects between electrode position, exercise condition, congruency and age group. This suggests acute exercise intensity did not selectively modulate executive control compared to information processing for both age groups, which is inconsistent with the Selective Improvement Hypothesis (Kramer et al. 1999). Unsupportive of the prediction that moderate intensity exercise compared to the control would significantly reduce P3b and N450 amplitudes for incongruent versus congruent trials (H8), both age groups showed no significant reduction in P3b or N450 amplitudes following moderate intensity exercise. However, for the young group congruent and incongruent P3b and N450 amplitudes were reduced at the parietal and frontal regions following moderate intensity exercise, whereas for the older group P3b and N450 amplitudes were reduced at the central and parietal regions. For the older group, P3b amplitudes at the frontal region increased for congruent and incongruent trials, but N450 amplitudes were slightly reduced at the frontal region for congruent trials only. This suggests that moderate intensity exercise had a positive effect on information processing in both young and older adults, although moderate exercise may impair processing efficiency at the frontal region for older adults. As no significant differences were observed between congruent and incongruent trials for P3b and N450 amplitudes, this suggests that acute exercise effects were not specific to executive control processing.

Inconsistent with H9, for both age groups high intensity exercise compared to the control did not significantly increase P3b and N450 amplitudes for incongruent compared to congruent trials. However, partially in line with H9 for the young group P3b and N450 amplitudes were reduced following high intensity exercise at the frontal and parietal regions, but showed a small increase at the central region for both congruent and incongruent trials. In contrast, P3b and N450 amplitudes for the older group increased at the frontal and parietal regions for congruent and incongruent trials, but were reduced at the central region following high intensity exercise compared to the control. This suggests that for the young group, high intensity exercise had a positive effect on cognitive processing efficiency indexed by a reduction in P3b amplitudes, whereas high intensity exercise had a negative effect on cognitive processing efficiency for older adults.

Inconsistent with H10, both age groups showed no significant increase in P3b and N450 amplitudes following moderate compared to high intensity exercise for incongruent versus congruent trials. However, for both age groups P3b and N450 amplitudes increased at the parietal and frontal regions following high intensity compared to moderate intensity exercise. These findings suggest that high intensity exercise had a negative effect on cognitive processing, which supports the assumption that acute exercise intensity modulates cognitive processing in a curvilinear fashion, with moderate intensity exercise yielding the most efficient neural processing (Brisswalter et al. 2002). Interestingly, high intensity exercise compared to the control was associated with positive effects for younger adults and negative effects for older adults. This suggests that high intensity exercise was beneficial for younger adults, which highlights the importance of acute exercise intensity for improving cognitive processing. As older adults did not benefit from high intensity exercise, in order to maximise the effects of acute exercise on cognitive processing in older adults light to moderate intensity exercise may be more beneficial than high intensity vigorous activity, which has been supported by previous research (Kamijo et al. 2009).

Although no significant higher order interactions in P3b amplitudes differentiated congruent from incongruent trials, a significant age group interaction effect was observed between electrode position and exercise. At the frontal region, P3b amplitudes showed no age group differences for the control, moderate, or the high intensity conditions. However, for the young group P3b amplitudes were reduced at the frontal region following moderate intensity exercise ($1.60 \mu V$ ± 5.56) compared to the control ($8.50 \mu V$ ± 6.79). This indicates that regardless of trial congruency, moderate intensity exercise reduced P3b amplitudes which suggest that processing efficiency was enhanced. The young group showed no other significant differences in P3b amplitudes between the moderate and high intensity conditions and the high intensity versus control condition. This indicates that moderate intensity exercise was associated with the most efficient allocation of attentional resources for younger adults during the Stroop test, supporting the positive effects of aerobic exercise on information processing (Barella et al. 2010).

For the older group, no significant differences were found in P3b amplitudes at the frontal region for the control versus moderate intensity condition, nor the high intensity versus control condition. However, for the older group P3b amplitudes were increased at the frontal region following high intensity ($23.49\mu V$ ± 21.83) compared to moderate intensity exercise ($9.76\mu V$ ± 16.68). This shows that regardless of trial congruency, information processing efficiency was impaired for older adults following high intensity exercise compared to moderate exercise, which supports the assumption that light to moderate exercise may be more beneficial for cognition in older adults (Kamijo et al. 2009).

