THE EFFECTS OF AN ACUTE BOUT OF CYCLING EXERCISE ON BRAIN FUNCTION IN YOUNG ADULTS AND CHILDREN

A Thesis Submitted for the

Degree of Doctor of Philosophy

By

Tamara Sam Dkaidek

Department of Life Sciences,

Brunel University of London

ABSTRACT

An acute bout of cycling may enhance brain function. A meta-analysis (Study 1) was conducted to elucidate the effect of acute ergometer cycling (EC) on executive functions (EFs) in young adults whilst addressing potential moderators. The findings revealed that 21-30 minutes of EC significantly improved EF task response time, predominantly during inhibitory control tasks administered immediately post-exercise. Study 2 compared the influence of EC, visual foraging (VF) and both combined (EC+VF) on young adults' EFs, affective state and prefrontal cortex (PFC) oxygenation. Participants with poorer baseline inhibitory control scores showed more pronounced improvements in the EC condition than those with higher levels. PFC activation and subjective arousal were higher in the cycling conditions than in VF. Yet, PFC activation, cadence levels, and energetic investment were greater in the EC condition than in the EC+VF condition, potentially due to distraction by the VF task. Study 3 compared the effects of EC and EC+VF on children's EFs, reasoning skills and affective state. Findings suggested that EC may be effective for improving working memory and academic reasoning – although practice effects cannot be ruled out. And as per Study 2, findings suggested that individual differences in participants pre-existing EF abilities may mediate exercise-induced changes in EF. The final study explored the effects of stationary cycling whilst viewing real-world 360-degree immersive on-road cyclist point-of-view footage on young adults' and children's EF and reasoning task performance and affective responses; one group heard reward sounds for adaptive foraging behaviour, a second one did not. Findings showed that the cycling intervention heightened participants' arousal and improved their nonverbal reasoning efficiency, irrespective of age or auditory rewards. This thesis partially lends support for using cycling-based interventions to improve brain function. Further research should consider individual differences in abilities, and using alternative tasks to assess cognitive function, for example, academic reasoning tasks.

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DECLARATION

I, Tamara Sam Dkaidek, declare that this thesis is my own work, and it was conducted for a PhD in Sport, Health and Exercise Sciences at Brunel University of London. This thesis was conducted in accordance with the University Code of Research Ethics, and I have completed all compulsory training requirements.

NOTE OF INCLUSION OF PUBLISHED WORK

Chapter 3

Dkaidek, T. S., Broadbent, D. P., & Bishop, D. T. (2023). The effects of an acute bout of ergometer cycling on young adults' executive function: A systematic review and meta-analysis. *Journal of exercise science and fitness*, *21*(4), 326–344. https://doi.org/10.1016/j.jesf.2023.07.001

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- **Tamara Sam Dkaidek (75%)** – Conception and design of study, acquisition of data, analysis and/or interpretation of data, drafting the manuscript
- **Dr Daniel Bishop** – Conception and design of study, analysis and/or interpretation of data, revising the manuscript critically for important intellectual content
- **Dr David Broadbent** – Conception and design of study, analysis and/or interpretation of data, revising the manuscript critically for important intellectual content

Chapter 4

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- **Amelia Dingley** – Acquisition of data, analysis and/or interpretation of data
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- **Tamara Sam Dkaidek (75%)** – Conception and design of study, acquisition of data, analysis and/or interpretation of data, drafting the manuscript
- **Dr Daniel Bishop** – Conception and design of study, analysis and/or interpretation of data, revising the manuscript critically for important intellectual content
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Chapter 6

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CHAPTER 1. INTRODUCTION

Although the benefits of physical activity are established, a significant proportion of UK adults and children do not meet the national guidelines for physical activity levels (National Health Service, 2024). Exercise is a subset of physical activity characterised by planned, repetitive and structured movements (Kern & Armstrong, 2023). Frequently cited barriers to exercise include lack of time and/or motivation (Anderson, 2003; Ferreira Silva et al., 2022; Hoare et al., 2017). However, exercise is an efficient form of physical activity that confers multiple health benefits – not least for brain structure and function (Chang et al., 2012; Tsukamoto et al., 2017; Sugimoto et al., 2020). While the efficacy of cognitive training for enhancing cognitive function is questionable (Gobet & Sala, 2023), evidence for the efficacy of acute and chronic exercise continues to grow (Basso & Suzuki, 2017; Audiffren & André, 2015).

1.1 Research Context

Despite accumulating evidence for the effects of acute exercise on cognition and mood (Basso et al., 2015; Jaffery et al., 2018; Liao et al., 2015; Reed & Ones, 2006; Tomporowski, 2003), the extent of these effects remains indeterminate – potentially due to methodological inconsistencies across studies (e.g., variations in exercise modality; Lambourne & Tomporowski, 2010). Moreover, there is no consensus about what constitutes an acute bout of exercise, namely in terms of various moderators such as the duration of the bout, its intensity and the exerciser's perception of their exertion; hence, delineation of this term is required (Basso & Suzuki, 2017). Although previous analyses have explored the differential effects of moderators such as exercise intensity and duration on subsequent cognitive function, it is timely to provide an updated and revised analysis of their effects. It is also timely to focus on a single exercise modality – in this case, stationary cycling – to reduce the heterogeneity, and resultant ambiguity, of the findings to date.

To illustrate the heterogeneity regarding exercise modality: Lambourne and Tomporoswki's (2010) meta-analysis revealed greater cognitive function improvements after acute cycling interventions relative to treadmill running of a similar duration. One explanation for such differences is that differential muscle fibre recruitment in these two activities may alter the contributions of aerobic and anaerobic energy pathways (Bijker et al., 2002). They suggested that, as supported by others (e.g., Scott et al., 2006) cycling exerts lower demands on lower and upper-body coordination, for example, which may reduce energetic demands. However, cycling is more inclusive than running due to the availability of various forms of adaptive cycles. For these reasons and others, cycling interventions are central to this thesis.

An advantage of ergometer cycling is its stability relative to running; this means that secondary tasks can be performed without unduly compromising exerciser safety. *Dual-task exercise* typically involves a combination of physical exercise with a cognitively demanding secondary task (Petrigna et al., 2021). In the case of cycling, there is the opportunity to mimic real-world behaviour such as paying attention to/navigating complex environments while commuting on a cycle, in laboratory setups. Hence, cycle commuting could be a viable intervention that can be incorporated into people's daily routines. However, recent reports suggest that, since 2021 (i.e., post-Covid), the proportion of UK adults cycling for both leisure and travel has increased (Department for Transport, 2024). Hence, it is timely to investigate potential benefits of dual-tasking during cycling – notably, whether concurrent performance of stationary cycling and a cognitively demanding secondary task might enhance cognitive function. This may bolster the argument for use of cycling as a mode of travel.

1.2 Research Objectives

Considering the above, the objectives of this thesis were to:

a. Review research over the past decade in which the impact of an acute bout of cycling exercise on EF task performance had been examined, and relatedly, to identify the extent to which four moderators – *exercise frequency*, *intensity*, *duration*, and *modality* – might optimise its effectiveness as an intervention.

b. Compare the effects of ergometer cycling, visual foraging and dual-task exercise – ergometer cycling and visual foraging combined – on young adults' cognitive function, affective state and cerebral oxygenation.

c. Compare the effects of ergometer cycling, visual foraging and dual-task exercise – i.e., ergometer cycling and visual foraging combined – on children's cognitive function, reasoning skills and affective state.

d. Explore the effects of viewing naturalistic 360-degree immersive footage and stationary cycling on children's and young adults' cognitive function, reasoning skills, and affect.

CHAPTER 2. LITERATURE REVIEW

2.1 Executive Functions

A growing body of evidence suggests a positive influence of acute aerobic exercise on executive functions (EFs; Aguirre-Loaiza et al., 2019; Chang et al., 2012; Ishihara et al., 2021; Lambourne & Tomporowski, 2010; Li et al., 2024). Our EFs are cognitive control processes that govern our thoughts and actions, and are seemingly inherited (Friedman et al., 2008). They engage prefrontal cortices and are central to our ability to make decisions, plan, remember information and pay attention to relevant stimuli. Through a process of factor analysis and structural equation modelling, Miyake and colleagues (2000) identified that EFs comprise three broad components, which they described as *inhibitory control*, *working memory* and *task-switching.* These components emerge in infancy and continue to develop into adulthood (Garon et al., 2008), with each EF developing at its own rate throughout childhood and adolescence (Ferguson et al., 2021).

Inhibitory control is our ability to avoid distractors or to suppress our prepotent responses to stimuli (Miyake et al., 2000). It enables us to control what we attend to, thereby mediating our thoughts, behaviours and emotions (Diamond, 2013). Hence, inhibitory control can help us decide how to react to a situation and focus on what we are doing and where we are going (Diamond, 2013). This ability emerges early in infancy and develops rapidly through the ages of 3 to 6 years, potentially due to rapid growth of the prefrontal cortex (PFC; Liu et al., 2015).

The Eriksen Flanker Task is commonly used to assess inhibitory control. Eriksen and Eriksen (1974) developed the task, in which a central target letter/arrow is presented on a display screen, flanked by distractor letters/arrows on both sides. The trials are either congruent – the flanker letters/arrows central letter/arrow are identical to the target – or incongruent (i.e., they differ). Performance of the Flanker task is determined by the ‘Flanker

Effect', calculated as the difference between average reaction times for congruent and incongruent trials. The Flanker Effect appears to be associated with individual differences in engagement of the PFC, which is involved in inhibitory control (Forstmann et al., 2008).

Our *working memory*, which is associated with dorsolateral prefrontal cortex (DLPFC) activation (Barbey et al., 2013; Lin et al., 2022), is responsible for monitoring new information, e.g., for its personal relevance, and replacing older information that is no longer relevant (Miyake et al., 2000; Morris & Jones, 1990). Working memory allows us to perform mental arithmetic, follow instructions, interpret novel information and act on the information we receive (Cowan, 2014). Improvements in working memory appear as early as 5-6 months old and appear to stem from development of attention at the same time (Reynolds & Romano, 2016). Working memory supports the development of inhibitory control, which are often engaged concurrently during everyday situations (Diamond, 2013). For example, individuals must remember their momentary goals so they can decide what potential courses of action are relevant to those goals and what they should disregard.

The 2-Back task developed by Kirchner (1958) assesses working memory. It typically involves presentation of a continuous sequence of letters, which are bordered above and below by grey horizontal lines. The participant must identify if the current letter is identical to the one presented two trials earlier (a *match*) by pressing a key on a traditional computer keyboard; they do not press the key if they believe that the letters do not match. If a participant incorrectly identifies a non-matching pair as a match, it is considered a *false alarm*, and if they miss a match, it is a *missed item*. Correct match accuracy is calculated using the formula (hits/hits + errors) x 100, false alarms using (false alarms/non-matching trials) x 100, and missed items using (missed items/non-matching trials) x 100.

Task-switching, also referred to as *cognitive flexibility,* is shifting of our attention from one task to another (Miyake et al., 2000). Task-switching allows us to be flexible, to change our priorities accordingly, and to multitask (Miller & Cohen, 2001). Unlike inhibitory control and working memory, the development of task-switching only starts to fully develop at around 7 to 9 years of age (Frick et al., 2022; Gupta et al., 2009).

The Wisconsin Card Sorting Task (WCST; Milner, 1963) is commonly used to evaluate people's ability to shift their attention between different tasks. Computerised versions of the task present four 'cards' (*response cards*), each of which comprises shapes that vary in their number, form and colour; a similar card is presented at the bottom of the screen. The participant's aim is to match the bottom card with one of the four response cards according to one of several classification rules: *number, form* or *colour*. However, the classification rules change randomly throughout the task – the participant must change their matching strategy when they make an incorrect match. So, if they select a correct response card, they apply this rule until it switches, and when the response becomes incorrect, they receive auditory feedback and must apply a new classification rule until a match is achieved. Task scores indicate the individual's ability to adapt to the switching rules. Task performance is defined by the participant's error count, calculated as the sum of Non-perseverative Errors (i.e., random errors) and Perseverative Errors (i.e., repeated errors).

2.1.1 Executive Functions and Academic Performance

EFs may play an essential role in academic success, although this role may differ according to how EFs and their effects are conceptualised (Perpiñà Martí et al., 2023). For example, EFs may directly impact learning (e.g., remembering instructions for a task; *working memory*) or indirectly influence learning behaviours (e.g., staying organised and engaged during lessons; arguably reliant on *working memory, task switching* and *inhibitory control*). Relatedly, Clark and colleagues (2010) showed that young children's ability to plan, switch their attention and exert inhibitory control explained a significant proportion of the variance in their mathematics ability several years later. Inhibition and working memory are also associated with reading comprehension (Foy & Mann, 2013; Sesma et al., 2009).

Higher-order EFs, such as reasoning and problem-solving, have been referred to as 'Fluid Intelligence' (Lunt et al., 2012). Higher-order EFs are built on the foundations of the core EFs (i.e., working memory, inhibitory control, cognitive flexibility). Relatedly, Brookman-Byrne and colleagues (2018) detected the contributions of verbal and nonverbal reasoning to adolescents' science and maths performance. Specifically, they found that those who scored higher on verbal reasoning tasks were more accurate and quicker when completing science and maths tasks, and that superior nonverbal reasoning was linked to greater accuracy in the science tasks.

2.2 The Effects of Acute Exercise on Cognitive Function

Previous findings have suggested that a single exercise session may be sufficient to alter cognitive abilities, including memory, attention, information processing and EFs (Chang et al., 2012; Hillman et al., 2009; Tomporowski, 2003; Zheng et al., 2021). Moreover, meta-analyses have identified various moderators that may optimise acute exercise-induced EF performance changes. For example, Etnier and Chang (1997) synthesised 134 studies to examine the influence of various moderators, including exercise paradigms (e.g., acute and chronic), cognitive test category (e.g., memory, reasoning, math), exercise group size (e.g., alone vs. in a group), sex (e.g., male, female, not reported, mixed), age group (e.g., elementary, adult, older adult), exercise intensity (e.g., low, moderate, high) and more. Their analysis showed a small positive effect of exercise on overall cognitive function, suggesting that chronic training and acute exercise may enhance cognitive performance. Additionally, the effects of exercise were moderated by the exercise paradigm, in which chronic training had a larger effect than acute exercise, as well as the participants, quality of the study and the cognitive tests. These moderators and their effects are explicated in section 2.2.2 and in Chapter 3.

2.2.1 The Effects of Acute Exercise on Academic Performance

Li et al. (2017) conducted a systematic review investigating the effect of chronic and acute exercise on adolescent's academic performance. The authors synthesised ten papers, the majority of which focused on acute exercise and reported significant effects of exercise on cognitive function. Academic performance was based on the participants' arithmetic skills, revealing that both acute exercise (Travlos, 2010) and chronic exercise (Lees & Hopkins, 2013) were beneficial. The authors suggested that acute exercise-induced improvements were mediated by increased arousal levels, facilitating classroom attention (Lees & Hopkins, 2013) – but this assertion requires closer empirical scrutiny.

Duncan and Johnson (2014) investigated the effect of acute cycling at different intensities on preadolescent students' academic ability. The authors employed a repeated-measures design comprising the following conditions: (1) 20 minutes of moderate intensity ergometer cycling (50% Heart Rate Reserve [HRR]), (2) 20 minutes of high intensity ergometer cycling (75%HRR), and (3) 20 minutes of rest. Academic ability was assessed using the Wide Range Achievement Test (WRAT 4), which consisted of questions to assess participants' spelling, reading, arithmetic, and sentence comprehension abilities. Their findings showed that both exercise conditions improved spelling ability, regardless of exercise intensity, and moderate intensity cycling improved reading ability. However, both exercise conditions impaired arithmetic, and did not affect sentence comprehension. The authors concluded that acute bouts of exercise may improve some aspects of cognition. But the effects of exercise on academic performance are far from clear-cut.

Ardoy and colleagues (2014) evaluated the effects of the intensity and duration of physical education lessons on adolescents' cognition and academic performance. Sixty-seven adolescents took part in a four-month trial. They were allocated to one of three groups: a control group who received their usual physical education lessons (i.e., two sessions per week), an experimental group who received four physical education lessons weekly, and a second experimental group who completed four high intensity physical education lessons weekly. Cognition was assessed using the Spanish Overall and Factorial Intelligence tests, including verbal and abstract reasoning, verbal, nonverbal, numerical and spatial ability; their average school grades for mathematics and science were also scrutinised. All performance variables, but verbal reasoning and average school grades in mathematics, were superior in the second experimental group compared to the control and the other experimental group; there were no differences between the latter two. These findings suggest that exercise interventions may enhance academic performance.

Despite an increasing body of evidence to show that acute exercise benefits both EF and academic performance, the influence of various moderators such as exercise intensity and duration is less clear.

2.2.2 Moderators of the Exercise-Cognition Relationship

Lambourne and Tomporowski’s (2010) meta-analysis assessed the influence of exercise-induced changes in arousal on cognitive performance . The authors revealed that cognitive performance was impaired during the first 20 minutes of exercise, whereas afterwards, exercise-induced heightened arousal levels mediated quick decisions and automated behaviour. Increased arousal levels facilitated processing speed and working memory. Finally, they found a difference in exercise modality, whereby cycling was associated with more significant cognitive enhancements during and after exercise than treadmill running.

In a subsequent review, Chang and colleagues (2012) explored the effects of acute exercise on cognition and the influence of moderators, namely, exercise intensity, general cognitive task type, fitness level, and cognitive administration after exercise. After synthesising 79 studies, the authors found exercise's small, positive effect on cognition during exercise and after a delay of 1 to >15 minutes. An analysis of the moderators revealed no significant effects of intensity during exercise; however, light-intensity exercise was shown to influence cognitive performance immediately after exercise, although this subsided after delays longer than one minute. Intense exercise elicited the largest effects on cognitive performance after a minimal delay – specifically, on cognitive tasks administered 0-10 minutes after exercise. Their analysis also revealed that tasks administered 11-20 minutes post-exercise enhanced cognitive performance the most. An exercise duration of 11-20 minutes negatively affected cognition, but durations greater than 20 minutes exerted beneficial effects, supporting Lambourne and Tomporowski's (2010) findings.

2.2.2.1 Affective Responses.

Debates over the years have argued what constitutes emotion, mood and affect (Ekkekakis & Petruzzello, 2000). A specific event usually triggers emotions, which are typically more intense and of shorter durations (Lochner, 2016; Scherer, 2005), whereas moods are undirected, unconscious and are commonly stable background sensations (Lischetzke et al., 2011; Lochner, 2016). Our affective state can broadly be described by emotional valence – whether we feel generally negative or positive – and this dimensionality underpins both emotions and moods (Ekkekakis & Petruzzello, 2000).

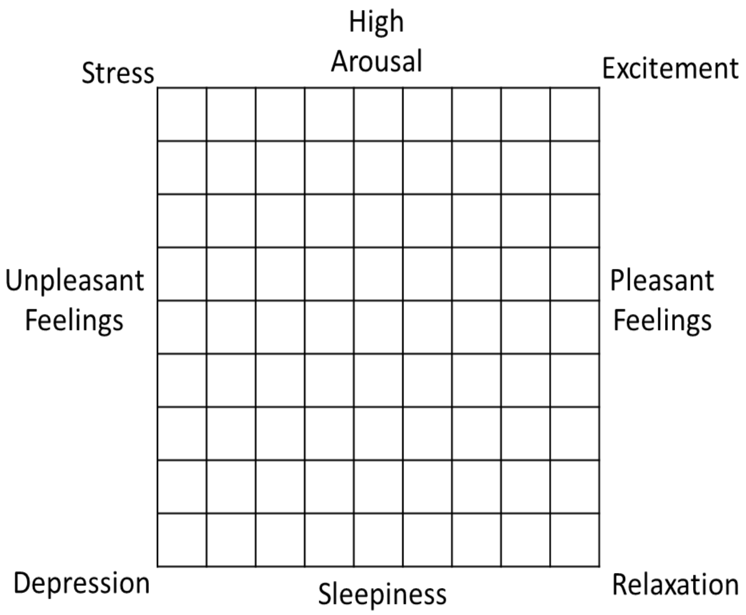
Self-report measures are widely used to assess a participant's perceived experience of emotions and their affective state (Harley, 2015). Broadly speaking, such measures either adopt either a categorical approach (i.e., identifying distinct categories of emotion such as, anger, happiness, love etc.; Ekman, 1992) or dimensional approaches (i.e., systematic affective states modelled as a set of dimensions; Russell et al., 1989). Although categorical conceptualisations of affect provide specificity and therefore differentiation of emotional states, participants' selection of affective descriptors can be somewhat rushed and/or arbitrary, leading to missing and/or impoverished data (Russell et al., 1989). Dimensional measures are a quick and effective methods to determine in-the-moment affective states, ones that account for individual differences in affective experiences (Mehrabian & Russell, 1974). One such measure is the Affect Grid (Russell et al., 1989).

2.2.2.1.1 The Affect Grid.

The Affect Grid (Figure 2.1) is a self-report measure that captures an individual's in-the-moment affect (Russell et al., 1989). It is a 9-by-9 grid comprising two dimensions, arousal-sleepiness and pleasure-displeasure, in which participants denote their affective state by marking one square of the grid with a cross. The Affect Grid is based on the Circumplex Model of Affect (Russell, 1980), which includes two perpendicular dimensions – *affective valence* (pleasure-displeasure) and *perceived activation* (arousal). The perpendicular dimensions create four quadrants: (1) *high activation-low valence,* (2) *high activation-high valence*, (3) *low activation-high valence,* and (4) *low activation-low valence*.

Figure 2.1

Russell et al.'s (1989) Affect Grid.



2.2.2.1.2 Exercise-Induced Arousal and EF Task Performance.

As illustrated in Lambourne and Tomporowski's (2010) meta-analysis, acute exercise-induced arousal levels may facilitate fast decision-making and responses. Byun and colleagues (2014) investigated the effects of light-intensity exercise (30% Maximum volume of oxygen [$\dot{V}O_{2max}$]) on EFs and functional Near-Infrared Spectroscopy (fNIRS) data (See further study explanation in Section 2.3.2.2). They also assessed psychological mood states using The Two-Dimensional Mood Scale (Sakairi et al., 2013), an 8-item scale using mood-expressing pleasure and arousal state words (i.e., calm, energetic, irritated, lethargic, lively, listless, nervous and relaxed). Their findings showed exercise-induced improvements in Stroop performance correlated with increased arousal. They also found increased cortical activations in the left DLPFC and frontopolar area during the cognitive task, corresponding with increased subjective arousal levels and cognitive performance. The authors suggest that exercise-induced EFs may be mediated by increased arousal levels, which increases cortical activation in task-dependent brain regions.

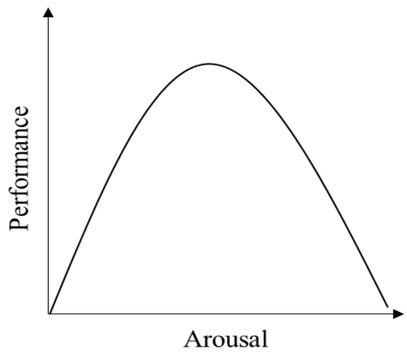
Contrarily, Hacker and colleagues' (2020) findings did not show an association between an exercise-induced increase in arousal levels and cognition. Hacker et al. (2020) aimed to investigate the dose-response relationship between exercise duration, cognitive attention, visual recognition memory tasks and objective (i.e., heart rate) and subjective arousal (Felt Arousal Scale; Hardy & Rejeski, 1989). The study comprised three conditions, which included durations of 15, 30 or 45 minutes of cycling at 60-70% $\dot{V}O_{2max}$. Cognitive measures were investigated using the One Card Learning Test (visual recognition memory) and the Detection Test (attention and psychomotor speed). All three conditions increased self-reported arousal and heart rate. Therefore, 15 minutes of exercise may be sufficient to increase subjective arousal. However, the processing speed of the cognitive tasks were not improved post-exercise, yet there was a small beneficial effect on accuracy. They suggested that increased arousal may not affect the necessary neuronal adaptions to elicit improvements in the selected tasks.

Yerkes and Dodson's (1908) inverted-U hypothesis suggests a nonlinear relationship between arousal levels and performance (see Figure 2.2). Predictions based on this hypothesis propose that moderate-intensity exercise is optimal for cognitive performance, potentially because of increased catecholamine and cerebral oxygenation levels (Lambourne & Tomporowski, 2010). However, Yerkes and Dodson's (1908) theory was based on their original paper examining the speed in which rodents learned to differentiate between boxes through electric shocks - the severity of shocks was dependent on the difficulty of the task (Nieuwenhuis, 2024).

Nieuwenhuis (2024) addressed that assessing arousal states is much more complicated in human participants than in rodents. Beerendonk et al. (2024) analysed pupil-indexed arousal and decision-making task performance to converge evidence for an inverted-U relationship. They presented a neurobiological model to explain the existence of the inverted-U hypothesis, yet were faced with challenges such as the influence of task difficulty and complexity as well as the potential benefits of high arousal in more stressful situations. These findings indicate that the arousal and performance relationship is not straightforward and may be impacted by contextual factors.

Figure 2.2

Performance-Arousal Relationship According to the Inverted-U Hypothesis



2.2.2.2 Exercise Intensity

Exercise intensity is frequently investigated as a moderator due to its apparent dose-response relationship with physiological changes (e.g., catecholamine upregulation) during exercise (Chang et al., 2012). However, the relationship between arousal levels and cognitive performance is still inconsistent. According to the inverted-U hypothesis (Yerkes & Dodson, 1908) there may be a curvilinear relationship between arousal and task performance, however, this may not be the case. The exercise-arousal relationship may be contingent on task difficulty and may be situational (Beerendonk et al., 2024).

Tsukamoto and colleagues (2017a) conducted a study assessing the effect of *exercise volume* – the product of exercise intensity and duration – on 12 healthy young males' EF task performance. They used a repeated-measures design comprising three exercise conditions: (1) 20 minutes of low-intensity exercise (30% $\dot{V}O_{2max}$), (2) 20 minutes of moderate intensity exercise (60% $\dot{V}O_{2max}$), and (3) 40 minutes of low-intensity cycling. EF performance was determined using the colour-word Stroop task pre-, immediately after and after a 30-minute delay of each exercise condition. There were greater improvements in EF task performance after 20 minutes of moderate intensity cycling relative to 40 minutes of low-intensity cycling. The authors concluded that moderate intensity cycling may sustain EF improvements for longer, even when compared to longer duration exercise at lower intensity yielding an identical exercise volume.

Zhu and colleagues (2021) assessed the difference between an acute bout of high intensity interval training and continuous moderate intensity cycling and running on young adults' EFs. They used a repeated measures design with four conditions: (1) 40 minutes of moderate intensity cycling (60% $\dot{V}O_{2max}$), (2) 40 minutes of moderate intensity running (60% $\dot{V}O_{2max}$), (3) 33 minutes of high intensity interval cycling (comprising 5-minutes of 60% $\dot{V}O_{2max}$, and then 4-minute bouts of 90% $\dot{V}O_{2max}$ separated by 3-minutes of active recovery at

60% $\dot{V}O_{2max}$), and (4) 33 minutes of high intensity interval cycling running (same as condition [3] but running rather than cycling). EFs were assessed pre-, immediately after and 10 minutes after the intervention using the Flanker Task. Their findings revealed improved reaction time in both cycling conditions and in the high intensity interval running condition after a 10-minute delay. Further, Zhu et al. found no difference in response accuracy after any of the interventions, potentially supporting McMorris and Hale's (2012) suggestion that complex tasks may be required to elicit exercise-induced changes in accuracy. A limitation of this study is the male-only sample, restricting generalisability, which is also a limitation in other studies in the field (e.g., Sugimoto et al., 2020; Tsukamoto et al., 2016, 2017).

Martins and Duncan (2021) investigated the differential effects of high intensity interval and moderate intensity cycling on children's EF task performance. They used a repeated measures design with two 15-minute conditions: (1) moderate intensity continuous cycling (70%HR_{max}), and (2) high intensity intermittent cycling (≥85%HR_{max}; 12 bouts for 30s). EFs were assessed before, immediately after and after a 30-minute post-exercise delay, via the Stroop task (*inhibition*), Corsi Block tests (*working memory*) and the Digit Span (*working memory*). Both conditions elicited improvements in EF task performance. Specifically, the moderate intensity exercise improved response times for congruent stimuli (e.g., blue word written in blue) at both post-exercise timepoints, suggesting that moderate intensity exercise may benefit EFs shortly after and may be sustained for 15-30 minutes after. The high intensity condition did not show any EF improvements shortly after exercise (post 1-minute), relative to the control condition, suggesting a delay in task administration may be required. The high intensity condition elicited improvements in reaction time 30 minutes after exercise for the Stroop task incongruent stimuli (e.g., red word written in blue), which demand higher inhibitory control.

Although the inverted-U hypothesis suggests that moderate intensity exercise is optimal for enhancing task performance, there is still inconsistency in support for the hypothesis. It is possible that exercise intensity-induced influence on task performance may be contingent on the exercise modality, as treadmill running and ergometer cycling, for example, may elicit different psychophysiological responses (Bogdanis et al., 2021). Therefore, it is prudent to investigate exercise in a single modality. For this reason, and others (see Section 1.1), this thesis focuses on stationary cycling.

2.2.2.3 Exercise Duration

Exercise duration may influence physiological responses, such as sensory alertness and heart rate, which may facilitate EF performance (Hacker et al., 2020). There is an established association between exercise duration and arousal, with predictions of deterioration in performance when exercise hits maximal levels (McMorris & Graydon, 2000). Chang and colleagues' meta-analysis reported that short exercise durations (e.g., 10 minutes) may be insufficient for improving cognition. Other studies investigating the effects of different exercise durations on EFs found similar results (Chang et al., 2015; Tsukamoto et al., 2017).

Chang and colleagues' (2015) study assessed the effects of exercise duration on cognition. Twenty-six young men participated in a repeated measures design with three exercise durations, 10, 20 and 45 minutes of moderate intensity (65% $HR_{reserve}$) cycling or a reading control treatment. The EF performance was assessed using the Stroop task. Their findings revealed improved cognitive performance (i.e., response time and higher accuracy) after 20 minutes of moderate-intensity cycling relative to the other two durations, which showed negligible effects. Their findings signify a dose-response relationship between duration and cognition; however, they do not align with Tsukamoto et al.'s (2017) findings.

Tsukamoto and colleagues (2017b) investigated the effect of different exercise durations on post-exercise EF task performance. A repeated measures design was used wherein 15 male participants completed ergometer cycling for three different durations: 10, 20 and 40 minutes of moderate-intensity exercise (60% $\dot{V}O_{2max}$). Inhibitory control was assessed pre-exercise, immediately after the intervention and 30 minutes later, using the colour-word Stroop task. No significant differences were found in post-exercise EF performance compared to prior. However, the difference between pre- and post-30 minutes of exercise was greater after the 40-minute cycling duration but not in the other two durations. These findings suggest EF improvements may be sustained for longer after longer exercise durations.

Like exercise intensity, there may be a minimum duration threshold to surpass to trigger the neurophysiological processes that underpin cognitive improvements. Also similar to exercise intensity, there may also be a higher threshold whereupon detriments to cognition occur (Tsukamoto et al., 2016). When considering this, it is important to manipulate each moderator in isolation from the others. However, testing the ‘optimal’ intensity and duration in combination is required to fully elucidate a dose-response relationship vis-à-vis exercise volume.

2.2.2.4 Dual-Tasking

Combining cognitive and motor tasks in experimental studies of exercise more closely reflect our everyday behaviour (i.e., multitasking). Accordingly, researchers are increasingly using dual-task paradigms to explore the effects on cognitive performance in adults (Zheng et al., 2021), older adults (Guo et al., 2020; Tait et al., 2017), and children and adolescents (Wollesen et al., 2022). Reviews of dual-tasking in older adult populations showed that dual-task paradigms effectively improved subsequent cognitive performance relative to control conditions (Guo et al., 2020; Lauenroth et al., 2016).

For example, Guo and colleagues (2020) conducted a meta-analysis exploring the effect of a combined physical and cognitive intervention on older adults' EFs. They categorised the study interventions based on moderators of the combined compared to the control group, including mode of combination, frequency, intervention length, and session duration. After synthesising 21 studies, their results revealed that the combined intervention elicited greater EF improvements than the control group. The authors moderated the combined interventions by study quality, intervention duration and frequency. The combined intervention effectively decreased the EF decline; however, there is not enough evidence to suggest that combined interventions have more pronounced effects on EFs than physical or cognitive interventions in isolation.

In their review, Wollesen and colleagues (2022) synthesised seven studies to evaluate the effect of dual-task training on children and adolescents' cognitive performance. The studies differed in the exercise protocols employed, specific or general dual-task, and the frequency of exercise sessions. *Specific dual-task training* is designed to improve performance and enhance the task-combination by increasing task complexity. *General dual tasking* has greater transfer effects as it involves practising different task combinations, such as walking while doing a secondary task. Their findings indicated that dual-task training, whether specific or general, has the potential to improve cognitive performance, such as EFs, or motor performance, such as balance. However, such findings were not consistent, likely due to different training methods and specifications. Additionally, dual-task effects are less pronounced when compared to an active control group, rather than a sedentary one (Wollesen et al., 2020, 2022). The authors suggested further investigations to explore individual differences' impact on outcomes and clarify the effects of dual-task exercise on cognition.

2.2.2.4.1 Dual-Tasking and Executive Function

Ji and colleagues (2019) investigated the effects of acute exercise on EFs and cerebral oxygenation. They recruited twenty older adults to take part in four experimental conditions lasting 15 minutes each: (1) passive reading control, (2) physical exercise (i.e., walking at 65% HR returned), (3) cognitive exercise (verbal fluency task), (4) cognitive + physical exercise (i.e., verbal fluency task + walking). Inhibitory control was assessed using the Stroop task, and PFC oxygenation was measured bilaterally using fNIRS. The authors found that acute exercise facilitates executive task performance, irrespective of exercise condition (physical exercise and cognitive + physical exercise). The physical condition showed facilitative effects on naming task performance. The fNIRS data showed acute exercise-induced oxygenation for the executive tasks, not the naming tasks. Higher oxygenation levels were demonstrated after the cognitive + physical condition during the post-exercise Stroop task. This suggests that combined exercise may be more beneficial than exercise in isolation, and cognition may be maximised using cognitively demanding exercise.

Kimura and colleagues (2022) recruited twenty healthy young adults to investigate the differential influence of varying exercise intensities while dual-tasking on PFC neural activity. The initial session included a maximal oxygen uptake exercise test on a cycle ergometer to establish their individualised low (23% $\dot{V}O_{2peak}$), moderate (40% $\dot{V}O_{2peak}$) and high (60% $\dot{V}O_{2peak}$) intensity heart rate thresholds to standardise exercise intensity. The second lab visit consisted of four different conditions, in which the order was randomised among participants: (1) low-intensity pedalling exercise, (2) moderate intensity pedalling exercise, (3) high intensity pedalling exercise, and (4) seated rest on the ergometer. The concurrent cognitive task consisted of serial subtraction of three from 100. Each of the conditions comprised four phases lasting approximately 60 minutes: (1) resting, (2) pedalling (single motor task prior to dual task), (3) dual-task (serial subtraction while pedalling), (4) pedalling (single motor task subsequent to dual-task). During the exercises, PFC activity was assessed using fNIRS. Findings revealed increased PFC activity in the low-intensity condition after the dual-tasking, under moderate activity during the pedalling phase, and sustained during and after the dual-tasking intervention. Finally, the high intensity condition revealed an increase during the dual-task phase; however, not after dual-tasking, possibly due to interference effects. Therefore, low and moderate intensity exercise with a cognitive load may be sufficient to increase PFC activity.

It is suggested that PFC activation exhibits an inverted-U relationship with exercise intensity and a similar one with cognitive load (Kimura et al., 2022). Therefore, as dual-task paradigms elicit physical and mental demands, future research should explore different load manipulations to understand the influence of dual-tasking on cognition and the extent of such effects (Kimura et al., 2022; Mandrick et al., 2013; Rémy et al., 2010).

2.2.2.4.2 Combining Gamified Tasks with Exercise

Exergaming – or active videogaming – is a dual-task paradigm that has gained interest over the years. The effects of exergaming on cognitive performance on young adults (Douris et al., 2018; Kunzler & Carpes, 2021; O'Leary et al., 2011), and children and adolescents (Benzing et al., 2016, 2018; Best, 2012) have been examined.

O'Leary and colleagues (2011) compared the effects of 20 minutes of exergaming (60% HR_{max}; Wii Fit™) on young adults' inhibitory control relative to 20 minutes of treadmill-based aerobic exercise (60% HR_{max}), seated videogame play (MarioKart®) and seated rest. Response times in the Flanker Task were improved after treadmill-based aerobic exercise relative to seated videogame play or seated rest. The authors concluded that although exergaming may positively improve exercise participation, it may not be as beneficial to cognition as aerobic exercise. Douris and colleagues (2018) obtained similar results when comparing 30-minute videogames and cycling sessions. Both videogaming and combined videogaming + cycling revealed improved processing speed and selective attention in the Stroop Colours and Word and Oral Trails B tests. However, the cycling condition benefited EF the most. The authors suggested that combined physical and cognitive tasks may have fatiguing effects (see Section 2.3.1.4.4), potentially reducing the individual's attentional capacity.

Benzing and Schmidt (2019) explored the effect of an 8-week exergame intervention (i.e., three 30-minute sessions per week) on EF task performance of 8-12-year-olds with attention deficit hyperactivity disorder (ADHD) relative to a waiting-list control group also with ADHD. EFs were assessed across the three core EFs: inhibitory control (modified Simon Task), switching (modified Flanker Task) and updating (modified colour span backwards task). The experimental group's EFs reaction time performance in inhibitory control and switching tasks improved relative to the control group. Based on the evidence presented above, it appears that physical activity is more effective than its cognitive counterpart for enhancing cognitive function. However, given the popularity of videogaming (Smirni et al., 2021), due to its engaging and motivating nature (Benzing & Schmidt, 2018), exergaming approaches could help increase engagement in physical activity and exercise in laboratory and real-world settings.

Best (2012) examined the impact of exergaming on children's EFs. They focused on an exergaming intervention to examine the combined effects of acute exercise and cognitive engagement compared to both aspects separately. The study comprised a repeated measures design in which children completed the following conditions: (1) physically active videogames, (2) sedentary videogames, (3) challenging and interactive videogames and (4) repetitive videogames. Cognitive functions were assessed using the Flanker task. Findings demonstrated that exergaming positively affected children's response time while resolving interference in the visuospatial stimuli.

2.2.2.4.3 Visual Foraging Tasks

Dual-task paradigms are particularly effective when the secondary task is, novel, mentally demanding and engages EFs (Guo et al., 2020; Ji et al., 2019). Previous studies have illustrated that these objectives are fulfilled to varying extents when exergaming (Benzing & Schmidt, 2019; Best, 2012; Douris et al., 2018; Kunzler & Carpes, 2021; O'Leary et al., 2011), sports (e.g., modified soccer; Van der Niet et al., 2016), and subtraction (Lüder et al., 2018) are employed as secondary tasks. However, given the wider societal context – i.e., the physical inactivity problem (Guthold et al., 2018; Haseler & Haseler, 2022) – and the imperative to increase people's daily physical activity levels accordingly (Tuso, 2015; Wu et al., 2017), it is prudent to investigate the use of secondary tasks that mimic real-world demands.

Cycling outdoors, particularly on roads, requires rapid switching of attention from one task to another (e.g., from changing gears to monitoring an approaching vehicle), inhibition of irrelevant information (e.g., noisy pedestrians in one's periphery), and retention of key information (e.g., the proximity of rearward vehicles when planning to change lanes); these are the EFs of task-switching, inhibitory control and working memory, respectively. Moreover, successful deployment of these EFs in the situations outlined above requires appropriate looking behaviour – namely, to look at the gear shifter and ahead in the roadway (task-switching), to override exogenous attentional capture by distracters/task-irrelevant phenomena (inhibitory control), and to fixate on task-relevant phenomena for subsequent retention (working memory).

A laboratory analogue of this behaviour is the visual search task paradigm. Common visual search tasks require a systematic search for a preidentified target that is defined either by one feature (e.g., its colour) or a conjunction of features (e.g., both colour and shape; Treisman, 1977). According to the Feature Integration Theory (Treisman & Gelade, 1980), visual features such as shape and colour are organised topographically by separate brain regions. Therefore, to identify conjunction stimuli, individuals must integrate the separate brain regions (Treisman & Gelade, 1980; Trick & Enns, 1998). Conjunctive visual search has been associated with increased activation in the frontal cortex (working memory), parietal cortex (spatial attention) and the frontoparietal regions (frontal eye fields; Parker et al., 2014). Visual search attributes, such as display size (Botch et al., 2023), search array and set size (Wolfe & Horowitz, 2017), and distractors (Woods et al., 2013), may impact an individual's efficiency in performing a visual search task. A more complex array and larger set size may result in distractor interference, inhibiting attention from the relevant stimuli, making it harder to maintain focus, and reducing search accuracy (Cave & Chen, 2016; Verghese, 2001).

One type of visual search task is *visual foraging*, the requirements of which are akin to our visual attention allocation when operating in dynamic environments – particularly when multiple targets are detected amongst many distracters (Kristjánsson et al., 2019). Kristjánsson and colleagues (2014) created a novel visual foraging task (VFT) displayed on iPads, wherein participants were instructed to locate and tap 40 targets among distractors. Jóhannesson and colleagues (2016) developed this VFT further by comparing finger foraging and gaze foraging in multitarget scenarios, evaluated using feature foraging (i.e., targets based on one feature such as colour) or conjunction foraging (i.e., targets based on conjunctive features such as colour and shape). Stimuli were displayed on a black background with random, adjusted positioning. Their findings revealed that participants had minimal difficulty switching between different target types, particularly during gaze foraging.

In a subsequent study, Kristjánsson et al. (2020) investigated the effect of set sizes on attentional allocation during a visual search. The authors assessed conjunctive foraging (i.e., colour-shape stimuli) in four different set sizes: 20, 40, 60 and 80. Their data suggests that the larger set sizes influenced the speed and efficiency of foraging, in which larger set sizes resulted in slower switching between target stimuli (i.e., mid-peak) and decreased ability to detect all target stimuli before the end of each trial (i.e., end-peak). These findings suggest that larger set sizes may increase attentional demands. Hence, due to the complexity of real-world foraging and with the goal of not exceeding attentional demands, moderate difficulty levels of visual foraging, such as set sizes of 40 or 60, may be optimal for investigation in this thesis.

Ólafsdóttir and colleagues (2019) explored the relationship between visual foraging ability through foraging speed, patterns and switch costs, and EFs. This was assessed in three age groups: 66 younger children (aged 4-7 years), 67 older (children aged 11-12 years), and 31 adults aged 20-37 years. Their findings showed differences in the abilities between younger and older children; the older children demonstrated foraging abilities similar to the adult group. The older children and adults tended to exhaustively forage one target type before moving on to the following one while maintaining low switch costs, exhibiting efficient foraging. However, there were major differences between the younger and older children’s foraging abilities, in which the younger children tended to focus on one target type for extended periods of time while feature foraging, proving that they had difficulty with the task. The younger children also showed less efficiency and slower foraging, shown through their higher switch costs compared to older children and adults.

The authors found an association between foraging ability and attentional flexibility and working memory, yet not inhibition. The connection between foraging ability and EFs suggests that different mechanisms are utilised while foraging for children and adults. The children with the greatest attentional flexibility were the quickest foragers, while foraging speed in adults was partially influenced by working memory, possibly due to different EF developmental trajectories. Also, there was no association between switch costs and EFs in adults. However, for children, both working memory and attentional flexibility influenced switch costs in feature foraging. For conjunctive foraging, there was an association with attentional flexibility, but it was stronger than with feature foraging. The lack of association with working memory during conjunction foraging may be related to the children's difficulty in remembering two conjunction targets simultaneously.

The findings of Ólafsdóttir et al. (2019) reveal that visual foraging may be a valuable method to investigate visual attention, especially in different age groups. Considering the potential association between visual foraging and EFs described above, combining VFTs and ergometer cycling may help to understand the influence of dual-tasking on subsequent EF task performance, giving insight into the possible effects of real-world cycling on EFs.

2.2.2.4.4 Mental Fatigue and Ego Depletion: A Cautionary Note

Mental fatigue is a feeling of exhaustion and lack of energy experienced after performing subjectively demanding cognitive tasks that require prolonged concentration (cf. Chen et al., 2024), and may result in a greater risk of error and a decline in cognitive performance (Van Cutsem et al., 2017). Mentally fatiguing tasks are suggested to modify brain activity patterns, increasing perceived exertion in tandem with changes in brain neurotransmitter concentrations (Brownsberger et al., 2013; Meeusen et al., 2021; Schiphof-Godart et al., 2018). For example, elevated dopamine may decrease due to mental fatigue, which can adversely affect individuals' evaluations of the effort they put into a task (Lorist et al., 2005).

Previous research suggests that prolonged cognitive activity during physical and cognitive tasks effectively induces mental fatigue (Marcora et al., 2009; Van Cutsem et al., 2017). Potential differentiating variables that may impact mental fatigue are arousal and individual differences in cognitive functions (O'Keeffe et al., 2020). O'Keeffe and colleagues (2020) investigated the effectiveness of inducing mental fatigue in single-task and dual-task paradigms. There were two control conditions: a set-up control, 2 minutes of seated rest, and a 90-minute documentary control. In one of the three experimental conditions, participants performed a 90-minute continuous single task (AX-CPT), where they pressed space bar if the letter 'X' was followed by an 'A'. In the second condition, participants completed a 16-minute Standardised Dual-Task condition (TloadDback STD), where they concurrently performed two cognitive tasks: the parity judgement task, differentiating between even and odd numbers, and the classic n-Back task, identifying if the current letter was identical to the one immediately before it. The third condition, Individualised Dual Task (TloadDback INDV), was 16 minutes and comprised an individualised presentation of the letter/numbers dependent on the familiarisation trial performance. Their findings revealed that participants were under-aroused after the single task, AX-CPT. Further, the TloadDback tasks induced mental fatigue more effectively than the AX-CPT, while sustaining arousal levels.

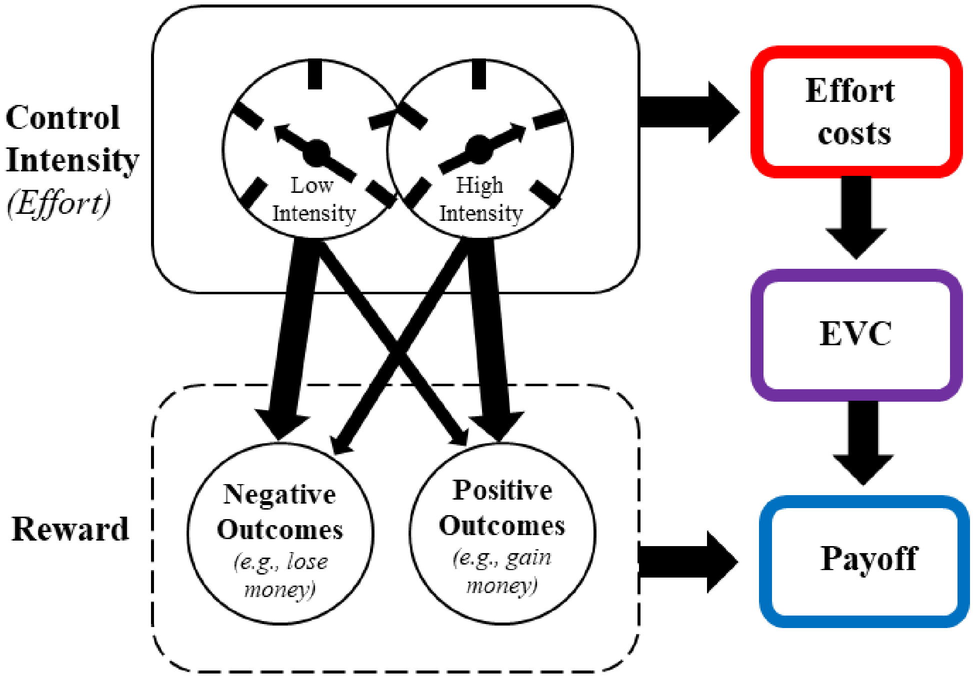
The term *ego depletion* is a closely related phenomenon in which performance of a task requiring a high degree of self-control interferes with performance on subsequent tasks (Baumeister et al., 1998), even if they are unrelated (Baumeister et al., 2007). According to Baumeister and colleagues (2006), ego depletion effects are not caused by a decline in self-efficacy or a refusal to exert oneself further in the secondary task, but by the amount of self-control that is expended in the initial task (Wallace & Baumeister, 2002). Baumeister et al. (2007) expanded on the strength model of self-control to include putative moderators (e.g., heightened goal-directed motivation), physical indicators (e.g., heart rate, neural changes) and mediators of ego depletion (e.g., time perception, blood-glucose levels). In doing so, inclusions in the strength model identify procedures that can moderate or block states of ego depletion.

Dallaway and colleagues (2023) explored the influence of sequential tasks on the ego depletion effect in physical and novel cognitive task performance. The study used a between-subjects design to assess the influence of cognitive task duration on: subsequent physical endurance performance, subsequent novel cognitive performance, and concurrent cognitive task performance. The cognitive task was the Stroop task, which participants performed for 5, 10 and 20 minutes. Physical endurance performance was assessed using a hand grip task (i.e., isometric handgrip until exhaustion). Their findings revealed that completing 10 minutes of Stroop task impaired subsequent endurance performance, but there was no effect in the 5- or 20-minute conditions, potentially because lower durations were not sufficiently ego-depleting in the former, and participants might have developed efficient strategies in the latter, thereby reduce the tasks demands. The authors also found that the cognitive task facilitated performance in the subsequent novel inhibitory control task, possibly due to a transfer effect. Ego depletion may be mediated by cognitive task duration, potentially explained by the expected value of control (EVC) model (Frömer et al., 2021; Figure 2.3), which suggests that cognitive control allocated to a task may be based on expected reward, an association between amount of cognitive control and associated effort (e.g., motivation; Shenhav et al., 2013).

Mental fatigue may help explain a state of ego depletion (Dallaway et al., 2023; Englert, 2016). Both mental fatigue and ego depletion propose that exertion of mental effort may impair subsequent task performance (Baumeister et al., 2007; Van Cutsem et al., 2017; Giboin & Wolff, 2019). The main difference between the two phenomena may be the durations: fatiguing tasks are typically 30 minutes or longer, whereas those use in ego depletion paradigms are shorter (Van Cutsem et al., 2017; Giboin & Wolff, 2019).