Additionally, the age-related P3b amplitude effects observed at the frontal region were consistent with previous research which has also showed increased P3b amplitudes for older adults at the frontal region during the Stroop test (Zurron et al. 2014). The finding that P3b amplitudes were maximal at the frontal region for older adults was also observed in the current study, supporting the view that age-related changes are associated with over-activation of the frontal region possibly reflecting reduced neural efficiency. At the parietal and central regions, no significant age group differences in P3b amplitudes were observed for the control, moderate intensity, or high intensity conditions. Similarly, both age groups showed no significant differences in P3b amplitudes at the parietal and central regions for the moderate versus control condition, the moderate versus high intensity, or the high intensity versus the control conditions. These findings suggest that aging and acute aerobic exercise mainly effect neural activation at the frontal region, particularly for later stage cognitive processing such as stimulus categorisation and conflict detection.

In relation to N450 amplitudes, a significant interaction effect was also found between age group, electrode position and exercise task. At the frontal region, no age group differences were found for N450 amplitudes for the control, moderate intensity, or high intensity conditions. However, for the young group frontal N450 amplitudes were reduced after moderate intensity exercise ($1.71\mu V$ ± 5.40) compared to the control ($9.15\mu V$ ± 7.93). This finding is consistent with previous research which has shown the N450 to be modulated over the frontal and frontocentral regions, but not posterior sites (Liotti et al. 2000). The young group showed no other significant differences in N450 amplitudes at the frontal region between the moderate and high intensity condition, and the high intensity versus the control condition. For the older group no significant differences in N450 amplitudes were found between the control versus the moderate condition, and the high intensity versus the control condition. However, N450 amplitudes at the frontal region were increased for the older group following high intensity ($24.88\mu V$ ± 22.04) compared to moderate intensity exercise ($9.00\mu V$ ± 17.51). This shows that following high intensity exercise older adults exhibited increased conflict-related functioning, which possibly reflected impaired conflict processing efficiency during the Stroop test.

At the central and parietal regions no significant age group differences were observed for N450 amplitudes during the control, the moderate intensity, and high intensity conditions. For both age groups, N450 amplitudes showed no significant differences at the central or parietal region between moderate intensity exercise and the control condition, the moderate and high intensity conditions, or the high intensity versus the control condition. These finding are consistent with research showing that the N450 is only modulated over the frontal region during the Stroop test (Liotti et al. 2000) and the current results show that acute aerobic exercise influences the N450 component at the frontal region.

For P3b and N450 amplitudes, no significant interaction effects were observed between age group and exercise task, age group and electrode position, or the interaction between electrode position and exercise task interaction. These results suggests that the significant exercise-induced age group effects observed at the frontal region for P3b and N450 amplitudes, were specific to the interaction between age group and acute exercise intensity and does not reflect a general age group or exercise intensity effect.

Regarding specific trial congruency effects for P3b and N450 amplitudes, no significant interaction effects were observed for congruency and electrode position, congruency and age group, congruency and exercise condition, or the interaction between congruency, electrode position and exercise condition. The lack of significant effects relating to Stroop congruency possibly reflects conflict adaptation (Egner and Hirsch 2005; Larson et al. 2009), which is also effected by the ratio of incongruent trials and the repeated measures design. When incongruent trials are frequent during the Stroop test, top-down attentional control is implemented throughout the task and the associated conflict is consequently reduced (Tillman and Wiens 2011; Botvinick et al. 2004). However, when incongruent trials are infrequent habitual responses are usually efficient (i.e. using visual colour cues on congruent trials), which results in reduced executive control activation. This decrease in activation results in higher conflict and increased Stroop interference which is consistent with the Conflict-Monitoring Theory (Botvinick et al. 2004). This is further supported by the finding that N450 amplitudes are increased when incongruent trials are infrequent (West and Alain 2000b; Tillman and Wiens 2011). As the Stroop test employed in the current study used an equal split of 80 incongruent and 80 congruent trials per exercise condition, it is possible that participants became habitualised to incongruent trials and therefore exhibited reduced conflict, which may explain why no significant congruency-related effects were observed for P3b and N450 amplitudes.