Figure 2.3

The Expected Value of Control (EVC) Model



Note. From: Frömer, R., Lin, H., Dean Wolf, C. K., Inzlicht, M., & Shenhav, A. (2021). Expectations of reward and efficacy guide cognitive control allocation. Nature Communications, 12(1), 1030. https://doi.org/10.1038/s41467-021-21315-z

Adverse effects on subsequent performance, such as mental fatigue and ego depletion, must be considered when creating a dual-task intervention. For example, as shown in O'Keeffe and colleagues' study, the arousal state may be associated with mental fatigue. Therefore, the intensity of the exercise may need to be adjusted to account for under or over-arousal states. Following Dallaway and colleagues' (2023) findings, cognitive task duration must be considered, suggesting that dual-task interventions at low-to-moderate durations may be optimal; however, this requires further research. Finally, appropriate comparison conditions should be chosen. Dallaway et al.'s (2023) findings revealed a transfer effect between a cognitive task and a subsequent novel cognitive task; therefore, a condition investigating a single-task transfer effect might help to understand if there is an ego-depleting state in the dual-task intervention.

Further. Milyavskaya and colleagues (2019) aimed to test whether rewards influence cognitive effort and boredom (i.e., an affective state). Event-related potentials using electroencephalographic (EEG) recordings were recorded after participants were randomly allocated into either the control condition, who completed the computerised door task immediately, or completing the computerised door task after a cognitive effort (addition task) or boredom (passive observation of numbers) condition. The computerised door task comprised two doors; participants chose one to open, and subsequently received feedback on whether they won or lost. Feedback negativity was assessed using event potentials detecting the brain's response to a reward, or the absence of one. Their findings revealed that participants in the boredom condition reported greater fatigue than those in the cognitive effort condition, despite the reduced effort, and they also deemed it somewhat mentally fatiguing. Control conditions that induce boredom (e.g., Baumeister et al., 1998) may increase subjective fatigue and reward sensitivity (Milyavskaya et al., 2019). Therefore, active controls may be a better comparison to avoid exaggerated depleting effects.

2.2.3 Putative Neurophysiological Bases for the Exercise-Cognition Relationship

Even after the peak development of EFs during childhood, the PFC exhibits plasticity in response to internal and external stimuli, resulting in both immediate and long-term changes in brain morphology and function – and exercise is a potent catalyst for such changes (Basso & Suzuki, 2017). According to Basso and Suzuki, there are multiple neurophysiological and neurochemical explanations to explain the influence of acute exercise on cognition. One such explanation is provided by the Catecholamine Hypothesis (Cooper, 1973).

2.2.3.1 The Catecholamine Hypothesis

Cooper (1973) proposed the catecholamine hypothesis to explain the fluid relationship between exercise and cognition – namely, that catecholamine concentrations may fluctuate according to the intensity at which exercise is performed, consequently helping or hindering cognitive performance. Other researchers have since developed the theory (Chmura et al., 1994; McMorris, 2016; McMorris, 2009).

The three neurotransmitters central to this hypothesis are *dopamine*, *serotonin* and *norepinephrine*. Basso and Suzuki (2017) noted that dopamine is associated with the motivation and reward factors of exercise (Greenwood & Fleshner, 2011) and is linked to positive exercise-induced cognitive effects (Winter et al., 2007). Serotonin has been connected to the antidepressant effect of exercise (Babyak et al., 2000). Serotonin is also positively associated with exercise-induced cognitive function; and linear correlations have been found between plasma serotonin, exercise intensity and improvements in inhibitory control task performance (Zimmer et al., 2016). Norepinephrine increases have been detected after acute exercise, and upregulation of norepinephrine is correlated with improvements in attention and memory-based tasks (Basso & Suzuki, 2017; Lehmann et al., 1985).

Increased circulating plasma catecholamines in peripheral tissues and organs during exercise result in the upregulation of norepinephrine and dopamine in the brain, which increases arousal through increased reticular formation activation (McMorris, 2021). Moderate levels of catecholamine concentration seemingly facilitate cognitive task performance (McMorris & Hale, 2012). According to the hypothesis, high intensity exercise or exercising for long durations will result in excessive catecholamine concentrations, which increases cortisol levels. The interaction of elevated cortisol and elevated catecholamines consequently inhibits working memory (Cooper, 1973). The study of this effect led Cooper to hypothesise that there is an inverted-U relationship (Yerkes & Dodson, 1908) between arousal levels and performance.

2.2.3.2 Interoception Theory

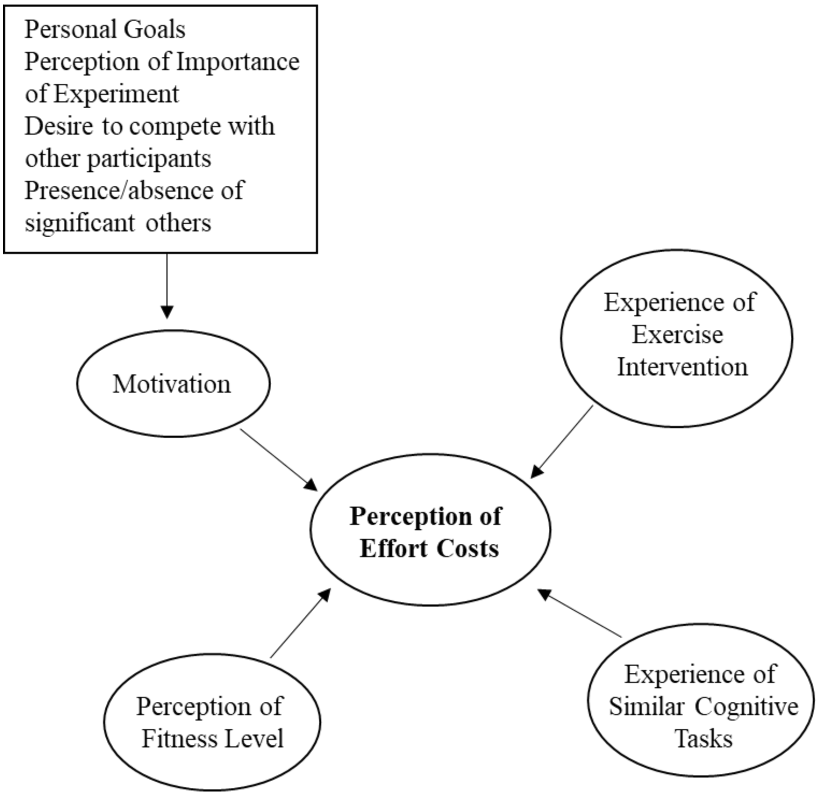
According to McMorris, the catecholamine hypothesis highlights an acute exercise-cognition interaction effect; however, it does not account for the potential effects of central fatigue (McMorris, 2021) – the brain's inability to sustain the necessary impetus for achieving desired power output (Davis & Bailey, 1997). In other words, the role of interoceptive feedback is not considered relative to the interaction (McMorris et al., 2018; McMorris, 2021). Specifically, the neurophysiological correlates of psychological factors such as motivation and perception of effort may mediate exercise's effects on cognitive performance (Craig, 2015; Aston-Jones & Cohen, 2005). McMorris suggested an interoception-based model to explain the acute exercise-cognition interaction (McMorris, 2021).

Like Cooper's (1973) Catecholamine Hypothesis, the interoception model posits that moderate intensity exercise elicits positive effects due to upregulation of dopamine and norepinephrine in brain regions that are responsible for cognitive function. Nonetheless, psychological factors – notably, motivation and perception of effort – affect how interoception affects the acute exercise-catecholamines-cognition interaction – and these are determined by a motivational/reward pathway which comprises dorsolateral prefrontal cortex, cingulate cortex, orbitofrontal cortex, basal ganglia and amygdala (Weng et al., 2017). Within this pathway, each brain region has its role; for example, the anterior cingulate cortex is responsible for the perception of effort, in which dopamine encodes expected rewards and norepinephrine sustains energy levels to complete the task successfully (McMorris, 2021).

Individual differences and external factors may mediate interoceptive feedback (Figure 2.4). For example, variation in people's fitness levels and in-session goals can influence their responses to exercise (McMorris, 2021), as can motivational incentives such as monetary rewards or competition (Carter et al., 2015).

Figure 2.4

Psychological Factors Affecting Perception of Effort Costs.



Note. From: McMorris, T. (2021). The acute exercise-cognition interaction: From the catecholamines hypothesis to an interoception model. International Journal of Psychophysiology, 170, 75–88. https://doi.org/10.1016/j.ijpsycho.2021.10.005

2.2.3.3 Neural Haemodynamics

fNIRS is a non-invasive method that uses near-infrared light to assess the hemodynamic response of the cerebral cortex (Basso & Suzuki, 2017). Yanagisawa and colleagues (2010) used fNIRS to investigate the influence of acute exercise on EFs. Participants cycled on a cycle ergometer at the participant's 50% $\dot{V}O_{2peak}$ with fNIRS probes covering the PFC. Their findings revealed a significant improvement in the Stroop interference task (i.e., response time) and bilateral PFC activation. Stroop-related activity was significantly heightened in the left dorsolateral PFC after the ergometer cycling.

Byun et al. (2014) also utilised fNIRS to assess the effects of ergometer cycling on the EFs; however, after 10 minutes of low-intensity exercise (30% $\dot{V}O_{2peak}$). They recruited twenty-five young adults to assess exercise-induced changes in the colour-word Stroop task, psychological mood state and PFC activation. Identical to Yanagisawa et al.'s findings, an acute bout of ergometer cycling results in improved Stroop performance and cortical activation in the left dorsolateral PFC. They also found increased arousal levels post-exercise cessation. Consistent with these studies, evidence supports the notion that, regardless of intensity, an acute bout of exercise improves EFs and may induce PFC activation (Endo et al., 2013; Li et al., 2005). Furthermore, fNIRS has also been a valuable tool in understanding the effects of dual-task exercise on the brain compared to isolated exercise (Basso & Suzuki, 2017).

2.3 Summary

Acute cycling exercise may evoke affective and physiological benefits that lead to EF task improvements. Moderators frequently considered to influence both affective response and cognition include exercise intensity and duration. Synthesising papers investigating acute exercise on EFs may help us to determine optimal parameters for acute cycling exercise interventions to enhance brain function. Such interventions may include exercise or cognitive training in isolation, or both combined – dual-task paradigms. A dual-task paradigm may highlight the additional cognitive demands that are encountered while real-world cycling. A complex, dynamic, novel task that engages EFs, such as a VFT, may be sufficient to mimic the attentional demands of real-world cycling. Combining cycling and a VFT may help to explain how a cycling commute to school or university can impact classroom readiness and academic achievement.

To better understand changes in exercise-induced EF performance, it is important to explore underlying mechanisms that may mediate such changes, such as PFC oxygenation and affective response. By doing so, it may help determine whether the chosen interventions are effective in enhancing brain function. Finally, technology, such as immersive reality, could enhance the indoor cycling experience. Immersive reality cycling – or exergaming – may be an enjoyable intervention that may benefit learning and post-intervention brain function. Overall, this thesis aims to explore the effect of acute bouts of cycling, with or without a secondary cognitive task, on subsequent cognitive function.

CHAPTER 3. THE EFFECTS OF AN ACUTE BOUT OF ERGOMETER CYCLING ON YOUNG ADULTS' EXECUTIVE FUNCTION: A SYSTEMATIC REVIEW AND META-ANALYSIS

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3.1 Abstract

Purpose: The extent to which acute exercise improves executive function (EF) remains indeterminate. The purpose of this systematic review and meta-analysis was to determine the effect of acute ergometer cycling exercise on executive function (EF), including the potential moderating effects of exercise intensity and duration, EF task type, and EF task onset.

Methods: We searched seven electronic research databases using cycling- and cognition-related terms. All 17 studies included were published in the last 10 years and comprised healthy participants aged 18–35 years who completed tasks assessing a variety of EFs before and after cycling exercise lasting 10–60 min. We analysed 293 effect sizes obtained from 494 individuals (mean age = 22.07 ± 2.46 yrs). Additional analyses were performed, using averaged effect sizes for each separate study to examine the omnibus effect across studies.

Results: There was a positive effect of acute ergometer cycling exercise on response time (RT) in 16 of 17 studies reviewed and a positive effect for response accuracy (RA) in 8 of 14 studies; three studies did not report RA data. Hedges' g effect sizes [95% CI] for RT ranged from 0.06 [-0.45, 0.56] to 1.50 [0.58, 2.43] and for RA from −1.94 [-2.61, −1.28] to 1.03 [0.88, 1.19].

Findings were similar in the omnibus analyses. Moderate-intensity bouts had the greatest effect on RT, $SMD = 0.79$ (95% CI [0.49, 1.08]), $z = 5.20$, $p < 0.0001$, as did cycling durations of 21–30 min, $SMD = 0.87$ (95% CI [0.58, 1.15], $z = 5.95$, $p < 0.0001$. The greatest benefits were derived for inhibitory control tasks, *SMD* = 0.70 (95% CI [0.43, 0.98]), $z = 5.07$, $p < 0.04$, and when the EF task was completed immediately post-exercise, *SMD* = 0.96 (95% CI [0.51, 1.41]), $z = 4.19$, $p < 0.001$. There were no overall effects on RA. **Conclusion**: Our findings indicate that acute bouts of cycling exercise may be a viable means to enhance RTs in immediately subsequent EF task performance, but moderating and interactive effects of several exercise parameters must also be considered.

Keywords: acute exercise, Task switching, Inhibitory Control, Working memory

3.2 Introduction

The effects of acute exercise on executive function (EF) have been extensively researched (Basso & Suzuki, 2017; Chang et al., 2012; Moreau & Chou, 2019). Executive functions (EFs) have been defined as a set of mental processes that rely on the prefrontal cortex (PFC) region of the brain and have previously been differentiated into three broad components (Miyake et al., 2000): *cognitive flexibility* or *task switching* (the ability to adapt how we behave based on changes in the environment; Huston, 2016) *working memory* (updating old information with novel information; Smith & Jonides, 1997) and *inhibitory control* (the ability to control our cognitions, emotions and behaviours to adapt to our environment; Weiner, 2000). Our EFs develop through childhood but are still malleable after they peak in early adulthood; the PFC continues to exhibit plasticity in response to both external and internal stimuli throughout the lifespan (Basso & Suzuki, 2017). Because changes in healthy adult PFC function can be facilitated by acute exercise (Basso et al., 2015), it is important to identify how we might optimise exercise parameters to maximise this facilitative effect. Several moderators may affect the optimisation of exercise interventions, including exercise intensity and duration, the types of EF tasks administered, the post-exercise delay before their completion, and the exercise modality (Barisic et al., 2011).

According to the American College of Sports Medicine (ACSM), exercise interventions may be categorised as low (37–45% $\dot{V}O_{2max}$), moderate (46–63% $\dot{V}O_{2max}$), or high (64–90% $\dot{V}O_{2max.}$) in intensity (American College of Sports Medicine, 2013). Yerkes and Dodson's (1908) seminal hypothesis proposes an inverted-U relationship between state of arousal and task performance. Researchers have subsequently made predictions based on this hypothesis – namely, that moderate intensity exercise should elicit greater cognitive improvements than low or high intensity. This notion has attracted research attention for half a century (Cooper, 1973; Craig, 2002; Davey, 1973; McMorris, Barwood, & Corbett, 2018; McMorris & Hale, 2012), although findings have been inconsistent. Recently, more nuanced mechanistic explanations have emerged, including the role of brain-derived neurotrophic factor (BDNF) in promoting exercise-related neural changes (Basso & Suzuki, 2017), and an interoception model that proposes an interaction between the exercisers' perceptions of effort, their motivation to exercise, and their perceptions regarding the availability of personal resources to exercise (McMorris, 2021). The inconsistent findings regarding the inverted-U hypothesis might be compounded by variation in psychophysiological responses to treadmill versus cycle ergometer exercise protocols (Bogdanis et al., 2021); previous research suggests differing effects of these modalities on EF task performance (Kunzler & Carpes, 2021; Lambourne & Tomporowski, 2010). For this reason, the current review and meta-analysis is focused exclusively on cycle ergometer protocols.

Previous meta-analyses (Chang et al., 2012; Lambourne & Tomporowski, 2010; Moreau & Chou, 2019) suggest that the effects of exercise intensity on cognition may also be contingent on the nature and complexity of EF tasks employed. For example, findings suggest that moderate exercise intensities enhance performance of EF tasks that prioritise speed over accuracy (e.g., Flanker Task), whereas the limited effects on accuracy may be due to the use of EF tasks that are not suitably sensitive to detect performance enhancements (McMorris & Hale, 2012). Importantly, while McMorris and Hale's meta-analysis suggests the enhancements of EF tasks after moderate intensity exercise, they found that heavy exercise resulted in effects close to zero, which may be due to neural noise (McMorris & Hale, 2012). Neural noise refers to large increases in catecholamine concentrations during or after exercise, which may impair the brain's ability to allocate the sufficient resources required for a task, thereby inhibiting performance (McMorris et al., 2008, 2011). Low complexity tasks can result in ceiling effects for accuracy, and so processing speed is often the variable of interest in such tasks (Aguirre-Loaiza et al., 2019). Furthermore, the point at which an EF task is administered – i.e., its onset – appears to influence the effect of acute exercise on subsequent EF task performance, although this may depend somewhat on the underlying neurophysiological mechanisms. The catecholamine hypothesis (Cooper, 1973) suggests that catecholamine release occurs constantly throughout an exercise bout, and thus, changes may be more influential immediately post-exercise. Conversely, BDNF elevations peak post-exercise, and as such, EF improvements related to circulating BDNF may be sustained for longer. Indeed, the BDNF protein initiates signalling pathways that are implicated in neurogenesis and consequently promotes post-exercise neuroplasticity (Basso & Suzuki, 2017; McMorris & Hale, 2012). Although the precise effects of BDNF are still being established, it has been suggested that even very brief acute exercise increases circulating peripheral and central BDNF, which has, in turn, been linked to improvements in memory and learning (Basso & Suzuki, 2017; McMorris & Hale, 2012). However, it has been suggested that moderate and high intensity protocols lead to higher levels of BDNF than low intensity protocols (Knaepen et al., 2010). Therefore, the effect of EF task onset delays should be considered.

Exercise duration is also purported to moderate the effects of acute exercise on EF. A previous meta-analysis found that exercise durations less than 10 min adversely affected subsequent cognitive performance, whereas longer ones tended to elicit positive effects (Chang et al., 2012). Relatedly, several authors have suggested that exercise bouts lasting approximately 31–40 min yield positive effects (Aguirre-Loaiza et al., 2019; Tsukamoto et al., 2017; Zhu et al., 2021), although further evidence is needed to determine whether those benefits persist past this duration or, alternatively, whether detriments occur with longer duration (Tsukamoto et al., 2016). Most studies to date have examined exercise duration and intensity separately; therefore, we adopted the same approach for this meta-analysis.

The purpose of this systematic review and meta-analysis was to build on the meta-analysis conducted by Chang et al. (2012), which examined various exercise modalities (e.g., treadmill running, cycling), by analysing data from literature published in the past decade that examined the effect of a bout of cycle ergometer exercise on EF. We sought to answer two research questions: First, to what extent does a single bout of cycling exercise affect subsequent EF task performance? Second, to what extent do exercise intensity, exercise duration, EF task type, and EF task onset moderate this effect? To address the first question, we focused on within-subject comparisons to reduce variability in the analyses. To facilitate the second, we provide empirically grounded delineations for each category of moderators.

3.3 Methods

3.3.1 Eligibility Criteria

The experimental studies included in this review were published in English between January 2012 and December 2022 in Full Text versions, which comprised young adults aged 18–35 years of age with no diagnosed impairments or medical complexities, and included cognitive assessments that assessed working memory, inhibitory control, and/or task switching. Additionally, studies were only included when the authors (a) provided effect sizes for the main effect or provided sufficient information for an effect size to be calculated for separate response time (RT) and/or response accuracy (RA) scores; (b) administered the cognitive assessments pre- and post-exercise; and (c) utilised cycling durations in the range of 10–60 min, at intensities of 37–90% $\dot{V}O_{2max}$. Elaboration on these criteria can be found in the *Moderators* section below.

3.3.2 Information Sources

Searches were conducted in PubMed, Web of Science, Academic Search Complete, CINAHL Plus, APA PsycArticles, APA PsycInfo and SportDiscus databases for dates ranging from January 1st, 2012 to December 7th, 2022. Searches were extracted and reviewed by the researchers. Additional studies were identified by reviewing the References sections of studies retrieved in the search process.

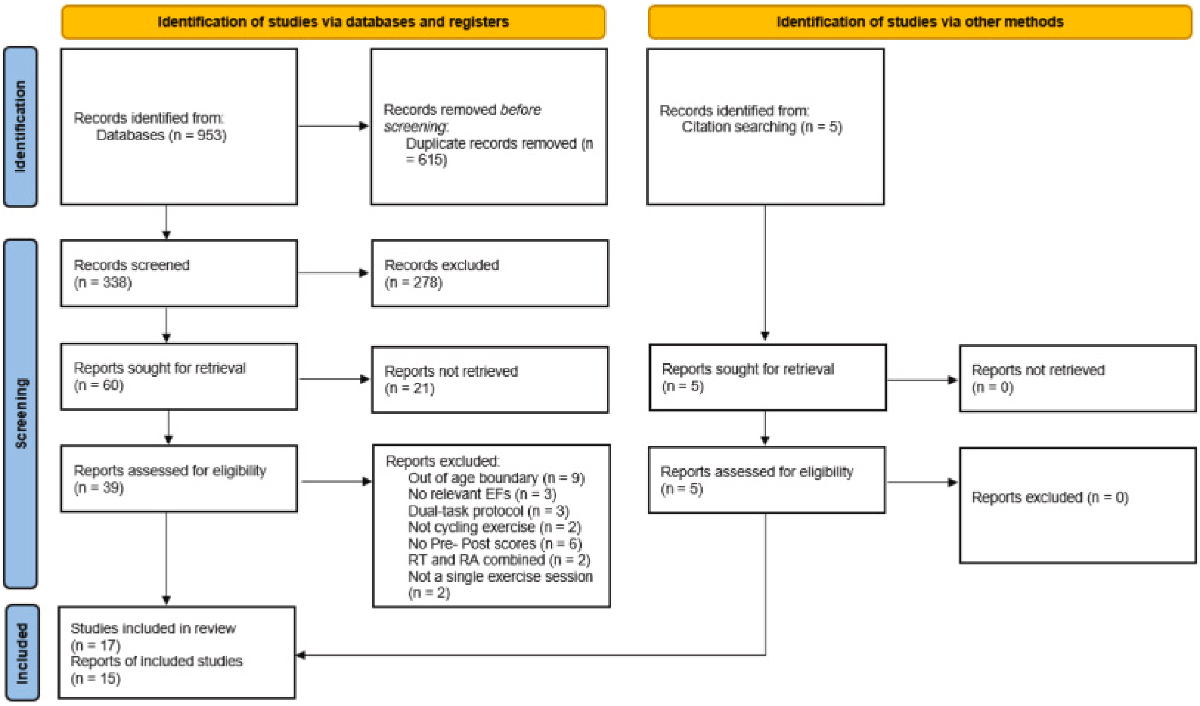
3.3.3 Search Strategy

The search terms consisted of the following: (cycl × OR bicycle × OR bike∗) AND (“executive function” OR cogniti∗) AND (planning OR memory OR attention × OR inhibit∗) AND exercise∗.

Consistent with previous meta-analyses, the search strategy focused on studies that investigated the effect of an acute bout of cycle ergometer exercise on EFs. Figure 3.1 depicts the search strategy we employed. We assessed the eligibility of published articles. First, duplicates were removed. Then, article titles and abstracts were screened based on the eligibility criteria. Records were excluded if the title or abstract indicated that the study included participants outside the age range, if they did not employ an acute single bout of cycling exercise, or if EF task performance was not assessed both before and after an exercise bout. Full-text copies of all retained articles were retrieved and independently assessed for eligibility by all authors before full consensus was reached regarding the articles to be included in the meta-analysis.

Figure 3.1

Prisma flow chart



3.3.4 Study Bias

Risk of bias assessment was conducted using the modified McMaster Critical Review Form (Law et al., 2022). Table 3.1 shows the adapted appraisal tool, for which the criteria were reduced from 17 to 12; the excluded criteria apply to all experimental studies, not just randomised control trials. Each met criterion was awarded one point. The criteria were independently rated by the first author and the ratings were discussed with the second and third authors until consensus was reached for each rating (Table 3.2).

Table 3.1

Adapted McMaster Critical Review

1.	Study purpose
2.	Relevant literature background
3.	Study design stated
4.	Sample described in detail
5.	Sample size justified
6.	Outcome measures are reliable
7.	Outcome measures are valid
8.	Intervention described in detail
9.	Results reported in terms of statistical significance
10.	Appropriate analysis methods
11.	Dropouts reported
12.	Appropriate conclusions based on methods and results

The effects of cycling on the moderators (cycling intensity, duration, EF task type and EF task onset) were examined using Studentized residuals and Cook's Distance to detect outliers. Potential outliers were determined based on whether the Studentized Residual value was larger than (100 × [1–0.05/[2 × n]]) the normal distribution, where n is the number of studies. Cook's Distance was considered influential if the value was six times the interquartile range (*The Jamovi Project*, 2021). Effects were tested using Bonferroni correction with alpha set at 0.05. Publication bias was also assessed via regression and rank correlation tests using the standard error scores of the outcome measures (Table 3.3). Funnel plots were used to illustrate asymmetry where applicable (Appendix A; Sterne et al., 2011).

Table 3.2

McMaster Critical Review Form for Each Study

Study	1	2	3	4	5	6	7	8	9	10	11	12	N
Aguirre-Loaiza et al. (2019a)	X	X	X	X	X	X	X	X	X	X	X	X	12
Aguirre-Loaiza et al. (2019b)	X	X	X	X	X	X	X	X	X	X	X	X	12
Brown & Bray (2018)	X	X	X	X		X	X	X	X	X		X	10
Chang et al. (2014)	X	X	X	X	X	X	X	X	X	X		X	11
de Diego-Moreno et al. (2022)	X	X	X		X	X	X	X	X	X	X	X	11
Douris et al. (2018)	X	X	X	X		X	X	X	X	X	X	X	11
Hashimoto et al. (2018)	X	X	X	X		X	X	X	X	X		X	10
Miyamoto et al. (2018)	X	X	X	X		X	X	X	X	X		X	10
Oberste et al. (2016)	X	X	X	X	X	X	X	X	X	X		X	11
Sugimoto et al. (2020)	X	X	X	X		X	X	X	X	X		X	10
Tsukamoto et al. (2017a)	X	X	X	X		X	X	X	X	X		X	10
Tsukamoto et al. (2017b)	X	X	X	X		X	X	X	X	X		X	10
Tsukamoto et al. (2016)	X	X	X	X		X	X	X	X	X		X	10
Wang et al. (2015)	X	X	X	X	X	X	X	X	X	X		X	11
Weng et al. (2015)	X	X	X	X		X	X	X	X	X		X	10
Yamazaki et al. (2018)	X	X	X	X		X	X	X	X	X		X	10
Zhu et al. (2021)	X	X	X	X		X	X	X	X	X	X	X	11

Note: All criteria are labelled as listed in the Methods section; N = Total Number of points.

Table 3.3

Publication Bias Assessments

Moderators		Fail-Safe N		BMRC*		ER**		Trim and Fill***	
		Value	**p**	**Value**	**p**	**Value**	**p**	**Value**	**p**
RT		409.00	<.001	0.47	0.01	2.61	0.01	2.00	–
RA		0.00	0.374	−0.03	0.91	0.32	0.75	4.00	–
				Duration					
10–20 min	RT	38.00	<.001	−0.05	1.00	0.84	0.40	0.00	–
	RA	22.00	<.001	−0.47	0.27	3.14	0.00	0.00	–
21–30 min	RT	65.00	<.001	−0.20	0.72	1.09	0.28	0.00	–
	RA	33.00	<.001	0.20	0.82	0.12	0.91	0.00	–
31–40 min	RT	88.00	<.001	0.33	0.47	1.24	0.22	1.00	–
	RA	0.00	0.45	−0.80	0.08	1.16	0.25	2.00	–
				Intensity					
Low	RT	0.00	0.10	0.00	1.00	−0.41	0.68	1.00	–
	RA	–	–	–	–	–	–	–	–
Moderate	RT	161.00	<.001	0.44	0.12	2.11	0.04	2.00	–
	RA	0.00	0.24	0.14	0.77	0.54	0.59	1.00	–
High	RT	79.00	<.001	0.05	1.00	1.07	0.29	0.00	–
	RA	0.00	0.07	−0.33	1.00	−1.97	0.05	0.00	–

Moderators		**Fail-Safe N**		**BMRC***		**ER****		**Trim and Fill*****	
		Value	**p**	**Value**	**p**	**Value**	**p**	**Value**	**p**
					EF Task				
Working Memory	–	–	–	–	–	–	–	–	–
Inhibitory Control	RT	198.0	<.001	0.30	0.20	1.30	0.20	1.00	–
	RA	25.00	0.001	0.07	0.86	0.92	0.36	0.00	–
Cognitive Flexibility	RT	13.00	<.001	−0.33	0.75	−1.05	0.29	2.00	–
	RA	–	–	–	–	–	–		–
					EF Task Onset				
0–9 min post	RT	247.00	<.001	0.42	0.11	2.45	0.01	1.00	–
	RA	2.00	0.04	−0.14	0.72	−0.48	0.63	3.00	–
10–19 min post	RT	120.00	<.001	0.50	0.11	2.78	0.01	1.00	–
	RA	0.00	0.30	−0.43	0.24	−0.81	0.42	1.00	–
20–29 min post	RT	31.00	<.001	0.33	0.75	0.16	0.88	1.00	–
	RA	14.00	<.001	−0.33	0.75	−0.93	0.36	0.00	–
>30 min post	RT	0.00	0.48	−1.00	0.33	−3.65	<.001	0.00	–
	RA	0.00	0.29	1.00	0.08	0.91	0.36	0.00	–

Note: Begg and Mazumdar Rank Correlation*, Egger's Regression** and Trim and Fill Number of Studies***

3.3.5 Synthesis Methods

Included studies were those in which intervention group participants' EF task pre- and post-intervention scores were provided; the latter were acquired either immediately or after a retention period. Descriptive data were collated and inputted into RevMan (v. 5.4.1) software (Review Manager Web (RevMan), 2020), which was designed specifically for systematic reviews.

RA and RT were analysed separately because evidence suggests that low complexity tasks such as the Flanker and Stroop tasks ultimately use processing speed as the criterion performance measure; accuracy measures are included only in these tasks to encourage participant response integrity (McMorris & Hale, 2012). We conducted analyses for overall effects and for each moderator – intensity, duration, EF task type and EF task onset. A positive effect size value corresponded to improvements in EF task performance, whereas a negative value indicated a deterioration in performance.

A random-effects model was applied to the data because the studies included in this review provided estimates of related yet different interventions (Higgins & Green, 2008). Because of the heterogeneity of methodological approaches and findings, an inverse-variance approach was used to calculate weighted mean effect sizes for each of the studies, which are reported as pre- and post-intervention scores: Hedges' (adjusted) g effect size. A value of 0.2 is considered a small effect size, 0.5 a medium effect size, and 0.8 a large effect size. Small effect sizes (< 0.20) are considered to be trivial regardless of probability level (Cohen, 1988).

Data heterogeneity was characterised in accordance with the Cochrane handbook as chi-squared values reported alongside their associated degrees of freedom (df) and I^2 values. Chi-squared values indicate whether differences are due to chance (Review Manager Web (RevMan), 2020). Notably, a random-effects model is used for this meta-analysis because the studies are different but follow a comparable protocol. Using a random-effects model we can consider that heterogeneity may be based on methodological differences rather than due chance (Higgins & Green, 2008).

3.3.5.1 Additional Analysis – averaged effect sizes

Because some studies' contributions to the observed effects may be overweighted in the first analysis, an Omnibus Q Analysis was also performed, using the average of effects in each separate study for each moderator. This analysis was also run using a random-effects model, using Q-test and post hoc Z difference tests. The averaged effect sizes for the dependent variables were inputted into Jamovi (2.6.1; The Jamovi Project, 2021) via the MAJOR (R Core Team, 2021) plugin. Heterogeneity was estimated using the restricted maximum-likelihood estimator (Viechtbauer, 2010) to yield the Tau^2 estimate, Q-test (Cochran, 1954) and the I^2 statistic, as for the previous analysis. These heterogeneity estimates can increase confidence in whether the effect sizes represent true effects in the population or are random.

3.3.5.2 Moderators

To provide further insight regarding the effect of an acute bout of cycle ergometer exercise on EF, we investigated the effect of four moderating variables on RT and RA (forest plots in Appendix B).

3.3.6 Intensity

Exercise intensities expressed as maximum heart rate (HR_{max}) or heart rate reserve (HRR) were converted to percentages of $\dot{V}O_{2max}$ in accordance with the ACSM: low intensities were defined as those performed at 37–45% $\dot{V}O_{2max}$, moderate intensities at 46–63% $\dot{V}O_{2max}$, and high intensities at 64–90% $\dot{V}O_{2max}$.

3.3.7 Duration

Exercise durations were classified as follows: 10–20 min, 21–30 min, 31–40 min, and greater than 40 min. This categorisation is comparable to those identified by Chang et al. (2012) in their meta-analysis, which showed that durations of 0–10 min elicited small negative effects, 11–20 min brought about small positive effects, and greater than 20 min yielded large positive effects. However, we selected a minimum duration of 10 min in accordance with the ACSM stipulation that exercise program should last for 10–60 min, notwithstanding moderating effects of exercise intensity (Tsukamoto et al., 2016). We anticipated that this categorisation would afford greater differentiation of exercise intensities and would consequently enable us to better understand whether an inverted-U relationship exists.

3.3.8 EF Task Type

Working memory tasks comprised the Trail Making Test (TMT; Reitan, 1956) and the n-Back task (Kirchner, 1958). Inhibitory Control Tasks comprised the Stroop Colour and Word Test (Stroop, 1935) and the Eriksen Flanker Task (Eriksen & Eriksen, 1974). The Wisconsin Card Sorting Task (Berg, 1948) was the only task switching measure used.

3.3.9 EF Task Onset

The EF task onset was defined as the period of delay, in minutes, between cessation of the exercise bout and commencement of the EF task. The delay periods were classified as follows: 0–9 min (*immediate*), 10–19 min (*short delay*), 20–29 min (*moderate delay*), and greater than 30 min (*long delay*). We based this categorisation on those used in published studies, although descriptions differ slightly (e.g., Post 0, Post 10, Post 20, Post 30; Oberste et al., 2016; Tsukamoto et al., 2016, 2017).

3.4 Results

3.4.1 Study Selection

An initial search of the databases identified 953 nonduplicate records (Figure 3.1). After reviewing the titles and abstracts, 44 full-text reports were screened based on the eligibility criteria. Of these, 15 papers comprising 17 empirical studies met the inclusion criteria.

3.4.2 Study Characteristics

The 17 included studies comprised 494 participants, of whom 59 were women and 254 were men; sex was not stated for some samples, and so could not be determined for 181 participants. The participants' average age was 22.07 ± 2.46 years. Two-hundred and ninety-three effect sizes were analysed.

3.4.3 Metabias assessment

Table 3.2 represents the modified McMaster Critical Review rankings of the studies, all of which scored 9–12 out of 12. Publication bias was also assessed according to asymmetry in the associated funnel plots for the overall effects on EF response time and accuracy, and the effects on those measures for each moderator (Figure 3.2, Figure 3.3, Appendix A). Finally, Publication Bias assessments were run using multiple tests: Fail-safe N, Begg and Mazumdar Rank Correlation, Egger's Regression, and the Trim and Fill Number of Studies (Table 3.3).

3.4.4 Overall RT

A total of n = 16 studies were included in this analysis**.** There was a moderate overall effect of an acute bout of cycling exercise on RT, Hedges' $g = 0.61$ (95% CI [0.41, 0.82]), $df = 16$ ($p = 0.01$), $I^2 = 49\%$. The I^2 value of 49% indicates moderate heterogeneity: approximately half of the variability in the observed effect sizes is based on between-study differences (Moreau & Chou, 2019).

Figure 3.2

Funnel Plot – Response Time (Overall).

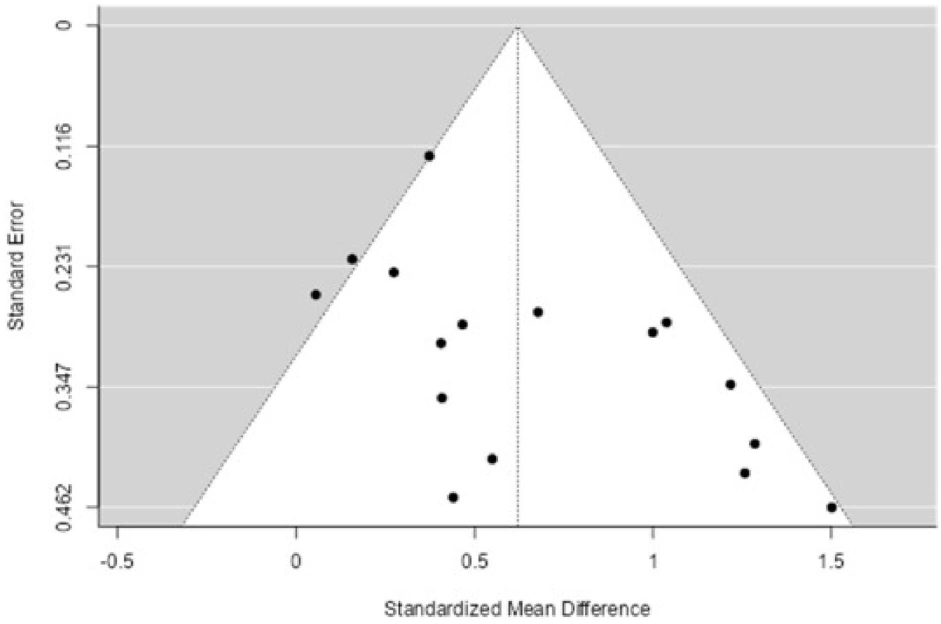
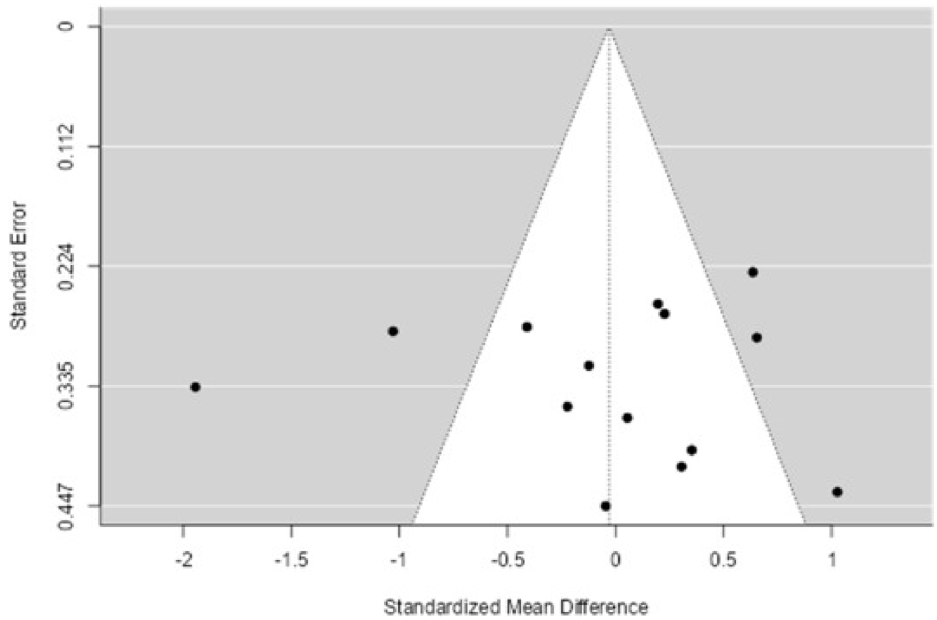


Figure 3.3

Funnel Plot - Response Accuracy (Overall)



3.4.4.1 Additional analyses - averaged effect sizes

The SMD ranged from 0.06 to 1.50, with the majority of estimates resulting in a positive effect (z = 5.93, p = < 0.0001). The Q-test determined that the true outcome was heterogeneous; however, both the true outcomes and the estimated outcome of each study were positive (Q (15) = 30.12, p = 0.01, Tau^2 = 0.08; please refer to Figure 3.4 for the forest plot, Table 3.4, Table 3.5 for random-effects model statistics and Table 3.6 for heterogeneity statistics). Based on the Studentized Residuals, there are no outliers in the context of this model, and both the regression and rank correlation tests showed potential funnel plot asymmetry (Figure 3.2 and Table 3.1).

Figure 3.4

RTs – Forest Plot.

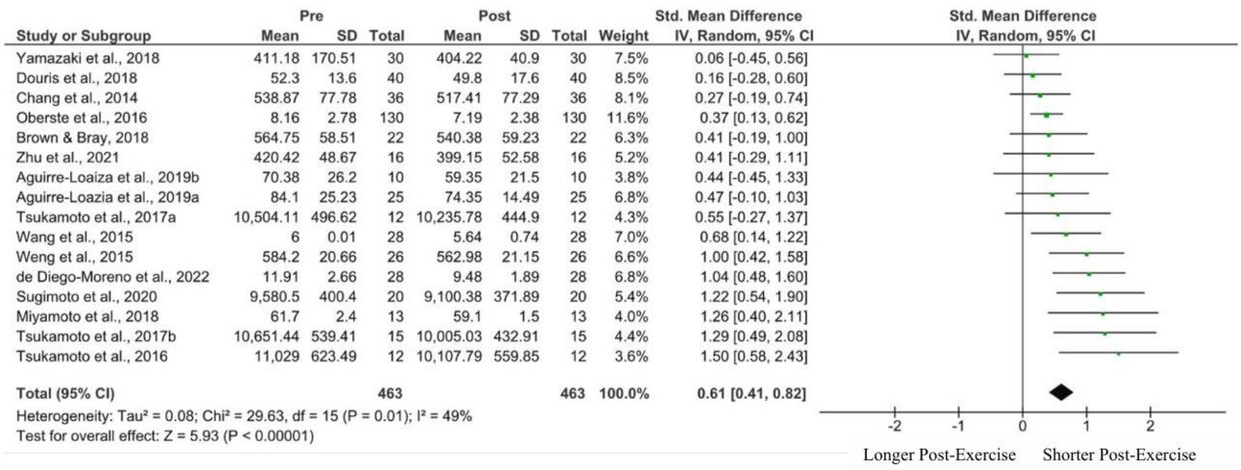


Figure 3.5

RAs – Forest Plot.

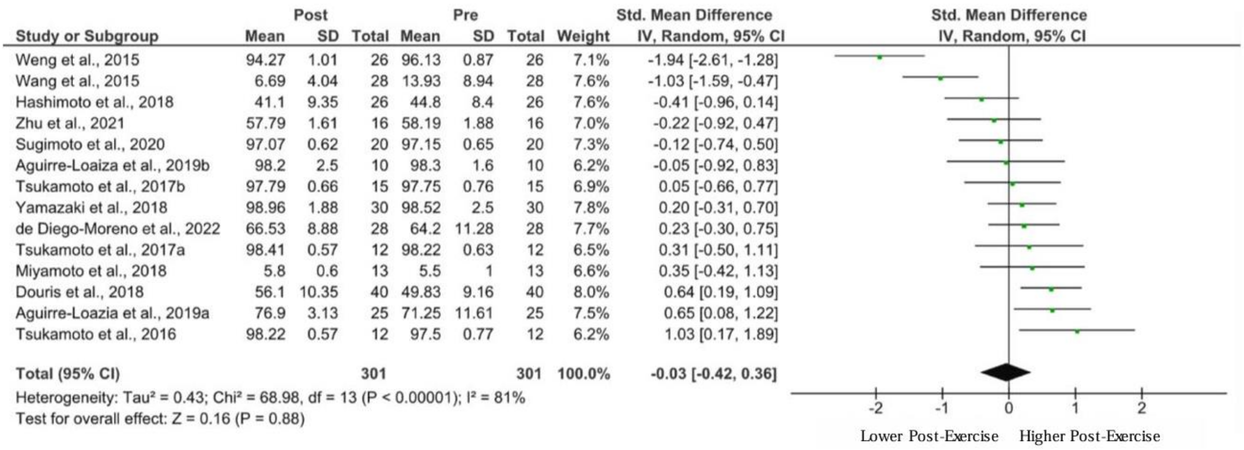


Table 3.4

Effects, by Moderator – Individual Effect Sizes

Paradigm	N		Analysis			
			Chi-squared	df	Hedge's g	95% CI
Intensity						
Low	628	RT	103.43	37	0.35	0.16, 0.55
	408	RA	118.41	27	−0.48	−0.80, −0.15
Moderate	1464	RT	327.83	86	1.03	0.88, 1.19
	1332	RA	369.43	81	0.03	−0.14, 0.20
High	874	RT	153.28	46	0.97	0.78, 1.16
	416	RA	222.53	25	−0.68	−1.13, −0.22
Duration						
10–20 min	1550	RT	348.20	95	0.79	0.65, 0.94
	1249	RA	551.20	77	−0.28	−0.51, −0.06
21–30 min	254	RT	39.44	11	0.77	0.41, 1.13
	275	RA	114.71	11	0.92	0.31, 1.52
31–40 min	1189	RT	257.92	64	0.99	0.81, 1.17
	740	RA	257.73	49	−0.09	−0.34, 0.16
>40 min	100	RT	13.58	3	0.40	−0.21, 1.00
	50	RA	0.43	1	−0.66	−1.06, −0.25

Paradigm	N		Analysis			
			Chi-squared	**df**	**Hedge's g**	**95% CI**
EF Task Type						
Working Memory	240	RT	0.52	7	0.07	−0.11, 0.25
	324	RA	8.04	10	−0.10	−0.26, 0.05
Inhibitory Control	2539	RT	553.10	156	0.91	0.80, 1.03
	1993	RA	936.04	132	−0.1	−0.34, 0.01
Task-switching	260	RT	8.85	10	0.71	0.53, 0.88
	41	RA	4.57	1	0.20	−0.80, 1.21
EF Task Onset						
Immediately post-exercise	968	RT	264.21	53	1.11	0.88, 1.33
	817	RA	309.62	43	0.11	−0.17, 0.39
Short delay	1124	RT	181.92	54	0.85	0.69, 1.02
	560	RA	215.41	35	−0.12	−0.43, 0.19
Moderate delay	435	RT	63.87	29	0.87	0.66, 1.08
	435	RA	151.40	29	−0.52	−0.85, −0.20
Long delay	362	RT	116.67	23	0.40	0.05, 0.76
	435	RA	348.62	29	−0.09	−0.62, 0.44

Table 3.5

Averaged Effect Sizes

Overall		SMD	SE	z	p	CI Lower	CI Upper
RT		0.61	0.11	5.84	<.001	0.40	0.82
RA		−0.03	0.20	−0.16	0.88	−0.42	0.36
Moderator		**Estimate**	**SE**	**z**	**p**	**CI Lower**	**CI Upper**
Intensity							
Low	RT	0.19	0.25	0.77	0.44	−0.29	0.67
	RA	–	–	–	–	–	–
Moderate	RT	0.79	0.51	5.20	<.001	0.49	1.09
	RA	0.08	0.12	0.63	0.53	−0.16	0.32
High	RT	0.72	0.14	5.24	<.001	0.45	0.99
	RA	−0.39	0.56	−0.69	0.49	−1.49	0.72
Duration							
10–20 min	RT	0.59	0.25	2.34	0.02	0.10	1.09
	RA	−0.58	−1.69	−1.60	0.11	−1.29	0.13
21–30 min	RT	0.87	0.15	5.95	<.001	0.58	1.15
	RA	0.77	0.45	1.72	0.09	−0.11	1.65
31–40 min	RT	0.21	0.21	4.58	<.001	0.56	1.39
	RA	−0.00	0.16	−0.02	0.98	−0.32	0.32

Overall		SMD	SE	z	p	CI Lower	CI Upper
EF Task Type							
Working Memory	–	–	–	–	–	–	–
Inhibitory Control	RT	0.70	0.14	5.02	<.001	0.43	0.98
	RA	0.39	0.32	1.21	0.23	−0.24	1.03
Task-switching	RT	0.62	0.17	3.71	<.001	0.29	0.95
	RA	–	–	–	–	–	–
EF Task Onset							
0–9 min post	RT	0.96	0.23	4.19	<.001	0.51	1.41
	RA	0.20	0.33	0.62	0.54	−0.44	0.84
10–19 min post	RT	0.80	0.19	4.25	<.001	0.43	1.17
	RA	−0.07	0.18	−0.36	0.72	−0.43	0.29
20–29 min post	RT	0.95	0.20	4.84	<.001	0.56	1.33
	RA	−0.64	0.19	−3.35	<.001	−1.01	−0.27
>30 min post	RT	−0.33	1.21	−0.28	0.78	−2.71	2.04
	RA	−0.11	0.19	−0.61	0.54	−0.48	0.25

Table 3.6

Heterogeneity Statistics

Overall		**Tau**	**Tau²**	**I²**	**H²**	**df**	**Q**	**p**
RT		0.29	0.08 (SE = 0.06)	49.00%	2.10	15.00	30.12	0.01
RA		0.67	0.43 (SE = 0.22)	81.00%	5.48	13.00	70.11	<.001
Modality		**Tau**	**Tau²**	**I²**	**H²**	**df**	**Q**	**p**
Intensity								
Low	RT	0.38	0.14 (SE = 0.20)	59.71%	2.48	3.00	7.49	0.06
	RA	–	–	–	–	–	–	–
Moderate	RT	0.30	0.09 (SE = 0.10)	46%	1.85	8.00	14.81	0.06
	RA	0.00	0 (SE = 0.056)	0%	1.00	6.00	3.24	0.78
High	RT	0.13	0.02 (SE = 0.07)	13.57%	1.16	6.00	8.04	0.24
	RA	0.90	0.80 (SE = 0.95)	85.17%	6.74	2.00	11.16	0.00
Duration								
10–20 min	RT	0.56	0.31 (SE = 0.26)	69.89%	3.32	6.00	19.58	0.00
	RA	0.80	0.64 (SE = 0.49)	82.81%	5.82	5.00	21.77	<.001
21–30 min	RT	0.00	0 (SE = 0.08)	0%	1.00	5.00	5.05	0.41
	RA	0.92	0.85 (SE = 0.71)	85.72%	7.01	4.00	29.83	<.001
31–40 min	RT	0.36	0.13 (SE = 0.17)	49.19%	1.968	5.00	9.80	0.08
	RA	0.00	0 (SE = 0.10)	0%	1.00	4.00	1.92	0.75

Overall		Tau	Tau^2	I^2	H^2	df	Q	p
EF Task Type								
Working Memory	–	–	–	–	–	–	–	–
Inhibitory Control	RT	0.33	0.11 (SE = 0.10)	45.85%	1.85	11.00	20.47	0.04
	RA	0.95	0.901 (SE = 0.492)	87.4%	7.93	9.00	64.17	<.001
Task-switching	RT	0.00	0 (SE = 0.09)	0%	1.00	3.00	1.58	0.66
	RA	–	–	–	–	–	–	–
EF Task Onset								
0–9 min post	RT	0.63	0.40 (SE = 0.25)	76.93%	4.34	9.00	36.58	<.001
	RA	0.86	0.731 (SE = 0.46)	86.79%	7.57	7.00	46.05	<.001
10–19 min post	RT	0.40	0.16 (SE = 0.15)	58.70%	2.42	7.00	16.96	0.02
	RA	0.28	0.08 (SE = 0.13)	38.27%	1.62	5.00	8.30	0.14
20–29 min post	RT	0.00	0 (SE = 0.13)	0%	1.00	3.00	3.30	0.35
	RA	0.00	0 (SE = 0.12)	0%	1.00	3.00	3.46	0.33
>30 min post	RT	2.05	4.20 (SE = 4.40)	96.07%	25.47	2.00	34.26	<.001
	RA	0.00	0 (SE = 0.11)	0%	1.00	3.00	1.46	0.69

3.4.5 Overall RA

A total of n = 14 studies was included in these analyses. When assessing all effect sizes, there was no effect of an acute bout of cycling exercise on RA, Hedges' $g = -0.03$ (95% CI [−0.42, 0.36)]), $df = 14$ ($p < 0.00001$), $I^2 = 81\%$, $z = 0.16$, $p = 0.88$ with no significant difference from zero. The Q-test determined that the true outcome was heterogeneous; however, the average outcome is negative (Q (13) = 70.10, $p = <0.0001$), $Tau^2 = 0.43$; please refer to Figure 3.5 for the forest plot, Table 3.4, Table 3.5 for random-effects model statistics and Table 3.6 for heterogeneity statistics). Based on the Studentized Residuals and Cook's Distance, the Weng et al. (2017) study may be a potential outlier in this model and may be too influential. Both the regression and rank correlation tests showed no funnel plot asymmetry (Table 3.3 and Figure 3.3).