In relation to physical activity group, no significant interaction effects were observed for P3b and N450 amplitudes between physical activity group and congruency, physical activity group and electrode position, physical activity group and exercise task, or the interaction effect between physical activity group, electrode position and exercise task. Similarly, no significant P3b and N450 amplitude effects were found for the higher order interaction between physical activity group, electrode position, exercise condition and congruency. It has been argued that cardiorespiratory fitness is related to the functional integrity of aging brain networks, but physical activity levels are not associated with enhanced cognitive processing (Voss et al. 2015), which may explain why no significant effects were observed for physical activity levels. Additionally, long term habitual physical activity has been shown to significantly modulate N450 amplitudes during the Stroop test, with physically active older adults exhibiting reduced N450 amplitudes compared to sedentary older adults (Gajewski and Falkenstein 2015). However, this physical activity effect was not specific to trial congruency (Gajewski and Falkenstein 2015), which is partially consistent with the lack of significant congruency effects for acute exercise and physical activity interactions in relation to N450 amplitudes. The lack of significant interactions between P3b amplitudes and physical activity levels is also contrary to previous research which found significant effects at the frontal region based on physical activity group (Hillman et al. 2004). However, Hillman et al. (2004) employed a Flanker task which may explain why no significant effects were observed in the current study.

4.3 General Discussion And Theoretical Interpretation of Findings

The current behavioural and neuroelectric results failed to show a selective improvement in executive control processing during the Stroop test following moderate intensity exercise for both young and older adults. These findings are consistent with research which showed that acute aerobic exercise was not beneficial to behavioural and neural indices of executive control (Themanson et al. 2006; Stroth et al. 2009). Previous research investigating the delayed effects of 20 minutes acute exercise in healthy older adults found significant effects following exercise compared to baseline, but did not show any specific congruency effects (Barella et al. 2010). It was concluded that for older adults, moderate intensity acute exercise (60% HRR) was associated with short term positive effects for information processing speed, but did not selectively effect higher order cognitive functioning during the Stroop test (Barella et al. 2010). The current findings support this interpretation and also failed to show a selective improvement during the Stroop. Age group effects were observed at a behavioural and neuroelectric level, although no significant effects specific to Stroop trial congruency were found which is inconsistent with the Selective Improvement Hypothesis for executive functioning (Kramer et al. 1999). However, age group effects were observed in P3b and N450 amplitudes at the frontal region following acute aerobic exercise, showing differential effects of exercise intensity for both age groups. For the young group, P3b and N450 amplitudes were reduced following moderate intensity exercise compared to the control, suggesting that moderate exercise was associated with improved neural efficiency related to the allocation of attentional resources and conflict processing. For older adults, P3b and N450 amplitudes were increased following high intensity exercise compared to moderate exercise, which possibly indicates that high intensity exercise had a negative effect on cognitive functioning at the frontal region. The observed increase in P3b amplitudes following high intensity exercise may reflect the fatiguing influence of acute exercise resulting in inefficient increases in the allocation of attentional resources to successfully execute task demands. These findings are in line with previous research which has found that age-related decline does not effect all areas of cognitive functioning such as perceptual processing, but does effect neural networks associated with evaluation and categorisation processing (West 2004; Zurron et al. 2014; Williams et al. 2016).

Consistent with the Posterior-Anterior Shift in Aging (PASA) theory (Davis et al. 2008), older adults showed increased frontal activation compared to younger adults during the Stroop test, although this effect was not significantly related to task difficulty. For older adults, neural activity reached a frontal maximum following high intensity exercise for both P3b and N450 amplitudes, indicating that high intensity exercise modulated higher order cognitive processing. According to the Scaffolding Theory of Aging and Cognition (STAC) (Park and Reuter-Lorenz 2009; Reuter-Lorenz and Park 2010; Reuter-Lorenz and Park 2014), increased frontal activation with age is a marker of an adaptive brain that engages in compensatory scaffolding in response to challenges posed by declining neural structures and cognitive functioning. The STAC argues that new compensatory neural scaffolding may be viewed as a form of age-accompanied positive plasticity, although these compensatory networks are not as efficient as the neural structures of younger adults (Park and Reuter-Lorenz 2009; Reuter-Lorenz and Park 2010; Reuter-Lorenz and Park 2014). The STAC theory provides a possible explanation as to why older adults did not show positive effects at the frontal region following acute exercise. The exercise-induced activation of neural networks engaged in the Stroop test may have resulted in an inefficient over-activation of the frontal region in older adults, particularly evident following high intensity exercise. This also explains why younger adults showed positive neural effects of high intensity compared to the control, whereas older adults demonstrated a general over-activation in order to meet current task demands.