3.4.6 Moderators

Table 3.4 shows the effect sizes for RA and RT, by moderator. Forest Plots for each individual moderator for both RT and RA can be found in Appendix B.

3.4.7 Intensity

Moderate intensity exercise resulted in the greatest improvements in RT, Hedges' $g = 1.03$ (95% CI [0.88, 1.19]). Similar large effects were found for RT in high intensity exercise, Hedges' $g = 0.97$ (95% CI [0.78, 1.16]), whereas low intensity exercise yielded smaller improvements, Hedges' $g = 0.35$ (95% CI [0.16, 0.55]). High intensity exercise yielded a negative effect on RA, Hedges' $g = -0.68$ (95% CI [−1.13, −0.22]) and low intensity exercise elicited a negative effect on RA, Hedges' $g = -0.48$ (95% CI [−0.80, −0.15]) Moderate intensity cycling had no significant effects on RA.

3.4.7.1 Additional Analysis – averaged effect sizes

Moderate intensity (n = 9 studies) showed the most significant positive effect on EF task RT, $SMD = 0.79$ (95% CI [0.49, 1.08], $z = 5.20$, $p < 0.0001$), however, the Q-test was not significant, which indicates that there may be heterogeneity. Following, High intensity cycling (n = 7 studies) also showed a positive effect on EF task RT, *SMD* = 0.72 (95% CI [0.45, 0.99]), $z = 5.24$, $p < 0.0001$. Low intensity (n = 4) cycling showed no significant effects on RT, and none of the intensities had a significant post-exercise effect on EF task RA.

3.4.8 Duration

The greatest improvements in RT were found for 31–40 min of cycling, Hedge's $g = 0.99$ (95% CI [0.81, 1.17]). Less improvement was found for 10–20 min of cycling, Hedge's $g = 0.79$ (95% CI [0.65, 0.94]), and 21–30 min, Hedges' $g = 0.77$ (95% CI [0.41, 1.13]). Bouts of 40 min or longer yielded no significant effect on EFs. The greatest improvements in RA were after 21–30 min of cycling, Hedges' $g = 0.92$ (95% CI [0.31, 1.52]). All other durations yielded a negative effect on RA; the smallest decline in performance occurred after 10–20 min of cycling, Hedge's $g = -0.28$ (95% CI [−0.51, −0.06]), and the greatest decline occurred after 40 min or longer, Hedge's $g = -0.66$ (95% CI [−1.06, −0.25]. There was no effect of cycling bouts lasting 31–40 min on EF performance.

3.4.8.1 Additional Analysis – averaged effect sizes

After averaging dependent effect sizes by individual study, 21–30 min yielded a positive effect on post-exercise EF RT (n = 6 studies), *SMD* = 0.87 (95% CI [0.58, 1.15]), $z = 5.95$, $p < 0.0001$, 21–30 min of cycling (n = 5 studies) yielded a positive but non-significant effect on post-exercise EF RA. A duration of 31–40 min of cycling yielded a positive effect on EF RT, *SMD* = 0.21 (95% CI [0.56, 1.39], $z = 4.58$, $p < 0.0001$. However, the effect of 31–40 min of cycling on post-exercise EF RA (n = 5 studies) was negative and non-significant. 11–20 min of cycling (n = 7 studies) yielded a positive effect on EF RT, *SMD* = 0.59 (95% CI [0.10, 1.09], $z = 2.34$, $p = 0.02$, and yielded a negative effect on RA.

3.4.9 EF Task Type

An acute bout of ergometer cycling exercise elicited the greatest improvement in RT for inhibitory control, Hedges' $g = 0.91$ (95% CI [0.80, 1.03]), followed by task-switching, Hedges' $g = 0.71$ (95% CI [0.53, 0.88]). There was no significant effect on working memory tasks performance. There was no significant effect of cycling on RA for any EF tasks.

3.4.9.1 Additional Analysis – averaged effect sizes

When averaging dependent effect sizes by individual study, acute cycling yielded the most beneficial effects on inhibitory control RT (n = 12 studies), $SMD = 0.70$ (95% CI [0.43, 0.98]), $z = 5.07$, $p < 0.04$. There was an insignificant effect of acute cycling on RT in tasks assessing inhibitory control (n = 10 studies). Acute cycling did not have a significant effect on RT in tasks assessing task-switching (n = 4 studies). There was a positive, non-significant effect of acute cycling exercise on RA for inhibitory control tasks. There was insufficient data to run an analysis for RA for task-switching (n = 2) and working memory tasks (n = 2).

3.4.10 EF Task Onset

Completion of EF tasks immediately post-exercise resulted in the greatest improvements on RT, Hedges' $g = 1.11$ (95% CI [0.88, 1.33]). Lesser improvements in RT were found after a short delay, Hedge's $g = 0.85$ (95% CI [0.69, 1.02]), and after a moderate delay, Hedge's $g = 0.87$ (95% CI [0.66, 1.08]), but the least improvement in RT was observed after a long post-exercise delay, Hedge's $g = 0.40$ (95% CI [0.05, 0.76]). There was a decline in EF task performance after a moderate delay, Hedge's $g = -0.52$ (95% CI [−0.85, −0.20]) and no significant effects on EF in any other delay category.

3.4.10.1 Additional Analysis – averaged effect sizes

When averaging dependent effect sizes by individual study, the greatest improvements in RT were found immediately post-exercise (n = 4 studies), estimated $SMD = 0.96$ (95% CI [0.51, 1.41]), $z = 4.19$, $p < 0.001$. Similar improvements in RT were found after a moderate post-exercise delay, *SMD* = 0.95 (95% CI [0.56, 1.33]), $z = 4.84$, $p < 0.0001$, and after a short post-exercise delay, *SMD* = 0.80 (95% CI [0.43, 1.17], $z = 4.25$, $p > 0.001$. However, a long delay yielded no effect on RT. There were no significant effects of an acute bout of cycling on RA, regardless of administration time.

3.5 Discussion

This meta-analysis aimed to (i) determine the effect of an acute bout of ergometer cycling exercise on EF and (ii) obtain some insight regarding the influence of established moderators on this effect. The findings of this current review support the inverted-U hypothesis, in which moderate intensity exercise protocols seem to elicit the greatest EF task performance benefits for RT. For RT, there was a marginally smaller effect size after high intensity exercise and a minimal effect after low intensity exercise. An acute bout of cycling exercise had no effect on RA, irrespective of intensity. A second analysis was conducted to consider the effect of sample size and study weight on the outcomes, which averaged the effect sizes of each separate study. The analysis of moderators suggests that optimal exercise intensities may be 46–63% of $\dot{V}O_{2max}$, optimal durations are approximately 21–30 min, and optimal EF improvements are manifested immediately post-exercise.

These findings may be contingent on the type of EF task employed. The EF task with the greatest RT improvements post-exercise was inhibitory control, with benefits also evident for task-switching RT tasks; however, there were no significant effects of acute cycling on RA across any EF task type. This is somewhat consistent with Yerkes and Dodson's claim that lower arousal levels are required for complex tasks. Still, high arousal levels may be preferable for simple ones (Yerkes & Dodson, 1908). McMorris and Hale noted that, when performing tasks such as the Flanker Task, the individual must choose their response while preparing to move and select their answer. If the individual decides to focus on increasing their speed, this may be at the cost of accuracy, and RT seems to be favoured over RA

(McMorris & Hale, 2012). Another reason for the effects of RA and RT is that, according to the catecholamine hypothesis, acute exercise-induced increases in catecholamines could positively affect RT but may cause neural noise that results in performance decrements (Cooper, 1973). For example, increased catecholamine levels have been shown to affect RT positively. However, the resultant noise in the dorsolateral prefrontal cortex (DLPFC) may impair task accuracy by reducing its capacity to prevent interference (e.g., from immediately preceding items in a 2-back task; McMorris et al., 2011). Although the previous study has only assessed the relationship between acute exercise and decline in RA during working memory tasks, the researchers suggest that this finding could be extended to other cognitive tasks as well, which leads to the importance of assessing RT and RA separately in future studies (McMorris et al., 2011; McMorris & Hale, 2012).

A negative or more negligible effect on RA compared to RT in healthy young adults could be explained in the context of McMorris's interoception theory (McMorris, 2021). This theory suggests that perceptions of fatigue associated with high intensity exercise may offset the physiological benefits of EF. The individual may perceive the task as having a high effort cost, resulting in decreased activation of dopaminergic projections from the nucleus accumbens to the dorsolateral prefrontal cortex, which culminates in lower motivational salience for the task, i.e., reduced incentive to be accurate (McMorris et al., 2009). Moreover, short task durations limit the possibility of in-task learning, so the individual's perceptions of the effort required in the cognitive task may be higher in the exercise condition. Future research in this area should consider affective responses, such as perceived exertion, alongside objective measures, such as $\dot{V}O_{2max}$, when determining the influence of exercise intensity on executive function task performance.

Exercise duration seems to influence the extent of improvement in EF task performance. The current analysis shows that 21–30 min of exercise elicited improvements in

EF task performance when considering RT. There were no significant effects of cycling exercise on RA at any duration. The timeframe of 21–30 may be optimal for triggering physiological mechanisms that promote neuroplasticity and cognitive optimisation, but it could be contingent on exercise intensity; the combined and interacting contributions of exercise intensity and duration – recently described as exercise volume (Tsukamoto et al., 2017) – may be a more accurate way of specifying target thresholds for neuroplastic changes and EF enhancement (Anderson-Hanley et al., 2012; Byun et al., 2014; Tsukamoto et al., 2017; Zhu et al., 2021). For example, in their volume-controlled analyses, Tsukamoto and colleagues (2017) found that exercise-induced benefits were sustained for longer retention periods after moderate intensity exercise than low intensity, volume-matched exercise, and longer-duration moderate intensity exercise seemed to prolong EF improvements. This finding indicates that sustained arousal may be influential in determining prolonged acute exercise-induced EF improvements. However, previous research has tended not to examine the interactive effects of two or more moderators, although there is some evidence of positive effects for short bouts at very high intensities (de Diego-Moreno et al., 2022; Miller & Cohen, 2001).

Exercise yielded a positive effect on RT in all task types. However, the most considerable effect was seen for inhibitory control and task-switching measures; there was no effect for working memory tasks. For RA, there were no effects for any EF task types. These findings agree with McMorris and Hale's findings, who noted that inhibition and working memory tasks might not be complex enough to assess RA (McMorris & Hale, 2012). As reflected in many of the studies in this review, working memory or inhibitory control is typically examined in isolation. One exception is the study by Weng and colleagues (2015), who found significant enhancement in working memory after 30 min of moderate intensity exercise, using the 2-Back condition of the facial n-Back but no effect for inhibitory control as measured using the Flanker Task. It would be prudent for future studies to directly compare performance on two different EF task types using equivalent experimental designs and samples.

The findings in this review suggests that the optimal EF task onset ranges from immediately to 9 min post-exercise (Basso & Suzuki, 2017). However, this finding is based on five studies that comprise varying ratios of exercise intensities with different durations (Chang et al., 2014; McMorris et al., 2011; Miyamoto et al., 2018; Tsukamoto et al., 2016, 2017). To account for such variability, it is important to employ volume-controlled protocols as done by Tsukamoto and colleagues (2017). The optimal improvement in EF task performance that occurred immediately post-exercise suggests that physiological changes that influence RT on EF tasks (i.e., peripheral and central BDNF, heart rate and catecholamine concentrations) may subside quickly after the exercise session (de Diego-Moreno et al., 2022).

3.5.1 Implications for cycling as an intervention

This review and meta-analysis suggest that an acute bout of cycling exercise may improve young adults' subsequent performance of EF tasks – specifically those dependent on working memory, shifting, and inhibitory control. These EFs serve an essential purpose in our everyday lives, enabling us to pay attention, regulate emotions, make decisions and retain information (Diamond, 2013). Accordingly, the relationship between EF task performance and academic achievement is established (Howie & Pate, 2012; Martins et al., 2021) cycling could be promoted as a mode of active school travel, and brief cycling exercise sessions could also be incorporated into school timetables to maximise students’ academic performance in class. However, additional research is required in this regard (Martins et al., 2021). Ergometer protocols may also be helpful for examining the potential effects of physical and cognitive exercise on EF task performance. For example, the greater stability of ergometer cycling relative to treadmill running may facilitate safe performance of a concurrent secondary task.

3.5.2 Limitations

This review has a few limitations to consider. First, our sample was restricted to healthy young adults and is therefore not generalisable to individuals outside this cohort. However, this approach mitigated the potential confounding effect of participant age, in line with previous recommendations (Bérdi et al., 2011; McMorris, Barwood, & Corbett, 2018). Second, studies were only included if cycling ergometer exercise was the sole intervention; all those that comprised one or more other intervention components (e.g., caffeine consumption) were excluded. Consequently, the applicability of the findings in this review may not extend to real-life cycling, which occurs under various circumstances, such as those in which caffeine has been imbibed prior to a cycle journey (e.g., the morning commute).

In this meta-analysis, we acknowledged the potential mediating effect of individual differences, such as age and health status, on EF performance in our inclusion criteria. However, we did not account for participants' sex, fitness levels, their perceived exertion during exercise or other individual differences because insufficient information was provided in previous research to characterise samples in these respects effectively. For example, according to McMorris' model, motivational factors may affect an individual's perception of effort/the perceived costs of exercising (McMorris, Barwood, & Corbett, 2018).

3.6 Conclusion

This meta-analysis, which included 293 effect sizes across 17 studies, found that when considering both RT and RA, the greatest improvements in EF task performance result from acute cycling bouts at moderate intensities for durations ranging from 21 to 30 min. EF task performance was greatest immediately post-exercise. The EF component that exhibited the greatest post-exercise improvements was inhibitory control. These findings lend support for the use of cycling-based interventions to enhance subsequent cognitive performance.

CHAPTER 4. THE EFFECT OF ERGOMETER CYCLING AND VISUAL FORAGING ON BRAIN FUNCTION

4.1 Abstract

The aim of this study was to examine the effects of cycling and visual foraging on executive function (EF). Twenty-seven participants (mean age 25.44 ± 4.31 years) completed four lab-based sessions, one in which their aerobic capacity ($\dot{V}O_{2max}$) and baseline EF scores assessed were determined, and three randomised experimental conditions: ergometer cycling (EC), visual foraging (VF) and both combined (EC+VF). Participants' EF performance was assessed at baseline, and pre-and post- intervention using the 2-Back task (working memory), the Flanker Task (inhibitory control), and the Wisconsin Card Sorting Task (WCST; task switching). Functional near-infrared spectroscopy (fNIRS) and eye-tracking data were collected throughout each condition. Affective state was assessed via the Affect Grid. Repeated measures ANCOVAs, incorporating baseline EF task scores as covariates, revealed condition x time x covariate interactions for the Flanker task only; task performance of participants with poorer baseline scores improved more profoundly in the EC condition. Subjective arousal and prefrontal cortex (PFC) activation were higher in both cycling conditions relative to VF; hence, ergometer cycling, rather than visual foraging, might be the more impactful intervention in these regards. However, these elevations were not associated with EF enhancements; near-ceiling effects in EF task performance may explain this. The EC condition elicited greater energetic investment than the EC+VF condition; possibly because the secondary VF task distracted from the cycling exercise. PFC activation was only correlated with gaze fixations during the EC+VF condition, potentially reflecting concurrent increases in supply of, and demand form oxygen during the combined condition.

Keywords: dual-task, executive function, exercise, fNIRS, prefrontal cortex

4.2 Introduction

An acute bout of physical exercise can improve subsequent cognitive function (Chang et al., 2012; Basso & Suzuki, 2017; Dkaidek et al., 2023), and a combination of physical exercise with cognitive training may be even more beneficial (Lauenroth et al., 2016; Tait et al., 2017; Guo et al., 2020; Zheng et al., 2021). Such combinations of cognitive and motor tasks have been described as *dual tasking*, wherein the individual performs physical and cognitive tasks in parallel, a demand that can lead to improvements in both motor (Hofheinz et al., 2016) and cognitive (Kunzler & Carpes, 2021) performance. Moreover, increased attentional demands posed by secondary tasks can compromise performance in the other, which is pertinent for real-world navigation tasks (Corp et al., 2018).

Dual-task interventions appear to improve executive function (EF) task performance, (Lauenroth et al., 2016; Tait et al., 2017; Guo et al., 2020). EFs are a set of mental abilities dependent on activity in the prefrontal cortex (PFC; Miyake et al., 2000) and comprise three core components: *inhibitory control* (the ability to regulate emotions, thoughts, and behavioural responses), *working memory* (updated temporarily stored information), and *cognitive flexibility* (adapting our behaviour in response to environmental changes; Diamond, 2013). Each of these components is crucial for successful navigation when cycling on roads; for example, to suppress anger-related responses to other road users' antisocial behaviour (*inhibitory control*), to recall the position of vehicles in the roadway (*working memory*), and to respond to changing road conditions (*cognitive flexibility*). Hence, it is prudent to examine the benefits of cycling in combination with cognitive exercise.

Availability of oxygen in the brain is crucial for cognition; oxygen depletion reduces cognitive performance (Herold et al., 2018; Chung et al., 2007). Accordingly, research suggests that improved cognitive task performance following an acute bout of exercise coincides with elevated levels of cerebral oxygen saturation (rSO_2) in the PFC (Herold et al., 2018; Yanagisawa et al., 2010; Byun et al., 2014), although the extent of this relationship is partly determined by exercise intensity and duration (Byun et al., 2014; Endo et al., 2013). However, recent evidence shows that combined cognitive and cycling exercise increases PFC oxygenation relative to a reading control condition and cognitive exercise alone, for both EF and non-EF tasks, albeit not significantly different from cycling per se (Ji et al., 2019).

However, not all dual tasks are created equal: some forms of exercise improve EF task performance more than others (e.g., see Etnier et al., 1997). Notably, several reviews have indicated that an acute bout of cycling exercise is beneficial (Brisswalter et al., 2002; Etnier et al., 1997; Chang et al., 2012; Dkaidek et al., 2023; Lambourne & Tomporowski, 2010). Moreover, Dkaidek et al. (2023) noted that cycle ergometers may be more appropriate for dual-task protocols, due to their stability relative to treadmills, which renders them safer when considering potential compromises of motor task performance that can arise in dual-task paradigms (Corp et al. 2018).

Dkaidek and colleagues (2023) conducted a meta-analysis focused on the effects of an acute bout of ergometer cycling on young adults' EF. Their findings showed a positive effect of cycling on EFs, and that this effect was moderated by exercise intensity and duration, and EF task type and onset. Dkaidek and colleagues suggested that moderate cycling exercise intensities (46-64% $\dot{V}O_{2max}$; American College of Sports Medicine, 2013) should yield optimal benefits, consistent with both Yerkes and Dodson's inverted-U hypothesis (1908) and Cooper's (1973) catecholamine hypothesis – and that this should be more pronounced for inhibitory control tasks (e.g., Flanker Task) – specifically, when EF tasks are completed immediately post-exercise. Although there is evidence to suggest that a duration of only ten minutes elevates catecholamine levels, and cognitive performance accordingly (Basso & Suzuki, 2017), Dkaidek and colleagues showed that 20-30 minutes of cycling appear to confer the greatest benefits on EF task performance, consistent with previous reviews (Basso & Suzuki, 2017; Chang et al., 2012).

When assessing potential EF task enhancements resulting from dual-task exercise, it is important to consider the nature of the cognitive task; recent evidence suggests that dual-task interventions that incorporate novel and mentally demanding tasks that engage EFs, may be particularly effective (Guo et al., 2020; Ji et al., 2019). A visual foraging task (VFT; (Kristjánsson et al., 2014) is a demanding visual search task in which participants must search for multiple targets simultaneously. There is also evidence that performance in these tasks may be associated with working memory and cognitive flexibility (Ólafsdóttir et al., 2019). Multitarget foraging is more representative of visual attention allocation in real-world contexts than traditional single-target tasks, and may consequently provide us with insights regarding human performance in dynamic environments (Kristjánsson et al., 2019; Kristjánsson et al., 2020). By combining acute cycling exercise with a VFT, we may also learn about the interplay between attentional resource allocation and physical load.

Outdoor cycling is often performed in visually demanding environments – for example, cycling on roads while paying attention to other road users' behaviour. Consequently, the effects of cycling exercise and visual foraging combined are worthy of exploration. The aim of this study was to investigate the effects of combining cycling exercise with a visual foraging task (EC+VF) on EF task performance, compared to ergometer cycling (EC) or visual foraging (VF) in isolation. We hypothesised that EC+VF would result in the greatest EF improvements, and that this would be reflected in increased PFC oxygenation.

4.3 Method

4.3.1 Participants and Study Design

A priori sample size estimate was calculated using a repeated measures ANOVA in G*Power 3.1 (Faul et al., 2007). Estimates were based on a published effect size for acute moderate intensity cycling on EF task performance (*d* = 0.52; Dkaidek et al., 2023). The power analysis was conducted with an alpha of 0.05, and desired power of 0.80, and a significance level of 0.05 in detecting effects exceeding f = 0.252 in a 3 X 2 repeated measures ANCOVA (3 [EC, VF, EC+VF] Condition X [pre-, post-) Time), yielded a sample of 27 participants.

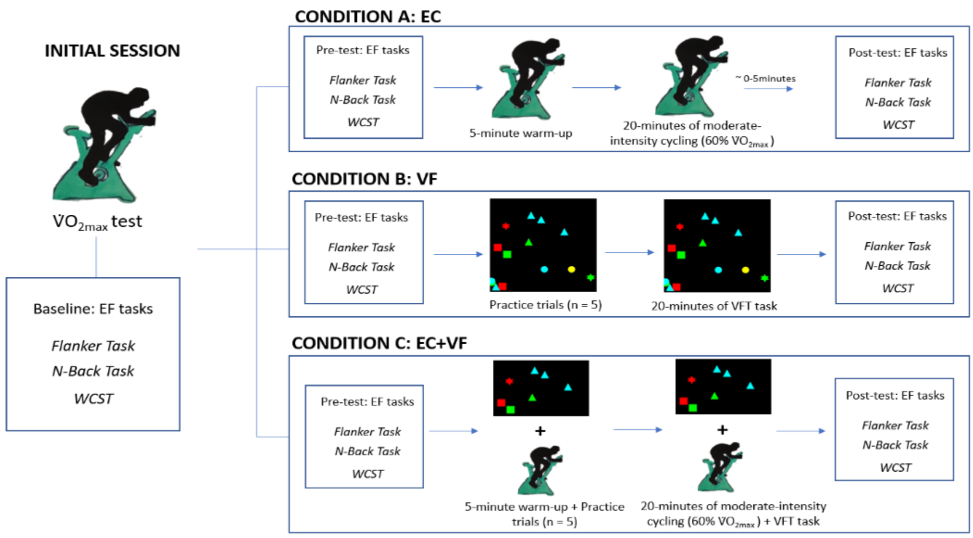
Twenty-seven healthy young adults (Female = 15; M age = 25.44 ± 4.31 years) participated in this study. All participants were volunteers and were recruited via the lead author's institutional intranet, word-of-mouth, posters, and social media platforms – notably, Instagram, Twitter (now X), and WhatsApp Messenger. Participants completed a modified version of the International Physical Activity Questionnaire Short Form (IPAQ short form, 2016; Booth, 2000; see Craig et al., 2003) during their initial lab visit to assess their physical activity levels. All participants were free of any known cardiovascular, neurological, and pulmonary disorders and had normal, or corrected-to-normal, vision and hearing.

An average metabolic equivalent (MET) score was calculated from the IPAQ data for each category of physical activity. The average value for vigorous physical activity was 1,457.56 ± 2,011.96 MET-minutes per week (Range = 0 – 6,697.67), moderate physical activity was 602.61 ± 965.73 MET-minutes per week (Range = 0 – 4,186.05), and walking, 2,241.73 ± 5,166.85 (Range = 132 – 1381.39). The average total physical activity was 4,301.89 ± 5,894.49 MET-minutes per week (Range = 132 – 11,576.72). Accordingly, 11 participants' physical activity level could be classified as *high*, 11 as *moderate*, and 5 as *low*.

A repeated measures pre-post design was employed, in which participants provided baseline data at an initial visit to the lab, followed by participation in each of three different experimental conditions, completed on three different occasions. Figure 4.1 illustrates the study design.

Figure 4.1

Study Design.



4.3.2 Equipment, Materials and Measures

4.3.2.1 $\dot{V}O_{2max}$ testing.

A Lode Excalibur Cycle Ergometer (Cranlea Human Performance Limited, UK) was used to perform $\dot{V}O_{2max}$ continuous ramp testing, which was preferred to an incremental protocol (see Boone & Bourgois, 2012). The participants wore face masks and mouthpieces during testing. During the ramp test, breath-by-breath pulmonary gas exchange data were collected using a Cortex Metalizer 3B gas analyzer (Cortex, Leipzig, Germany) and averaged every 30 s.

Participants' height and weight were measured using weighing scales and tape measure for data to be inserted into the PC. Heart rate (HR), Blood lactate levels (capillary blood sample), respiratory exchange ratio (RER) and Rate of Perceived Exertion (RPE) data were inputted to Cortex Metalizer 3B analysis software running on a dedicated PC (Dell, Latitude 5290).

4.3.2.2 Measurements

Measurements of blood metabolites, cardiovascular parameters and perceived exertion were obtained before and after the $\dot{V}O_{2max}$ testing (see physiological data in Appendix C).

4.3.2.2.1 Blood metabolites.

Participants' blood lactate levels were taken from the earlobe with a disposable lancet; approximately 0.05 ml of blood was used for analysis using an electronic lactate analyser (Biosen C-Line; EKF Diagnostics Holdings plc, UK) Machine. Capillary Blood samples were taken prior to and immediately post-incremental testing.

4.3.2.2.2 Cardiovascular parameters.

Heart rate measurements were continuously measured via Polar Bluetooth Smart chest strap (Polar Electro Oy, Professorintie, 90440 Kempele, Finland).

4.3.2.2.3 Perceived and actual exertion.

The Rate of Perceived Exertion (RPE; Borg, 1982) scale was used to measure the participant's perceived exertion before, and immediately after the exercise. The scale ranges from 6 (no exertion) to 20 (maximal exertion).

Also, considering the indeterminate and potentially nuanced relationship between exercise intensity and cognitive performance (Basso & Suzuki, 2017; Chang et al., 2012; Dkaidek et al., 2023), we assessed *cycling efficiency* – the balance between energy output and input, which is influenced by cycling cadence (MacDougall et al., 2022) – via the Lode Ergometry Manager Software.

4.3.2.3 EF Tasks.

Participants completed a computerised battery of cognitive EF tasks to assess their inhibitory control (Flanker Task), working memory (2-back version of the n-Back task) and task-switching (Wisconsin Card Sorting Task; WCST) abilities (cf. Lefferts et al., 2019). Multiple measures of EF were included, as suggested by Etnier and Chang (2009). The tasks were created in Psytoolkit (v. 3.4.2.; Stoet, 2010, 2017). The EF tasks were displayed on a monitor (Ilyama ProLite 82280HS) measuring 61.2 cm wide and 47.9 cm high. At a viewing distance of 65 cm, the screen bisected 50.4° of visual angle in the horizontal plane and 40.4° of visual angle in the sagittal plane. Participants provided trial-by-trial responses for each task by pressing keys on a UK QWERTY keyboard.

4.3.2.3.1 Flanker Task.

This task assessed inhibitory control (Eriksen & Eriksen, 1974). It comprised 128 trials in which a target letter was presented centrally and flanked on both sides by two distractor letters (cf. Lefferts et al., 2019; Figure 4.2). Each set of letters included a central fixation point underneath. Sixty-four of the trials were congruent (i.e., the central letter was identical to the flanking letters) and 64 were incongruent (i.e., they differed). All trials were presented in a randomized order across two blocks of 64 items with a 10-second break between blocks. Participants were instructed to press the ‘A’ key if the target letter was an X or a C, and to press the ‘L’ key if it was a V or a B. If the participants pressed the correct key, the central fixation point flashed green for 150 ms and if the participant pressed the incorrect key, the central fixation points flashed red for 300 ms.

The ‘Flanker Effect’ was calculated as the difference between the average reaction time the incongruent and congruent trials. By considering the magnitude of the interference effect, it has been shown to relate to individual difference in PFC engagement of which is associate with inhibitory control (Forstmann et al., 2008; Ridderinkhof et al., 2021).

Figure 4.2

Flanker Task Trial Examples – Congruent (left) and Incongruent (right)

4.3.2.3.2 2-Back Task

This task assesses working memory (Kirchner, 1958). The 2-Back Task comprised 50 trials in which letter stimuli were presented for a duration of 500 ms (cf. Kamijo & Abe, 2019), bordered by grey horizontal lines at the top and bottom (see Figure 4.3). Trials were divided into two 25-trial blocks, separated by a 10-second break. For 1 in every 3 trials on average, when cued to do so, the participant was instructed to state whether the current letter was identical to one they saw two trials earlier by pressing the 'M' key; they had 3000 ms to respond before a new stimulus appeared. If the letters were different the participant was instructed not to press any keys. If participants responded correctly, green borders appeared at the top and bottom of the letter (see rightmost image of Figure 4.3); if they were incorrect, then a red border appeared. Accuracy was calculated as the percentage of hits, otherwise referred to as 'correct matches', using the formula: (hits/hits + errors) x 100. Other reported data include the percentage of false alarms, hits that were detected as matches but were not, and missed items, matches that were not identified by pressing the 'M' key.

Figure 4.3

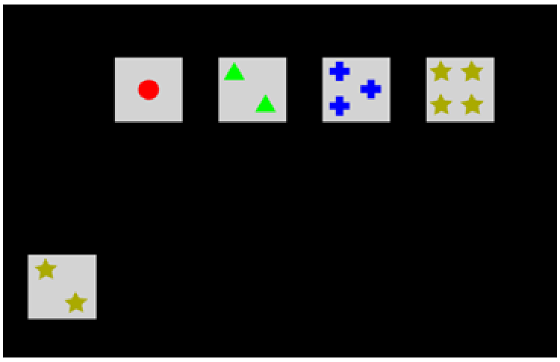
2-Back Trial Example (correct participant response shown in rightmost image)

4.3.2.3.3 Wisconsin Card Sorting Task (WCST).

This task assesses participants' ability to shift attention between different tasks (cognitive flexibility and problem-solving; Kolakowsky-Hayner, 2011). This version of the task comprised 64 trials. Four cards were shown at the top of the screen. The participant's aim was to figure out a classification rule that could be used to sort a card displayed in the bottom-left corner of the screen. The participant was instructed to click on one of four cards at the top that they thought belonged to the same category as the bottom-left card; for example, the correct selection in Figure 4.4 for the rule *'2 items on a card'* would be the second card from the left. After they made their selection, the participant received feedback, but if the rule they adopted was incorrect, they had to make another selection, based on a different rule. Classification rules changed according to the shape of the symbols, the colour of the symbols, or the number of shapes on each card - and the rules changed randomly. Task scores reflect how well participants adapt to these changing rules – i.e., changes in task requirements. The reported raw scores were derived for statistical analysis: Perseverative Errors (i.e., repeated ones) and Non-perseverative Errors (i.e., random ones). Error count was calculated as the sum of all errors, i.e., Non-perseverative Errors + Perseverative Errors.

Figure 4.4

WCST Trial Example (rule = 2 shapes OR stars OR gold coloured)



4.3.2.4 Ergometer Cycling

All cycling was completed on a Lode Excalibur Ergometer (Excalibur Sport, 2006) connected to the Lode Ergometry Manager Software (V9). Participants warmed up for three minutes at 25W. During the intervention each participant cycled at the load corresponding to 60% of their $\dot{V}O_{2max}$. Participants' accumulated energy levels (kJ) and cadence (revolutions per minute; rpm) were continuously recorded throughout, to determine equivalence of effort across the two cycling conditions. After completing the intervention, participants cooled down for three minutes at warmup intensity. All data were downloaded for analysis in Microsoft Excel.

4.3.2.5 Visual Foraging Task (VFT).

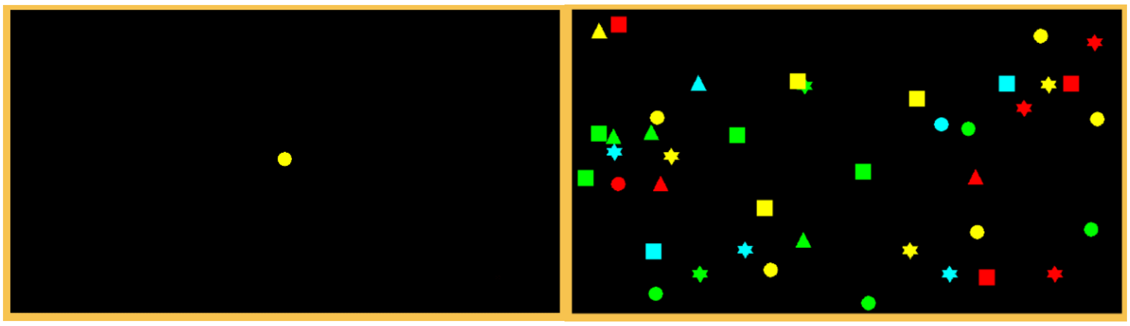
The VFT was developed using Clickteam Fusion 2.5, a game development tool that allows for game and software creation of any 2D game or application. Pilot testing was conducted to optimise the VFT for the current purposes: regarding clarity and size of shapes, the display settings, and behaviours. The iterative design process comprised 11 testing phases, during which adjustments were used to augment its overall effectiveness and difficulty level.

The VFT task was designed based on that used by Kristjánsson and colleagues (2019). Our VFT comprised dynamic, multitarget, conjunctive foraging, in an attempt to mimic the complexity of visual search in the real world. Each trial incorporated 40 moving shapes; this number was chosen according to Kristjánsson and colleagues' (2020) findings, which implied that forty targets presented a moderate-difficulty challenge relative to set sizes of 20, 60 and 80 shapes; this level was chosen to avoid extensive effort costs; response times increase linearly as set size increases (Kristjánsson et al., 2020).

The VFT was displayed on a projection wall to provide an image that measured 3.90 m in width by 2.17 m in height, 1.68 m away from the participant when seated on the ergometer. It bisected 33.6° of visual angle in the horizontal plane and 49.2° of visual angle in the sagittal plane. An array of 40 moving shapes – specifically, squares, circles, triangles, and stars displayed in different colours (green, red, blue, or yellow) on a black background – were presented to participants, whose aim was to identify specific colour-shape combination target stimuli. Shapes 'rebounded' from the borders of the display in a way that was consistent with the kinematics of physical counterparts. Prior to the start of each trial, the target stimulus would flash on the screen for 3 seconds. If the target was a yellow circle, then the participant would be required to find all instances of yellow circles in that trial (see Figure 4.5). The minimum number of targets was one, the maximum was six. Each trial lasted 6 seconds and shape-colour target combinations varied from one trial to the next. Participants verbally reported the number of target shapes they think they saw after each trial; responses were scored as correct if their response matched the actual value. Trials were presented in six blocks of 20 trials – a total of 120; there were 25-second breaks between blocks. The percentage of trials for which a correct response was provided was calculated for each participant.

Figure 4.5

VFT Trial Example (yellow circle target; correct answer = 5)



4.3.2.6 Eye Tracking.

Participants wore Tobii Pro Glasses 2 which were wirelessly connected to a PC running iMotions software (v. 9.3). The glasses were calibrated for each participant using a calibration card held parallel to the eye tracker at a distance of 0.8 to 1.2 meters from the participant, in front of a plain and static background. Participants were instructed to keep their head still and look at the calibration dot in the middle of the card until calibration was complete. Eye movement data were captured using the iMotions software.

4.3.2.7 Functional Near-Infrared Spectroscopy (fNIRS).

Cerebral oxygenation of the PFC was measured using fNIRS (INVOS 5100C Near-infrared Cerebral Oximeter; Somanetics, Troy, MI) via two pads, each housing two optodes, positioned above the eyebrows on the left and right sides of the forehead (i.e., over PFC; cf. Hyodo et al., 2012, Yanagisawa et al., 2010). Alcohol wipes were used to remove excess sebum from the participant's forehead, which was then dried with a sterile gauze pad prior to taping the pads to the skin to minimise daylight interference. The optodes emitted a signal at 300 and 810 nm wavelengths. The oximeter determined rSO_2 by analysing reflected near-infrared (NIR) light at each sensor, to obtain an averaged value every thirty seconds.

4.3.2.8 Affect Grid.

Given the influence of affective state on executive function (Dube et al., 2022; Peterson et al., 2022), we sought to capture participants' in-the-moment affect using the Affect Grid (Russell, Weiss, & Mendelsohn, 1989), which originates from Russell's Circumplex Model of Affect (Russell, 1980). It comprises a 9-by-9 grid single-item self-report measure of affect that has been used to differentiate affective states in various contexts (e.g., Bishop et al., 2009; Bishop et al., 2014; Vitali et al., 2019). The original circumplex model comprises two perpendicular dimensions – perceived activation (arousal) and affective valence (pleasure-displeasure) – creating four quadrants that represent *high activation-high valence*, *high activation-low valence*, *low activation-high valence,* and *low activation-low valence* states. Participants indicate their affective state by marking a cross in one square of the Affect Grid.

4.3.3 Procedure

Institutional research ethics committee approval was obtained prior to commencing data collection. Participants provided their written informed consent and had the opportunity to ask questions before any testing began. All participants completed an initial lab visit followed by three conditions in a randomised and counterbalanced order. Consecutive visits were separated by at least 48 hours to minimise the effects of fatigue, and all three conditions were completed within a six-week period (M days between sessions = 8.31 ± 7.29). Participants were instructed to avoid drinking coffee or alcohol, and strenuous exercise for 24 hours prior to their visit, to abstain from eating in the preceding two hours, and to be adequately hydrated. They were also required not to take any non-essential medication that could affect their physical or cognitive performance in the 12 hours preceding their participation.

4.3.3.1 Initial Lab Visit.

Health status was assessed at the initial lab visit via a Health Check Questionnaire and a COVID-19 form. Participants then completed familiarisation trials until they felt confident with the three EF tasks and the VFT, followed by five practice trials. Then, they provided baseline data for each of the three EF tasks.

4.3.3.2 Testing Session.

$\dot{V}O_{2max}$ data were collected in accordance with the British Association of Sport and Exercise Sciences (BASES; 1997) guidelines, which state that, for measurements to be valid, it must meet three out of the five criteria shown in Table 4.1. Once the data for the $\dot{V}O_{2max}$ were collected in the Cortex Metalizer 3B analysis software, the breath-by-breath data were exported into Microsoft Excel. $\dot{V}O_{2max}$ was calculated as the average oxygen consumption during the 30-second epoch prior to voluntary termination of the test. Between participants, sterilizing solution was used to disinfect the mouthpieces and face masks to avoid cross-contamination. Each participant's $\dot{V}O_{2max}$ was used to calculate the appropriate cycle ergometer load for them to perform moderate intensity exercise – designated as 60% of $\dot{V}O_{2max}$ (see Dkaidek et al., 2023).

Table 4.1

BASES $\dot{V}O_{2max}$ Measurement Criteria

1	A plateau in the $\dot{V}O_{2max}$ and exercise intensity relationship
2	A respiratory exchange ratio of 1.15 or above
3	A final heart rate within 10 beats min per minute of the participant's age predicted maximum heart rate (calculated as 220 – age)
4	The participant reaches fatigue and volitional exhaustion
5	An RPE of 19-20 is indicated

4.3.3.3 Experimental Conditions

Following the initial lab session, participants completed three experimental conditions: ergometer cycling (EC), visual foraging (VF) or a combination of ergometer cycling and visual foraging (EC+VF); the running order was partially counterbalanced across participants. At the beginning of each lab visit, the participants completed the Flanker Task, WCST and the 2-Back Task; the order in which these were completed was also partially counterbalanced, across experimental sessions. Eye tracking and fNIRS data were acquired continuously in the VF and EC+VF conditions. Only fNIRS data were acquired in the EC condition, but eye tracking glasses were worn for standardisation purposes and participants were instructed to look as they would typically when performing a stationary activity. In all conditions, participants completed the computerised EF test battery a second time within five minutes of finishing the intervention (see Dkaidek et al., 2023).

4.3.3.3.1 Ergometer Cycling (EC)

Participants completed a 3-minute warmup at a 25W load. After this, the ergometer load was gradually increased until their oxygen consumption reached 60% of their $\dot{V}O_{2max}$, at which they continued to cycle steadily for 20 minutes (cf. Dkaidek et al., 2023; Chang et al., 2012) at a cadence of 60-70 rpm. Participants finished the session with a three-minute cooldown with a resistance of 25W at a self-selected rpm.

4.3.3.3.2 Visual Foraging (VF)

Participants completed five familiarisation trials followed by 20 minutes of VF. Before the end of each trial, participants verbally reported the number of targets they detected, for the researcher to record their response. The participants were informed that each trial was six seconds long and that each trial would commence immediately after its predecessor. If the participants did not report a number for a trial, their response was recorded as incorrect.

4.3.3.3.3 Ergometer Cycling and Visual Foraging (EC+VF).

As for the EC condition, participants began with a 3-minute warmup at a 25W load; they simultaneously completed five practice VFT trials. Then, the ergometer load was gradually increased to 60% of their $\dot{V}O_{2max}$, at which they cycled for 20 minutes at a cadence of 60-70 rpm, while concurrently performing the VFT. Participants finished the session with a cooldown with no resistance and a self-selected rpm. An image of the EC+VF set up is shown in Figure 4.6.

Figure 4.6

Experimental Setup (EC+VF condition)

4.3.6 Data Analysis

All statistical analyses were conducted using IBM SPSS software (IBM Corp., 2023). Where the assumption of sphericity was violated, a Greenhouse-Geisser correction factor was applied. When a significant interaction or main effect was detected, it was followed up by a post hoc pairwise comparison with Bonferroni Correction. For all statistical comparisons, an alpha level of $p < .05$ was used.

4.3.6.1 EF Data.

Pre-test and post-test data were expressed as mean scores for the Flanker Task, WCST and the 2-Back task. To compare EF task performance in each of the three conditions, repeated measure analysis of covariance (ANCOVA) was used to determine interactions and main effects in a Condition (EC, VF, EC+VF) x Times (Pre, Post) design with EF baseline scores used as a covariate for the EF outcome measures (cf. Tarantino et al., 2021; Clifton & Clifton, 2019; Nunes et al., 2011). Mauchly's Test of Sphericity was used to assess statistical assumption of sphericity and in the case of a violation, Greenhouse-Geisser correction was applied. Finally, Bonferroni-corrected pairwise comparisons were run to determine where any group differences lay.

4.3.6.2 Affect Grid Data

A 3 X 2 (Condition x Time) repeated measures ANOVA was used to examine changes in self-reported affect as assessed using the Affect Grid.

4.3.6.3 VFT Performance and Gaze Data.

VFT scores were expressed as the mean and were analysed using a paired samples t-test between the EC + VF and VF conditions. The number of gaze fixations was compared across the two conditions, as an index of the extent of visual foraging. Gaze data were into iMotions software. Gaze behaviour was analysed as the number of fixations as an index metric for visual attention. The mean numbers of fixations in the two visual foraging conditions were compared using a paired samples t-test.

4.3.6.4 fNIRS Data

rSO_2 levels were each condition were expressed as the mean and were compared using a repeated measure ANOVA. Correlational analyses were performed to explore potential relationships between (a) VFT scores and rSO_2 levels (b) Affect and rSO_2 levels and (c) rSO_2 levels in left and right PFC.

4.3.6.5 Accumulated Energy and Cadence.

Accumulated energy (kJ) in the EC and EC+VF conditions was expressed as the mean and compared using a paired samples t-test. Cadence was calculated as the average rpm across four timepoints throughout the cycling protocol: 5 minutes, 10 minutes, 15 minutes and 20 minutes, then expressed as the mean for each condition, for comparison using a paired samples t-test. Correlations were also performed to examine the relationship between these two measures. Due to missing data caused by hardware malfunction, energy level and cadence data were only available for 21 participants, for both cycling conditions.

4.4 Results

4.4.1 EF Task Performance.

Table 4.2 shows descriptive data for all three EF tasks, expressed as means (SDs) (see also Appendix D).

Table 4.2

EF Tasks – Descriptive Data

Executive Function Tasks	Baseline	EC		VF		EC+VF	
		Pre	Post	Pre	Post	Pre	Post
Flanker Task							
Compatible RT (ms)	670.33 (102.02)	615.67 (87.83)	578.74 (99.22)	622.37 (96.00)	614.56 (92.51)	632.72 (99.81)	606.23 (99.15)
Incompatible RT (ms)	693.04 (98.06)	655.19 (94.59)	602.15 (95.30)	650.85 (85.85)	634.04 (93.03)	645.33 (85.17)	625.77 (93.48)
Flanker Effect (ms)	22.25 (51.64)	39.44 (28.52)	23.41 (23.55)	28.48 (36.55)	19.48 (31.58)	18.31 (32.92)	19.54 (21.67)
WCST							
Error Count	19.00 (6.54)	13.81 (6.34)	14.93 (5.79)	16.78 (15.90)	15.26 (5.28)	15.52 (5.14)	14.36 (4.71)
Perseveration error count	11.00 (3.56)	8.81 (3.18)	9.48 (3.37)	8.11 (6.14)	8.85 (2.66)	9.72 (2.82)	9.52 (3.12)
Non-Perseveration error count	7.96 (4.38)	5.46 (3.48)	5.41 (3.35)	8.19 (14.99)	6.22 (4.38)	5.76 (3.57)	5.08 (2.86)

2-Back Task							
Total trials with a match	18.80 (4.86)	16.22 (3.86)	15.42 (3.28)	15.04 (2.79)	15.07 (3.05)	15.21 (4.36)	15.19 (3.16)
Total trials without a match	41.96 (10.86)	33.41 (4.47)	33.50 (5.95)	34.96 (2.79)	34.93 (3.05)	35.35 (6.42)	33.92 (5.04)
Number of correct matches	13.32 (5.94)	14.70 (4.30)	14.31 (3.73)	13.41 (3.94)	13.44 (4.10)	14.17 (4.46)	14.23 (3.81)
Number of missed items	5.27 (5.87)	1.48 (1.70)	0.81 (1.17)	1.63 (2.68)	1.33 (2.30)	1.48 (2.43)	0.96 (1.43)
Number of false alarms	1.92 (2.45)	2.44 (3.42)	4.35 (13.28)	1.96 (2.91)	2.41 (4.24)	2.36 (2.64)	2.19 (2.02)
Percentage of correct matches	73.80 (25.97)	89.00 (13.31)	92.75 (14.76)	88.87 (19.33)	91.33 (14.47)	88.88 (17.29)	93.02 (11.47)
Percentage of missed items	26.24 (25.95)	11.13 (13.28)	4.90 (7.97)	11.39 (19.40)	8.80 (14.46)	11.48 (17.32)	6.90 (11.68)
Percentage of false alarms	5.61 (7.05)	7.43 (10.30)	4.96 (4.73)	5.72 (10.06)	6.83 (12.36)	6.88 (7.03)	5.88 (5.81)

4.4.1.1 Flanker Task Data

There was no significant condition x time interaction, albeit one approaching statistical significance, $F(2,42) = 2.62$, $\eta_p{}^2 = .11$, $p = .085$. There was a main effect of condition, $F(2,42) = \eta_p{}^2 = 0.14$, $p = .046$. Bonferroni-corrected pairwise comparisons revealed no significant differences between pairs of conditions, all $p > .05$. However, there was a significant interaction between condition, time and baseline EF task scores (the covariate), $F(2,42) = 3.54$, $\eta_p{}^2 = .14$, $p = .038$.

To explore this interaction further, separate correlations were run for each condition to reveal any relationships between baseline scores and pre-to-post change scores. These variables were negatively correlated in the EC condition, $r(22) = -.56$, $p = .005$ – as the baseline Flanker Effect increased (i.e., performance worsened), pre-to-post improvements in task performance increased. There were no significant correlations between baseline score and pre-to-post change scores for VF or EC+VF, *p*'s > .05. Figure 4.7 shows the interaction.