Older adults also exhibited increased activation at the central region during the Stroop test, which may be understood by the CRUNCH (Dinteren et al. 2014). The CRUNCH argues that the aging brain may increase activity in a neural network to compensate for declining-processes in the same network, or compensation might be achieved by increasing activation in other connected networks. The current P3b and N450 amplitudes results partially support CRUNCH as older adults showed increased activation at the central region compared to younger adults. In addition, these results are also consistent with the PASA theory (Davis et al. 2008) which predicts an age-related reduction in occipital activity coupled with increased activation at the frontal region, which has typically been attributed to functional compensation. Taken together, both the CRUNCH and PASA theories may explain the differences in neural activation observed between young and older participants, particularly at the central and frontal regions.

The STAC-revised theory includes multiple life factors which may also influence the extent of neural scaffolding occurring in later life (Reuter-Lorenz & Park 2014). Higher levels of education, cardiovascular and physical fitness, cognitive engagement, and increased activity in leisure and social activities have all been related to better cognitive abilities, reduced aged-related decline and a decreased risk of Alzheimer’s disease in middle-aged and older adults (Reuter-Lorenz & Park 2014). This demonstrates that cognitive-decline is not a standardised process and there are many individual factors which influence the cognitive aging process. Further research is needed in these areas in order to provide a deeper understanding of age-related cognitive decline and potentially highlight which life factors provide the most cognitive protection.

The current neuroelectric effects of acute exercise may have also been influenced by individual arousal levels, which have been shown to modulate later stages of cognitive processing such as the P300 and N400 complexes (Polich and Kok 1995; Magnié et al. 2000; Polich 2007). Magnié et al. (2000) argued that P300 and N400 were modulated by acute exercise due to a general arousal effect independent of aerobic fitness level. As moderate and high intensity exercise was associated with enhanced neural efficiency for younger adults, this may indicate that the general arousal effect had a positive influence for younger adults. However, older adults showed a substantial increase in neural activity following high intensity exercise, but only a small increase following moderate intensity exercise. This possibly indicates that the moderate exercise condition (40% HRR) in the current study was slightly over the optimum arousal level for older adults, but not for the younger group. Therefore older adults may require a lower exercise-induced arousal level (30% HRR) in order to show positive cognitive benefits of acute aerobic exercise during the Stroop test.

4.4 Limitations, Methodological Issues, Practical Applications and Suggestions for Future Research

In relation to limitations of the current study design, the effects of acute exercise on cognitive processing were assessed after a standardised delay which limits the extent to which the findings can be generalised. The behavioural and neuroelectric effects observed following acute exercise may not provide an accurate representation of the cognitive effects during exercise and it is unclear whether the effects of acute exercise were partially diminished following the standardised delay. As the P3b component is influenced by individual arousal levels (Polich and Kok 1995; Polich 2007), following the termination of acute exercise the exercise-induced changes in neural activity may have normalised and returned to a pre-exercise baseline during the delay period (Dietrich 2006). Therefore the current results should be interpreted with regard to this limitation, as it difficult to know the extent to which the body recovered at a neural level following the cessation of exercise. However, acute exercise effects were still observed for both age groups following this standardised delay, although it is difficult to infer whether the data provides a true representation of acute exercise effects on cognitive processing. As acute aerobic exercise modulated attentional resource allocation during the Stroop test presumably mediated by an increase in arousal levels, this effect highlights the importance of individual motivational factors on cognitive task performance (Brisswalter et al. 2002). Due to the repeated measures design and the increased number of experimental trials required for ERP averaging (Luck 2005), it is currently unclear whether participant motivation levels were modulated following acute exercise. It has been argued that motivation can differentially effect both perceptual competition and executive control processing, with increased motivation improving executive functioning and decreased motivation impairing performance (Pessoa 2009). As participant motivation was not investigated in the current study, future research should explore the interaction effects of motivation and acute exercise intensity on executive control to determine whether acute exercise effects are partially mediated by motivational changes. In addition, the present study investigated acute exercise effects following a standardised delay resulting in the confounding factor of individual exercise recovery rates, which may be different for both young and older adults based on the intensity of exercise performed.