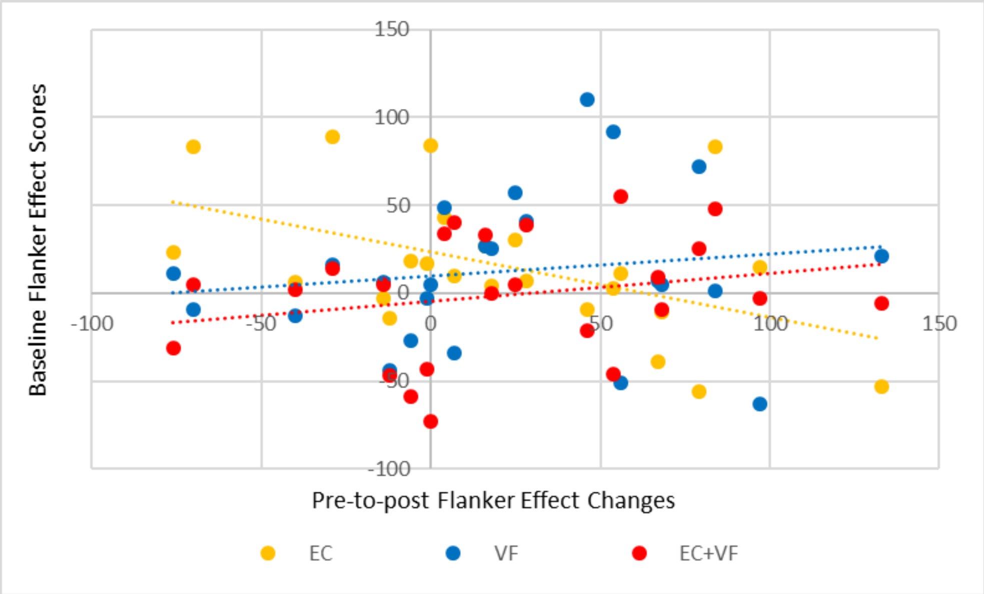
A main effect was found for condition, $F(2,42) = 3.32$, $\eta_p{}^2 = .14$, $p = .046$; and Mauchly's Test of Sphericity revealed no violations of the sphericity assumption, $W = .96$, $\chi(2) = 1.00$, $p = .607$. However, Bonferroni-corrected pairwise comparisons revealed no significant differences between EC and VF, $t(21) = 1.36$, $SE = 6.26$, $p = 0.563$, EC and EC+VF, $t(21) = 2.18$, $SE = 5.71$, $p = 0.123$ nor VF and EC+VF, $t(21) = 0.57$, $SE = 6.92$, $p = 1.00$.

4.4.1.2 WSCT Data

Error Count. A repeated measures ANCOVA did not reveal a condition x time interaction for error count, $F(2,28) = 1.09$, $\eta_p{}^2 = .07$, $p = .35$, nor main effects of condition, $F(2,28) = .01$, $\eta_p{}^2 = .00$, $p = .991$, or time $F(2,28) = .08$, $\eta_p{}^2 = .01$, $p = .784$.

Figure 4.7

*Flanker Effect Condition * Time * Covariate Interaction.*



4.4.1.3 2-Back Task Data

Correct Matches. A repeated measures ANCOVA revealed no significant condition x time interaction, $F(2,22) = 1.78$, $\eta_p^2 = .08$, $p = .181$. However, there was a main effect of time, $F(2,22) = 8.06$, $\eta p^2 = .27$, $p = .010$; Bonferroni-Corrected pairwise comparison revealed that the number of correct matches increased from pre- to post-intervention, $t(22) = 3.08$, $SE = 1.18$, $p = .005$.

4.4.1.4 Affect Grid Data

4.4.1.4.1 Arousal.

Average arousal levels over time, by condition, are shown in the top panel of Figure 4.8. There was a significant condition x time interaction, $F(2,50) = 4.89$, $\eta_p^2 = .16$, $p = .012$; Mauchly's Test of Sphericity did not reveal any violations of the sphericity assumption, $W = .95$, $\chi(2) = 1.73$, $p = .554$. Bonferroni-corrected pairwise comparisons revealed that self-reported arousal levels increased significantly after EC+VF compared to VF, $t(25) = 4.25$, SE

= .42, p < .001. A main effect of condition was also revealed, $F(2,50) = 4.93$, $\eta_p^2 = .17$, p = .011. Bonferroni-corrected pairwise comparisons revealed that self-reported arousal were greater at both time points, on average in the EC condition, compared to the VF condition, $t(25) = 2.88$, $SE = .37$, $p = .024$.

4.4.1.4.2 Pleasantness.

Average pleasantness levels over time, by condition, are shown in the bottom panel of Figure 8. There was no significant condition x time interaction, although it approached significance, $F(2,50) = 2.49$, $\eta_p^2 = .09$, $p = .093$. There was no main effect of condition, $F(2,50) = .06$, $\eta_p^2 = .00$, $p = .944$. However, a main effect was found for time, $F(1,25) = 6.07$, $\eta_p^2 = .20$, $p = .021$. Bonferroni-corrected pairwise comparisons revealed that self-reported pleasantness increased over time, $t(25) = 2.46$, $SE = .26$, $p = .021$.

4.4.1.4.3 Affect and rSO2 levels.

There were no significant correlations between affect and PFC rSO_2 levels, all p's > .05.

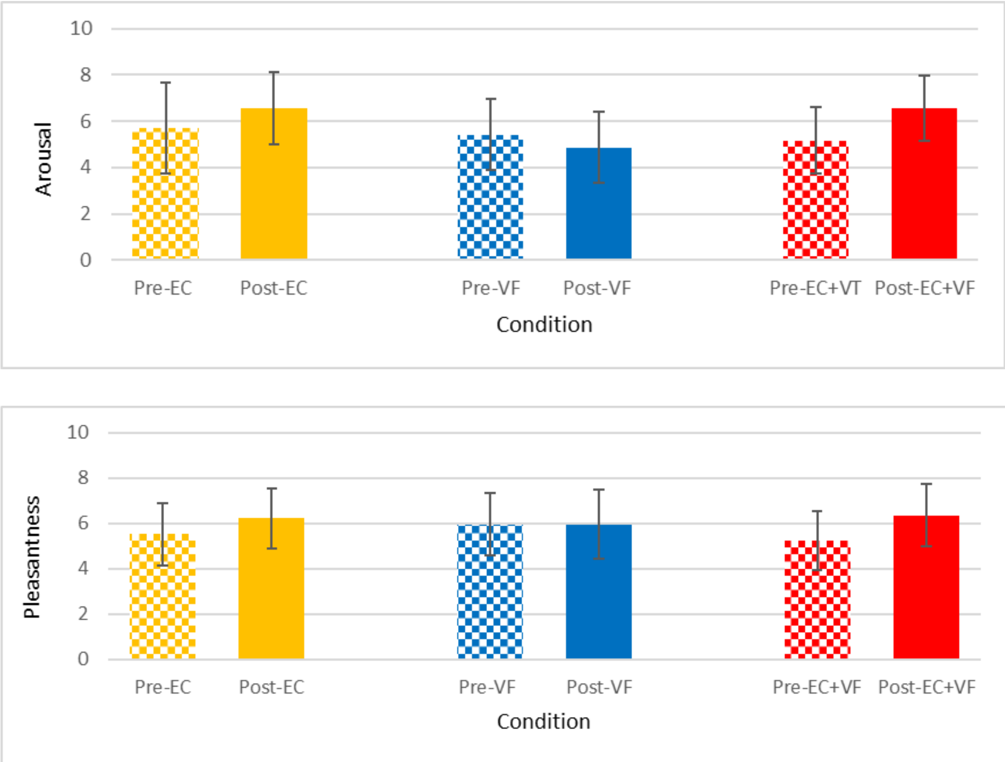
4.4.1.5 VFT Data

Figure 4.9 shows the relationships between average rSO_2 levels and the number of fixations, for both visual foraging conditions. There was no main effect of condition on VFT task performance and no significant difference between the number of gaze fixations in EC+VF and VF, $t(21) = .97$, $SE = 202.90$, $p = .335$ (see Appendix E; see also Appendix F).

However, there were significant correlations between the number of fixations and right rSO_2 levels, $r(23) = .46$, $p = .029$, and left rSO_2 levels, $r(23) = .51$, $p = .014$, during EC+VF. There was no such relationship between the number of fixations and right rSO_2 levels, $r(24) = .28$, $p = .166$, or left rSO_2 levels, $r(24) = .16$, $p = .425$, during VF.

Figure 4.8

Mean (± SE) Self-Reported Affect Over Time, by Condition



4.4.1.5 fNIRS Data

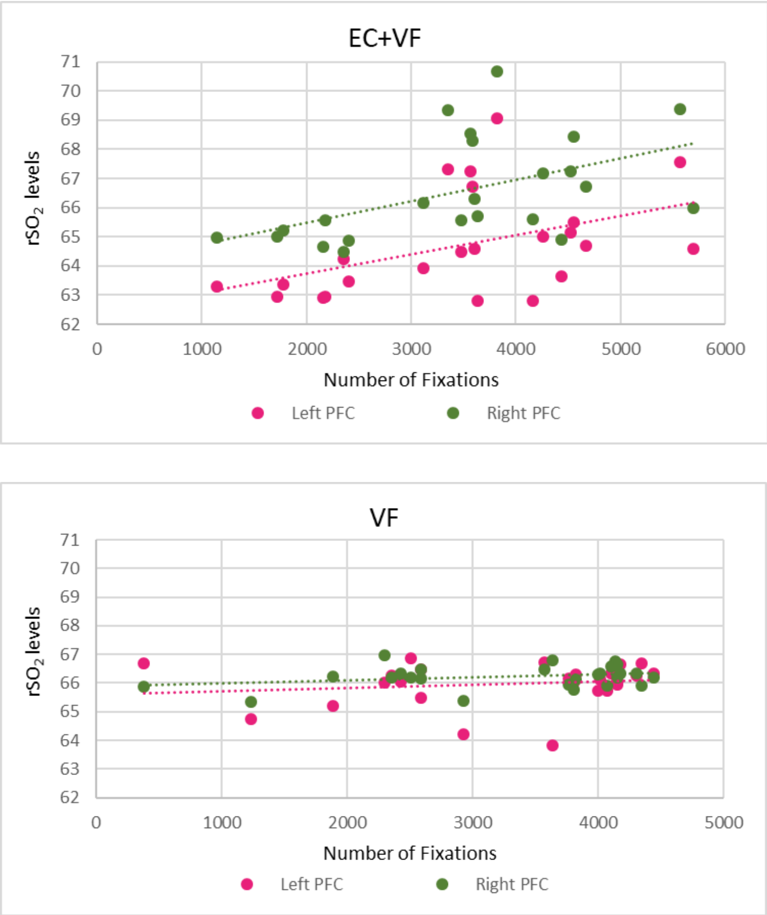
4.4.1.5.1 Left PFC.

The upper panel of Figure 4.10 illustrates average rSO_2 at the left optode, by Condition. Average baseline rSO_2 was 69% ± 2% across all conditions. Average rSO_2 was 68% ± 2% during EC+VF, 66% ± 0.6% during VF, and 72% ± 3% during EC.

Mauchly's Test revealed a violation of the sphericity assumption, $W = .27$, $\chi(2) = 49.32$, $p <.001$; hence, a Greenhouse-Geisser adjustment was applied, $\varepsilon = .58$. A main effect was found for condition, $F(1.16,45.17) = 94.18$, $\eta_p{}^2 = .71$, p < .001. Bonferroni-corrected pairwise comparison indicated that EC resulted in greater left PFC activation than EC+VF, $t(39) = 22.23$, $SE = .18$, $p < .001$, and VF, $t(39) = 9.21$, $SE = .47$, $p < .001$. However, there was no significant difference between EC+VF and VF, $t(39) = .60$ $SE = .35$, $p = 1.00$.

Figure 4.9

Correlations Between rSO_2 Levels in the Left and Right PFC and Number of Gaze Fixations, by Condition



4.4.1.5.2 Right PFC.

The lower panel of Figure 4.10 illustrates average rSO_2 at the right optode, by Condition. Average baseline oxygen saturation (rSO_2) was 64% ± 8% across all conditions. Average rSO_2 was 66% ± 2% during EC + VF, 66% ± 1% during VF, and 70% ± 3% during EC.

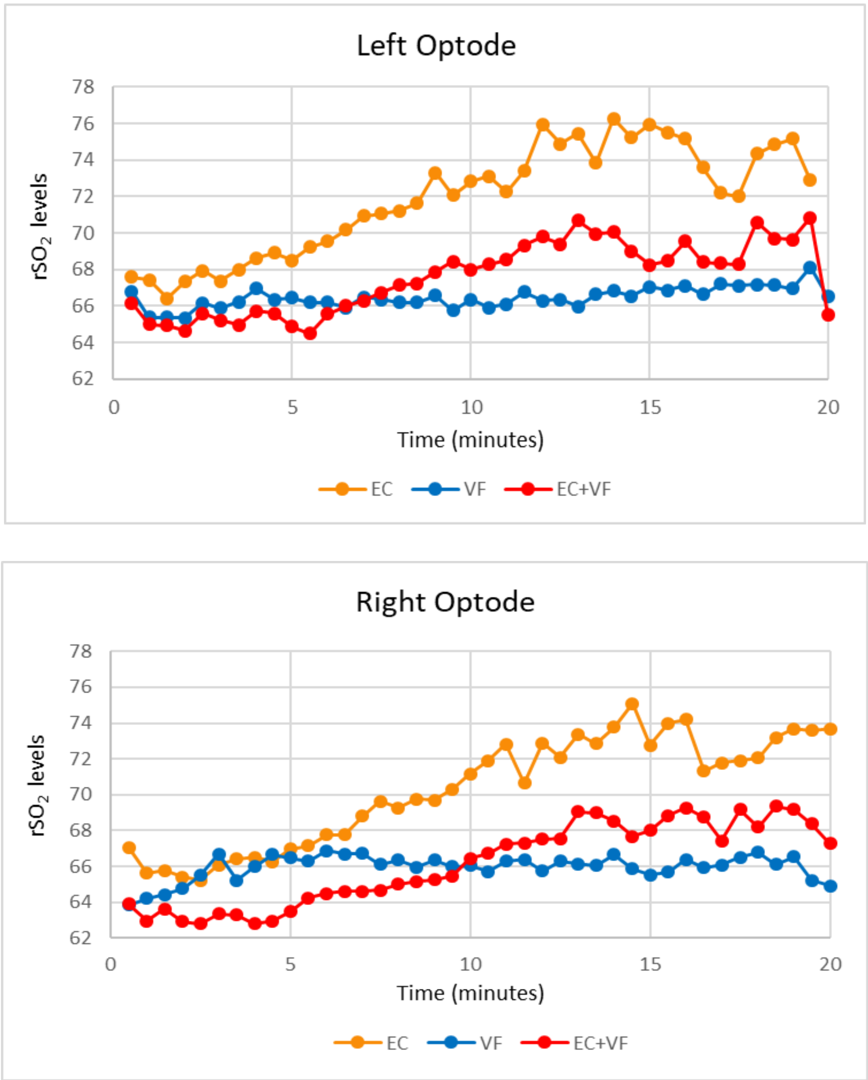
Mauchly's Test revealed a violation of the sphericity assumption, $W = .43$, $\chi(2) = 32.47$, $p < .001$; hence, a Greenhouse-Geisser adjustment was applied, $\varepsilon = .64$. A main effect of condition was found, $F(1.27,162.19) = 156.70$, $\eta_p^2 = .80$, $p < .001$. Bonferroni-corrected pairwise comparisons indicated that EC resulted in significantly greater right PFC activation than EC+VF, $t(39) = 18.00$, $SE = .24$, $p < .001$, and VF, $t(39) = 12.66$, $SE = .43$, $p < .001$. Further, right PFC activation was significantly higher in EC+VF compared to VF, $t(39) = 4.13$, $SE = .27$, $p < .001$.

4.4.1.5.3 Left and Right PFC rSO2 Levels – Correlations.

There were positive correlations between left and right PFC rSO_2 Levels for EC, $r(40) = .94$, $p <.001$, and EC+VF, $r(40) = .89$, $p <.001$. However, there was no correlation revealed between left and right PFC for VF, $r(40) = .23$, $p =.159$.

Figure 4.10

rSO_2 by Condition

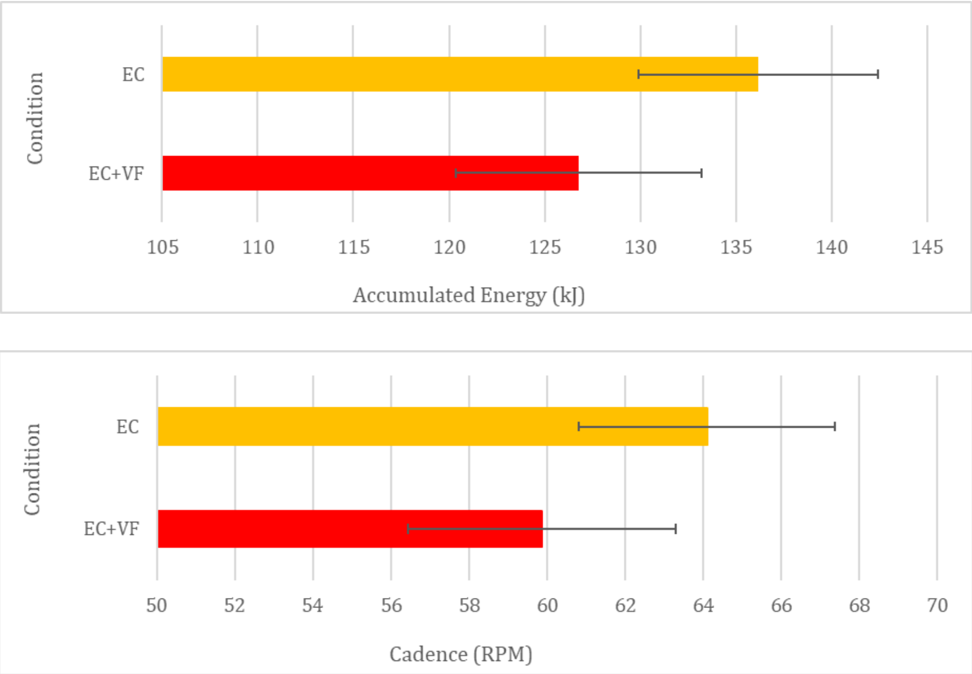


4.4.1.6 Accumulated Energy and Cadence Levels by Condition

A paired samples t-test revealed significantly greater accumulated energy during EC than during EC+VF, $t(16) = 2.31$, $p = .035$. A separate paired samples t-test also revealed that average cadence was higher during EC than in EC+VF, $t(14) = 2.78$, $p = .015$. Figure 4.11 illustrates average energy levels and cadence in the EC and EC+VF conditions. Correlations revealed a moderate correlation between accumulated energy and cadence during both cycling conditions, $r(17) = 0.60$, $p = .007$. Considering this relationship, and the differences between conditions, plus the differential effect of the cycling conditions on PFC oxygenation, we performed exploratory correlations to investigate potential relationships between accumulated energy and cadence with rSO_2 levels. There were no significant correlations between accumulated energy and rSO2 in the EC or EC+VF conditions, *p*'s > .05. In the EC condition, cadence and rSO_2 levels in left PFC, $r(17) = .73$, $p < .001$, and right PFC, $r(17) = .69$, $p = .001$, were moderately correlated. There were no significant correlations between cadence and rSO_2 in the EC+VF condition, *p*'s > .05.

Figure 4.11

Mean (± SE) Accumulated Energy (kJ) and Cadence (rpm), by Condition



4.5 Discussion

The aim of this study was to determine whether dual-task exercise comprising ergometer cycling and a visual foraging task (EC+VF) could enhance EF task performance, relative to ergometer cycling (EC) or visual foraging (VF) in isolation. Individuals with poorer baseline inhibitory control benefited most from the EC intervention compared to those with higher baseline scores. The cycling-based conditions (EC and EC+VF), increased arousal levels more than the VF condition, and PFC oxygenation levels were correspondingly higher, too; more so in the EC condition. Moreover, during the EC+VF condition, rSO_2 levels in the left and right PFC were correlated with the number of gaze fixations.

However, the above differences this did not manifest in EF task performance, albeit the time x condition interaction for Flanker task performance approached significance (*p* = .085). However, there was a condition x time x covariate interaction for the Flanker task: As participants' baseline Flanker task performance worsened, the greater the improvements in their performance post-intervention. In their review, Ishihara and colleagues (2021) reported similar findings: when children performed well in cognitive tasks at baseline, the benefits of acute exercise interventions were not as pronounced. Our findings, together with those of Ishihara et al., suggest that, in future work, researchers should consider individual differences in executive function.

The EC and EC+VF conditions elicited higher subjective arousal than the VF condition. However, the increased arousal levels in this present investigation were not associated with improvements in EF task performance, contrary to previous suggestions (Basso & Suzuki, 2017). Relatedly, Hacker and colleagues (2020) examined the relationship between ergometer cycling durations, EF task performance and subjective arousal and found no relationship between the latter and information processing speed; they suggested that heightened arousal levels might not promote neural adaptations required for cognitive performance improvements. The authors also suggested that increases in cerebral blood flow could be a potential mechanism for exercise-induced cognitive improvements; contrarily, subcortical mechanisms appear to determine subjective arousal (e.g., the amygdala; Wing et al., 2018). Relatedly, there were no correlations between pre-to-post changes in self-reported arousal and PFC rSO_2 in the present study.

PFC rSO_2 levels increased significantly in the EC and EC+VF conditions relative to the VF condition, but this did not translate into EF task performance improvements (cf. Moriarty et al., 2019). Exercise-induced improvements in EF performance have been associated with increased cerebral blood flow, which appears to improve frontoparietal EF network efficiency (Tari et al., 2020) – which can be improved with long-term training. For example, Liu and colleagues (2023) reported that 12 weeks of moderate intensity cycling improved participants’ Trail Making Task performance, including young adults at their cognitive peak. Byun and colleagues reported similar findings, showing that cortical activation in the left dorsolateral PFC (lDLPFC) increased after cycle ergometer exercise, which also corresponded with improved cognitive task performance.

Our findings also showed that PFC oxygen saturation increased throughout the course of the cycling intervention (EC and EC + VF), although the increases over time were more linear in left PFC; changes in right PFC were more variable, as reflected in the absence of a correlation between left and right PFC rSO_2 values. Left DLPFC is involved in performance of working memory-based executive tasks (Kane & Engle, 2002). However, unlike during the VF condition, both cycling conditions elicited bilateral prefrontal activation, and left and right PFC rSO_2 levels were correlated accordingly. Left DLPFC is strongly implicated in top-down control of attention (Knight et al., 2020), and arises from acute exercise bouts (Moriarty et al., 2019; Zhang et al., 2021); hence, we might have expected to see such lateralization during the combined condition, but this was not the case.

The increases in PFC activation during the EC condition may reflect greater cerebral blood flow resulting from higher exercise intensities (Moraine et al., 1993; Raasch & Zajac, 1999). Despite the overt requirement for participants to maintain a cadence of 60 rpm in both cycling conditions, average cadences and accumulated energy were higher in the EC condition than in EC + VF (NB: the two are closely related; Moore et al., 2008). It is possible that, in the combined condition – a dual-task paradigm, effectively – the VF task acted as a distractor from the physical task, thereby impeding performance of the latter; such trade-offs are commonly observed in studies of dual-task performance (Hogg et al., 2022; Kimura & Matsuura, 2020). Relatedly, we observed correlations between cadence and bilateral rSO_2 levels in the EC condition, lending support to the notion that increased blood flow when cycling exercise might have facilitated oxygen turnover. Furthermore, the EC condition elicited greater increases in PFC $rSO_{2,}$ cadence and accumulated energy than the EC+VF condition, suggesting higher exercise intensities (cf. Ludyga et al., 2016), albeit ones that were not reflected in participants' subjective arousal.

The above finding could also partly explain the observed correlation between PFC rSO_2 levels and the number of gaze fixations in the EC+VF condition. Increased oxygen demand in PFC due to greater top-down control of visual attention arguably elicits smaller changes in blood flow than the more intense exercise stimulus, which causes macroscopic vasodilation (Claassen et al., 2021; Ogoh & Ainslie, 2009). Hence, when we considered the reduced cadence and accumulated energy in the EC + VF condition, there is greater scope for the VFT task to exert effects on prefrontal oxygen demand. Indeed, our complex VF task, which comprised 40 similar and sometimes overlapping shapes, which possibly increased interference between target stimuli and distractors – a phenomenon that increases frontal lobe-mediated top-down control (Lavie & Fockert, 2006).

A limitation of this study may be the selected EF tasks. The complexity of EF tasks may influence the quality of the associated outcome measures (McMorris & Hale, 2012), hence, employing more sophisticated tasks may yield larger effects (McMorris & Graydon, 2000; Dietrich, 2003; McMorris & Hale, 2012). Our findings suggest that the EF tasks were relatively low in complexity, resulting in a near-ceiling effect in participants' performance. For example, average pre-test scores for the 2-Back and Flanker tasks were 89% and 96%, respectively, leaving limited scope for improvement. For this reason, higher-order EF task measures, such as those requiring reasoning and problem-solving (Hacker et al., 2020), may be more appropriate.

Dual-task interventions comprising physical and cognitively demanding tasks improve cognitive abilities in children and adolescents (Wollesen et al., 2022), including children with ADHD (Benzing et al., 2018) and autism (Anderson-Hanley et al., 2011). Given the putative contributions of physical activity to academic achievement (Latino &

Tafuri, 2023), and of commuter cycling to physical activity levels (Menai et al., 2015), it may be prudent to examine the effect of combined cycling and visual foraging interventions on children's cognitive performance, employing more sophisticated cognitive performance measures.

4.6 Conclusion

Individual differences in inhibitory control may mediate exercise-induced improvements in executive function following a brief bout of moderate intensity cycling. However, the attentional demands of visual foraging while cycling may have reduced attention to the latter, and participants' physical output accordingly. Consistent with previous studies, cycling increased both self-reported arousal and prefrontal oxygenation, although these two metrics were uncorrelated. Given the relationship of oxygen saturation with gaze behaviour in the combined condition only, we tentatively propose that whilst an exercise stimulus may increase the supply of oxygen to PFC, increased top-down attentional demands while visual foraging may increase the demand for that oxygen.

CHAPTER 5. THE EFFECT OF ERGOMETER CYCLING AND VISUAL FORAGING ON CHILDREN'S EXECUTIVE FUNCTION AND ACADEMIC REASONING SKILLS

5.1 Abstract

Introduction - An acute bout of ergometer cycling exercise appears to improve adults' executive function. The aims of this study were to explore whether ergometer cycling interventions might elicit similar improvements in children, and whether performance on academic reasoning tasks could benefit similarly.