Another important limitation of the present study is that it is only possible to make conclusions based on a single session of acute exercise and not the chronic effects of aerobic exercise training or cardiorespiratory fitness on executive control functioning. Although the current results do not support the beneficial effects of acute aerobic exercise on executive control indexed by the Stroop test, aerobic exercise training performed over a longer time period has been associated with greater executive control processing (Smiley-Oyen et al. 2008; Liu-Ambrose et al. 2010). Therefore, future research examining the effects of aerobic exercise on executive control processing should focus on aerobic exercise training conducted over a period of time rather than the effects of a single bout of aerobic exercise.

In relation to the chronic effects of physical activity levels on cognitive processing following acute exercise, the current study failed to show any significant effects. The lack of significant effects related to physical activity levels highlight the issue of inferring individual fitness levels from self-reported physical activity scores. Research has argued that cardiorespiratory fitness is related to the functional integrity of aging brain networks, but physical activity levels are not associated (Voss et al. 2015). Therefore future research investigating the effects of acute exercise on cognitive processing at a behavioural and neuroelectric level, should measure both self-reported physical activity levels and cardiorespiratory fitness employing an objective assessment measure such as VO_2 max or predicted VO_2 max to provide a more detailed investigation of fitness effects. By the same token, research interested in investigating aerobic exercise and fitness effects on executive control would benefit from conducting a longitudinal study while still employing objective cognitive assessment measures such as EEG, ERPs, MEG, fNIRS and do not rely solely on behavioural performances which offer little insight into the associated neural activity.

As exercise and fitness effects on cognitive functioning typically yield small to moderate effects and the current study employed a small sample size (N = 10), this may have made it difficult to observe fitness and congruency interactions. In order to improve statistical power, future ERP research should increase the number of participants tested. In addition, the current study only tested the effects of cycling at various intensities on information processing and executive control during the Stroop test. As different modes of exercise have differential effects on cognitive processing (Smiley-Oyen et al. 2008; Lambourne and Tomporowski 2010; Liu-Ambrose et al. 2010), it is currently unclear how walking or running at various intensities may influence executive control processing compared to cycling during the Stroop test. There are also various cognitive tests which can be used to assess information processing and executive control functioning such as the Flanker test, the Simon test and the Stroop test, although no research has utilised these tests within the same ERP study to examine acute exercise effects in young and older adults. Therefore, future research could explore exercise-induced effects at a behavioural and neuroelectric level to investigate whether acute exercise at various intensities shows similar effects across these tasks which are presumed to measure similar attentional functioning.

Regarding the neuroelectric cognitive assessment in the current study, later ERP components were selected for analyses. However, the timings of both the P3b and N450 components widely vary in the neuroscience research making it difficult to compare ERP results across studies. In addition, the current study employed two ERP components which overlap in their temporal and spatial domains which contribute to the problem of knowing whether the correct ERP component was successfully isolated and adds to the difficulty of attributing the observed effects to specific cognitive processes. Future ERP research would benefit from selecting a combination of early (P1, N1, P2, N2) and later ERP components (P3a, P3b, N450, SP) to provide a more detailed investigation of the exact stages of cognitive processing influenced by acute aerobic exercise. Current results support acute exercise intensity modulating later stages of attentional processing, namely the P3b and N450 amplitudes which are associated with attentional allocation, goal-directed behaviour, stimulus evaluation, and conflict processing. However, previous research has failed to show any temporal factor that corresponds with the N450 during the Stroop test, suggesting that the reported differences in amplitude between congruent and incongruent trials in the latency window 300-450ms may actually be related to the P300 complex (Zurron et al. 2009).

While ERPs provide accurate temporal information (ms), they are not very insightful for investigating the neural generators of the observed effects which may be viewed as a limitation of the method. A second major disadvantage of the ERP method is that the functional significance of an ERP component is never as clear as the functional significance of a behavioural response (Luck 2005). In most cases the biophysical events that underlie the production of an ERP response or the consequences of the ERP response for cognitive processing, are virtually unclear and rely on many assumptions and inferences required to interpret the data (Luck 2005). For example, with the P3b component some interpret increased amplitudes as a positive effect as more attentional resources were devoted to a given task, whereas, it may also be interpreted as a negative effect if understood from a neural processing efficiency assumption as more cognitive resources were required to successfully perform the task.

In terms of the practical application of the current findings, results suggest that for older adults moderate intensity aerobic exercise was associated with improvements in information processing efficiency, but not for areas of cognitive functioning susceptible to age related decline such as executive control. In older adults, high intensity aerobic exercise was associated with general negative cognitive effects for processing efficiency regardless of trial congruency, particularly at the frontal region which is known to functionally decline with increased age (Hasher and Zacks 1988; Dempster 1992; West 1996). Taken together, these findings support the assumption that areas of cognitive processing reliant on the frontal region are impacted disproportionately by age-related deterioration and may benefit from acute aerobic exercise. However, light to moderate intensity exercise (< 40% HRR) may be more effective than high intensity aerobic exercise (> 70% HRR) at improving processing efficiency in these cognitive domains. For younger adults, the practical applications of the present results support the beneficial effects of moderate and high intensity exercise on information processing and executive control at a neural level, although this tendency was not observed at a behavioural level. Younger adults exhibited enhanced neural efficiency following acute aerobic exercise, which supports the beneficial effects of acute moderate to high intensity exercise (40%-70% HRR) on cognitive processing. The present results highlight the necessity of tailoring exercise intensity to the individual's age and also show the importance of acute exercise intensity on specific aspects of cognitive functioning. In order to maximise the cognitive benefits of acute aerobic exercise on particular cognitive domains, bespoke prescriptions may be required to determine the optimum exercise intensity for an individual with participant age as a contributing factor.

In relation to suggestions for future research, research investigating the effects of aerobic exercise on cognitive functioning should focus on the chronic effects of aerobic exercise training on executive control processing including cardiorespiratory fitness, but not physical activity levels or an acute bout of aerobic exercise. Research examining the relationship between acute exercise intensity and cognitive processing in older adults should also include a mild exercise condition, as well as moderate and high intensities. Research examining exercise modes in relation to older adults and executive functioning could investigate the effects of brisk walking compared to light and moderate intensity cycling, which are similar to the exercise modes older adults usually partake (DiPietro 2001). In the current study moderate and high intensity exercise may have been over the optimal level of arousal for older adults, but not for younger adults. Research has found that younger adults usually perform more vigorous physical activities compared to older adults who perform light to moderate exercise over longer periods of time (DiPietro 2001). Therefore, exercise duration effects should also be considered with the aim of determining the optimum duration of acute exercise in relation to age. Finally, level of education and intelligence are also known to influence neural aging (Reuter-Lorenz & Park 2014) and were not examined in the current study. All younger participants in the current study were undergraduate students who may be more cognitively stimulated compared to the older group. Therefore, future research would benefit from addressing these confounding factors and exploring other lifestyle factors which may be related to cognitive decline in healthy aging.

4.5 Conclusions

During the Stroop test, executive control processing was not selectively improved following acute aerobic exercise at a behavioural or neuroelectric level for young and older adults. This suggests that acute aerobic exercise does not selectively enhance executive control which is inconsistent with the Selective Improvement hypothesis, but rather facilitates a non-specific global activation of neural resources at the frontal region. Acute moderate and high intensity exercise were associated with enhanced frontal processing for younger adults, but for older adults high intensity exercise was associated with inefficient increases in neural resources to meet task demands. The interaction between acute exercise intensity and age group differentially modulated frontal brain activation during the Stroop test, providing evidence that later stage cognitive processing such as the allocation of attentional resources (P3b amplitude) and conflict detection (N450 amplitude) were effected following acute exercise. These findings are understood in terms of Compensatory-Related Utilization of Neural Circuits, the Posterior-Anterior Shift in Aging and Scaffolding Theory of Cognitive Aging.

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Appendices

Appendix 1 - Instructions Presented for the Stroop Test

In this experiment you will be presented with a number of words.

For each one, you will need to identify the COLOUR OF THE FONT the word is presented and not the semantic meaning of the word.

Your responses should be made as quickly and as accurately as possible.

The researcher will inform you when to begin.