Method - On two separate laboratory visits, 20 participants (11 females, mean age = 13.19 years, SD = 1.17) performed 20 minutes of ergometer cycling (EC; at 60% HRmax) or combined ergometer cycling and visual foraging (EC+VF; EC also 60% HRmax) in a counterbalanced order. Before and after the intervention, participants completed the Flanker Task (inhibitory control), the 2-Back Task (working memory), and verbal and nonverbal reasoning tasks. Participants reported their affective state pre- and post-intervention using the Affect Grid.

Results - Repeated measure ANOVAs revealed no condition x time interactions in the EF tasks, reasoning tasks or affect. Individual differences may have masked genuine interactions. There were negative correlations between participants' pre-intervention scores and pre-to-post-intervention changes in their scores, for the Flanker Task and verbal and nonverbal reasoning efficiency in the EC condition, and verbal reasoning efficiency in the EC+VF condition. A main effect of Condition was revealed for the Flanker Task and nonverbal reasoning percent correct in the EC condition, and a main effect of Time for the 2-Back task correct matches, verbal reasoning percent correct, and nonverbal reasoning completion time.

Discussion - The reasoning task relationships suggest that participants who performed inferiorly in these tasks during the pre-test benefited most from the interventions; on the

contrary, individuals with better inhibitory control abilities may benefit more from the interventions.

Keywords: Adolescents, Affect Grid, Children, Cognitive, Dual-Task, Nonverbal Reasoning, Verbal Reasoning

5.2 Introduction

Simultaneous integration of physical and cognitive tasks has become a popular paradigm for studying real-life multitasking scenarios that children commonly encounter (e.g., cycling while navigating; Wollesen et al., 2022). Physically active children (e.g., those who actively commute to school) outperform their non-active counterparts academically (Buck et al., 2008; Donnelly et al., 2016; Hillman et al., 2009) as evidenced by Hillman and colleagues (2009), who demonstrated the use of moderate intensity treadmill exercise to increase attention and academic success. Moreover, both chronic and acute exercise enhance children's executive function (EF) performance (Best, 2010; Hillman et al., 2009), and evidence is increasing for the positive long-term impact of combining physical tasks with cognitive ones – effectively, a dual-task paradigm (Hofheinz et al., 2016) – on children's EFs (Anderson-Hanley et al., 2011; Benzing et al., 2018; Nejati & Derakhshan, 2021; Wollesen et al., 2022). In their recent review, Wollesen and colleagues (2022) suggested that researchers should explore current gaps in dual-tasking research, such as its effects on cognition during adolescence and explore different secondary tasks for the intervention.

EFs are a set of mental abilities comprising three broad components: *inhibitory control* (regulating thoughts, feelings, and actions to adapt to surroundings), *working memory* (updating outdated data with novel information), and *cognitive flexibility* (adjusting behaviours according to environmental/task demands; Diamond, 2013; Miyake et al., 2000). Accumulated evidence shows a small positive effect of acute exercise on cognition (Chang et al., 2012; Dkaidek et al., 2023), predominately on EFs associated with prefrontal cortex (PFC) activation (Basso & Suzuki, 2017). EFs emerge in the early years of life, and the three components of inhibitory control, working memory and cognitive flexibility develop at variable rates throughout childhood and adolescence (Best & Miller, 2010). Despite this developmental variability, there is evidence that acute aerobic exercise enhances children's performance in EF tasks (Martins et al., 2021). However, some studies suggest that EF tasks which only assess one EF component in isolation (e.g., Flanker Task, 2-Back Task, Stroop Task, Wisconsin Card Sorting Task) may not be appropriate tests of improvements in cognitive function because of ceiling effects in the performance of these tasks (Dkaidek et al., 2024; Hacker et al., 2020) .Therefore, it is prudent to explore the effects of acute aerobic exercise on higher-order tasks that engage multiple EF components (Diamond, 2013).

Although individual studies show that performance of lab-based EF tasks is associated with academic success (Gordon et al., 2018; Gunzenhauser & Nückles, 2021), a recent meta-analysis concluded that training EFs rarely predicts academic success or real-world outcomes (Aksayli et al., 2019). Niebaum and Munakata (2023) suggested that interventions should incorporate content relevant to desired performance contexts, albeit still engaging EFs, to maximise the benefits for academic achievement. For example, higher-order thinking abilities, such as a child's reasoning ability, influence knowledge acquisition and academic achievement (Gómez-Veiga et al., 2018). Learning in the classroom is influenced by reasoning abilities as it plays a role in understanding and addressing new, complex problems (Gómez-Veiga et al., 2018; Greiff & Neubert, 2014). Reasoning can be differentiated into two subcomponents: verbal reasoning (e.g., semantic problem-solving abilities) and nonverbal reasoning (e.g., visuospatial problem-solving abilities; Brookman-Byrne et al., 2019; Gómez-Veiga et al., 2018). Gómez-Veiga and colleagues (2018) showed that, although verbal reasoning skills may predict academic performance, abstract reasoning skills (e.g., nonverbal reasoning and cognitive reflection) appear to be even stronger predictors; hence, abstract reasoning may be a key higher-order cognitive skill that underpins academic success. Therefore, it is worthwhile to explore the impact of acute exercise on verbal and nonverbal reasoning skills.

Research shows that dual-tasking may enhance children and adolescents' cognitive performance and academic achievement (Wollesen et al., 2022). Dual-tasking paradigms typically comprise a cognitive secondary task that places attentional and/or cognitive demands on the individual, one that may distract attention or effort from the physical task (Dkaidek et al., 2024a). For the secondary task to be more ecologically valid, i.e., one that might be encountered in real-world situations (e.g., navigating busy streets while cycling), its task should reflect the attentional and/or cognitive demands of those situations. Visual foraging tasks (VFTs) comprises visual search for multiple targets that requires both selective and divided attention (Jóhannesson et al., 2016; Kristjánsson et al., 2014; Ólafsdóttir et al., 2016). Ólafsdóttir and colleagues (2016) compared children’s foraging ability relative to that of adults and whether foraging ability rely on EF abilities. They found that foraging abilities were comparable in older children and adults, and also that foraging abilities was positively associated with attentional flexibility and working memory. The authors suggested that VFTs may help us to understand visual attentional allocation during real-world contexts and its link with cognitive functions.

Dkaidek and colleagues (2024a) developed a VFT based on those used by Kristjánsson and colleagues (2019) to investigate the effects of visual foraging and acute cycling exercise combined on EFs. Their task comprised dynamic, multitarget foraging to reflect the complex nature of visual attention allocation in dynamic environments such as cycling on roads. Specifically, the task comprised conjunctive foraging, requiring participants to identify target stimuli according to preidentified shape-colour combinations (e.g., yellow triangles). The authors found that acute cycling exercise resulted in more significant energetic investment relative to the combined condition, suggesting that performance of the VFT might have distracted attention, and consequently effort, from the cycling task. They also demonstrated that during the combined condition, PFC activation correlated with gaze fixations, which possibly demonstrates that, while the cycling exercise increased blood flow to the PFC, the increased top-down control of eye movements during the VFT may have concurrently increased PFC demand for oxygen. Combining a VFT task with cycling exercise relative to the latter in isolation may provide us with insights regarding attentional demands during real-world cycling, and the potential consequences for their subsequent cognitive function.

Arousal theories predict that acute exercise has the potential to significantly improve cognitive performance, depending on resource allocation and task demands (e.g., Yerkes and Dodson, 1908; Kahneman, 1973). If perceived available resources are too low to meet the task demands, this may result in mental fatigue (Brown & Bray, 2019) or ego depletion (Baumeister et al., 2000). Mental fatigue refers to a lack of energy and a feeling of exhaustion after engaging in a demanding cognitive task requiring extended concentration, which may result in an increased risk of error and worsened cognitive performance (Harris & Bray, 2019; Van Cutsem et al., 2017). Such fatigue may cause the individual to adjust the amount of physical effort they are willing to invest during exercise to cope (Brown & Bray, 2019). Mortimer and colleagues (2024) explored the effect of isolated physical, isolated mental fatigue and combined mental and physical fatigue on the performance of a psychomotor vigilance task. Their findings demonstrated that mental fatigue was more detrimental to task performance than combined fatigue, implying that the physical exercise component might mitigate the adverse effects of mental fatigue.

Similarly, the concept of *ego depletion* may also explain inferior task performance after prolonged mental exertion (Giboin & Wolff, 2019). Ego depletion suggests that if high levels of self-control are expended on one task, then self-control in subsequent tasks will diminish, and individuals will aim to conserve remaining resources rather than becoming exhausted (Baumeister et al., 2000). However, it is difficult to assess mental fatigue and ego depletion as several covariates including engagement, enjoyment, task difficulty, durations and various individual differences affect induced mental fatigue and ego-depleting states (e.g., physiological and subjective variables; Lambourne & Tomporowski, 2010). For this reason, affective response may be a quick and effective option, especially considering the role affect plays in exercise-induced EF improvements (Lambourne & Tomporowski, 2010). Considering that exhaustion is a highly negative affective state, assessing affect may help us understand the effects of mental fatigue and ego depletion on post-intervention task performance (Mangin et al., 2021).

The aim of this study is to investigate the effects of combining ergometer cycling with a VFT (EC+VF), and ergometer cycling (EC) in isolation, on children's EF task performance and affect. And considering the potential limitations of EF tasks, a second aim was to assess the differential effects of these interventions on verbal and nonverbal reasoning skills – higher-order EFs. We hypothesised that both conditions would improve EF task performance, academic reasoning task performance and affect. However, given the additional cognitive and attentional demands posed by dual tasking, we also proposed that ergometer cycling in isolation would have the greatest effect.

5.3 Method

5.3.1 Design and Participants

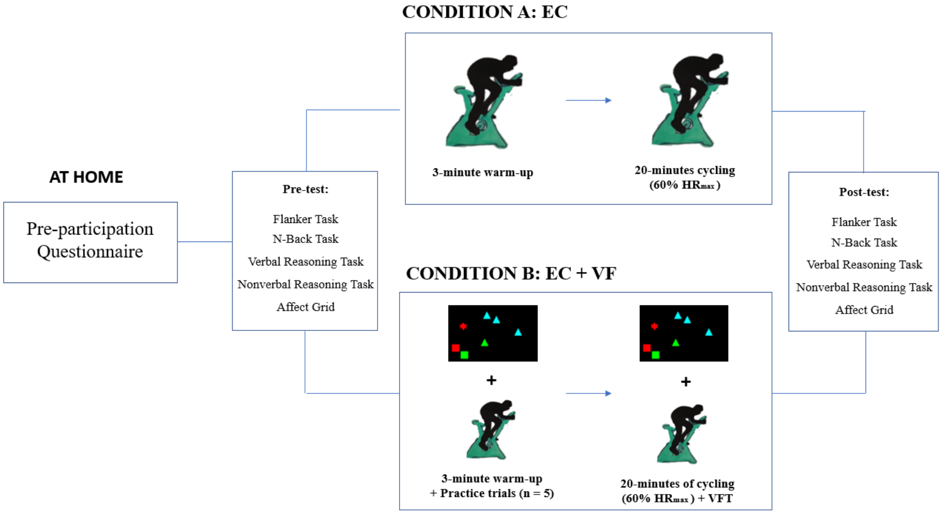
Required sample size was estimated using a repeated measures ANOVA on G*Power 3.1 (Faul et al., 2007). The published effect size was estimated based on the same effect sizes used in studies comparing EC and EC+VF (Dkaidek et al., 2023, 2024a). The parameters were as follows: $\alpha = 0.05$, power $(1-\beta) = 0.80$ Cohen's $f > 0.252$ for a 2 x 2 repeated measures ANOVA (Condition [EC, EC+VF] x Time [pre-, post-]). The analysis yielded an estimated sample size of 20.

Hence, 20 children aged 11-15 years (mean age = 13.19 SD = 1.17 years; 11 females) took part. All participants attended a secondary school in west London, UK, and were free from injury, had no cardiovascular, neurological, or pulmonary disorders, and reported normal or corrected-to-normal vision and hearing. A range of ethnicities were reported including Indian (11), Asian-Other (4), Asian-British (2), Bangladeshi (1) and Sikh Afghan (1); one participant chose not to report their ethnicity. One child reported a diagnosed learning difficulty without specification.

Participants reported their physical activity levels using the Modified International Physical Activity Questionnaire (IPAQ short form, 2016; Booth, 2000; cf. Craig et al., 2003). Average metabolic equivalent (MET) scores were derived from the IPAQ data. The average vigorous physical activity level was 1738.60 ± 1558.51 MET-minutes per week (Range: 0 – 3348.51); for moderate physical activity, it was 1038.14 ± 894.01 MET-minutes per week (Range: 0 – 2790.70), and the level for walking was 1573.87 ± 749.41 MET-minutes per week (Range: 460.47 – 856.94). Correspondingly, 11 participants were categorised as exhibiting high levels physical activity levels, 9 as moderate and none as low. Figure 5.1 illustrates the study design. Participants completed the two experimental conditions in two separate lab visits.

Figure 5.1

Study Design



5.3.2 Equipment, Materials and Measures

5.3.2.1 Executive Function Tasks

The EF tasks were displayed on a Dell laptop (Vostro 15 3000) with a 15.6-inch display and a resolution of 1920 x 1080. It bisected 36.23° of visual angle in the horizontal plane and 17.54° of visual angle in the sagittal plane at a viewing distance of 45 cm. Participants provided trial-by-trial responses for each task by pressing keys on a UK QWERTY keyboard. The tasks were created using Psytoolkit (Stoet, 2010, 2017).

5.3.2.1.1 Flanker Task

This task examines inhibitory control (Eriksen & Eriksen, 1974). It consisted of 128 trials in which a central target arrow was presented, flanked on both sides by a pair of distracter arrows (Ridderinkhof et al., 2021). A central fixation point was underneath each set of arrows. Sixty-four trials were congruent (the central arrow pointed in the same direction as the other arrows; see left image in Figure 5.2), and 64 were incongruent (the central arrow pointed in the opposite direction; see right image in Figure 5.2). The presentation of these trials occurred in a randomised order across two blocks of 64 trials. Participants were instructed to press the 'A' key if the target arrow pointed to the right and to press the 'L' key if the middle arrow pointed to the left. The central fixation point turned green for 150 ms if the participant answered correctly and flashed red for 300 ms if they answered incorrectly.

The ‘Flanker Effect’ was determined as the difference between reaction times for congruent and incongruent trials. This interference effect is related to inhibitory control through individual differences in PFC involvement (Forstmann et al., 2008; Ridderinkhof et al., 2021).

Figure 5.2

Flanker Task Trial Example Stimuli – Congruent (left image) and Incongruent (right image)

5.3.2.1.2 2-Back Task

This task assesses working memory (Kirchner, 1958). The task comprised one block of 25 trials (not including familiarisation and practice trials), in which each trial was presented for 500 ms; new stimuli appeared automatically every 3000 ms. Participants were instructed to press the 'M' button on the keyboard if they believed the current letter was identical to the one presented two trials earlier. If the letters differed, the participants were instructed not to press any keys. Each letter was surrounded by a grey border at the top and bottom, which flashed green if they answered correctly (rightmost image of Figure 5.3); the border flashed red if incorrect. Accuracy was determined for correct-match trials as the percentage of ‘hits’ (correct matches), using the formula (hits/(hits + errors)) x 100; time was calculated as the participant’s average response time for match trials.

Figure 5.3

2-Back Task Example

5.3.2.2 Academic Reasoning Tasks

Verbal and nonverbal reasoning were assessed separately, using papers similar to those used as examinations for children aiming to gain entry to selective schools in England (BOND 11+ tests; Oxford University Press, 2020). There were two versions of the verbal reasoning task (A & B) and the nonverbal reasoning task (A & B), in which the running order of pre- and post-intervention tasks were counterbalanced within and across participants. Participants were allowed a maximum of ten minutes to complete each task. Participants’ accuracy and completion time were recorded for both tasks.

5.3.2.2.1 Verbal Reasoning

Twenty questions were presented, collectively representing the following categories: *Sorting Words*, *Selecting Words*, *Anagrams* and *Coded Sequences and Logic*. Table 5.1 provides an example of each category.

5.3.2.2.2 Nonverbal Reasoning

Twelve multiple choice questions were presented. The categories comprised *Similarities*, *Analogies*, *Sequences*, *Symmetry* and *Codes*. An example of each section can be found in Table 5.2.

Table 5.1

Verbal Reasoning Categories

Sorting Words	Underline the two words which are the odd ones out in the following groups of words. **lane path pedestrian car way**
Selecting Words	Move one letter from the first word and add it to the second word to make two new words. **parking night ______ ______**
Anagrams	Rearrange the letters in capitals to make another word. The new word has something to do with the first two words. **scanty, scarce SPARES ______**
Coded Sequences and Logic	Fill in the missing letters. **AX is to CX as HS is to ______**

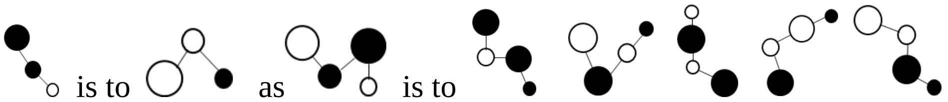
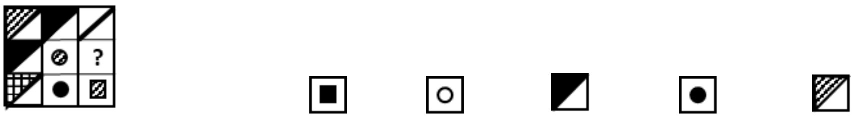
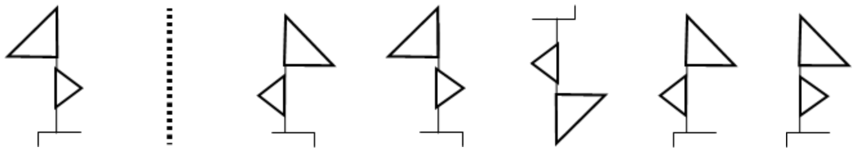
Note: From. BOND 11+ 10 Minute Tests; Oxford University Press, 2020.

5.3.2.3 Affect

The Affect Grid, developed by Russell and colleagues (1989) and based on Russell's Circumplex Model of Affect (1980), is a single-item measure comprising a 9-by-9 grid on which participants self-report their momentary affective state. The Affect Grid has been used in exercise-based contexts (Bishop et al., 2009, 2014; Dkaidek et al., 2024a) and incorporates two orthogonal dimensions –affective valence (pleasure-displeasure) and perceived activation (arousal), creating four quadrants: *high activation-low valence*, *high activation-high valence*, *low activation-high valence* and *low activation-low valence*. Participants reported their affective state by marking a cross in one square of the Affect Grid.

Table 5.2

Nonverbal Reasoning Categories

Similarities	Which pattern on the right belongs in the group on the left?  **a b c d e**
Analogies	Which shape or pattern on the right completes the second pair in the same way as the first pair?  **a b c d e**
Sequences	Which shape or pattern completes the larger square?  **a b c d e**
Symmetry	Which shape on the right is the reflection of the shape given on the left?  **a b c d e**
Codes	Which code matches the shape or pattern at the end of each line?  AX AY BZ CY BX ? BZ AZ CX BY CZ **a b c d e**

Note: From. BOND 11+ 10 Minute Tests; Oxford University Press, 2020.

5.3.2.4 Maximum Heart Rate/Exercise Intensity Determination

Heart rate (HR) was continuously monitored throughout the study using a Polar Bluetooth Smart chest strap (Polar Electro Oy, Professorintie, 90440 Kempele, Finland). Each participant's maximum HR (HR_{max}) was determined using Tanaka's (2001) formula:

208-0.7(age) (Cicone et al., 2019; Mahon et al., 2010). Exercise intensity was set at 60% of the participant's HR_{max}.

5.3.2.5 Cycle Ergometer

All cycling was completed on a Monark 874E ergometer. Safety mats were positioned on both sides of the ergometer throughout the protocol. Participants stood on weighing scales (Seca 875, Hamburg, Germany) for the researcher to record their bodyweight to enable calculation of correct cycle ergometer loads. Participants warmed up at a self-selected intensity for 3 minutes before they were instructed to maintain a cadence that elicited an HR corresponding to 60% of their HR_{max} at a workload of 1.2W per kg of body mass.

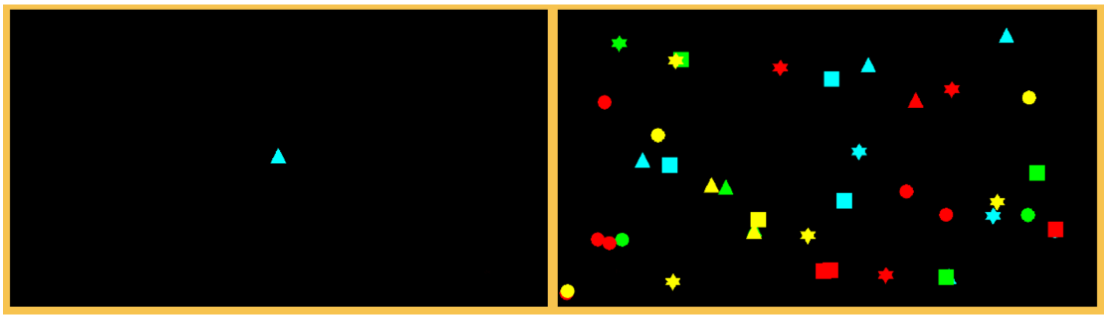
5.3.2.6 Visual Foraging Task (VFT)

The VFT task developed by Dkaidek et al. (2024a) was used. The task was developed on a game development software called Clickteam Fusion 2.5. The VFT was designed based on those used by Kristjánsson and colleagues (2019). The VFT encompassed multitarget and dynamic conjunctive foraging, aimed to mimic a visual search in the real world. Each VFT trial included 40 moving shapes, a number determined by Kristjánsson and colleagues' (2020) findings to present moderate-difficulty levels.

The VFT was presented on a wall-mounted Smart Board measuring 2.21 m in width and 1.96 m in height, positioned 2.30 meters away from the participant seated on the ergometer. It bisected 51.13° of visual angle in the horizontal plane and 38.87° in the vertical plane. A collection of 40 moving shapes – specifically, triangles, stars, squares and triangles coloured blue, green, red or yellow – on a black background – were presented at each trial to identify a specific colour-shape conjunction target stimulus. Before each trial, a colour-shape target, for example, a blue triangle, would flash for three seconds on the screen. In this instance, the participant must identify all blue triangles in that trial (see Figure 5.4). There was at least one target stimulus per trial and a maximum number of six. The length of each trial was 6 seconds, and the target colour-shape combination changed in each trial. Participants were instructed to verbally report the number of target colour-shape stimuli they found at the end of each trial; responses were marked as correct if their response corresponded with the actual value. Trials were presented in six blocks of 20 trials –120; there were 25-second breaks between blocks. Overall scores were calculated as the percentage of correct responses in the trials.

Figure 5.4

VFT Trial Example (blue triangle target; correct answer = 3)



5.3.3 Procedure

Institutional research ethics committee approval was obtained prior to data collection. Parents/carers and children provided their informed consent and answered health-related questions, demographics, the IPAQ and cycling efficacy questions via an online questionnaire (*Joint Information Systems Committee (JISC) Online Survey Platform*, 2023) before the child's arrival at the testing room.

Participants took part during school lessons. Upon entering the testing room, the participant was invited to sit at a desk where they were given a brief overview of the session. The researcher explained the protocol to the participant – this varied slightly according to experimental condition – and answered any questions they had; they also gave the participant the opportunity to express their desire to withdraw and reiterated that they could do so at any time. Participants started with familiarisation trials of the EF and reasoning tasks until they felt confident, followed by five practice trials of the two EF tasks and one question from each subsection of the reasoning tasks. The running order of the reasoning and EF tasks was counterbalanced across participants.

After measuring the participant's body mass, the researcher explained how to put on and adjust the chest strap HR monitor before indicating the target HR they should reach and then maintain throughout the protocol. Thereafter, the participant mounted the cycle ergometer and adjustments to saddle height were made according to their comfort.

If the participant was happy to proceed, they were told to commence their warmup followed by either ergometer cycling (EC) or ergometer cycling + visual foraging (EC+VF)**.** The researcher provided no feedback to participants during the protocol. Once the participants had completed the intervention, they dismounted the ergometer and completed the Affect Grid, verbal and nonverbal reasoning tasks, and EF tasks for a second time.

5.3.3.1 EC Condition

The exercise session started with a self-paced 3-minute warm up period with no resistance (Ellemberg & St-Louis-Deschênes, 2010; Kunzler & Carpes, 2021; Martins et al., 2021), during which the participant gradually raised their HR to 60%HR_{max} (Ellemberg & St-Louis-Deschênes, 2010). The researcher adjusted the loads to maintain target HR range during the protocol and the workload was gradually increased to 1.2 W/kg by adding resistance in 0.1 kg increments as required. Participants cycled at this intensity for 20 minutes. At the end of the 20 minutes, the participant performed a 3-minute self-paced cooldown.

5.3.3.2 EC+VF Condition

Participants completed a minimum of five VFT familiarization trials. Thereafter they performed a self-paced warm up for three minutes before completing the same EC protocol as in the **EC Condition** while simultaneously performing the VFT. Participants also performed a 3-minute self-paced cooldown after completing this condition.

5.3.4 Data Analysis

All statistical analyses were conducted using IBM SPSS software (IBM Corp., 2023). Because the academic verbal and nonverbal reasoning tasks are typically performed under time pressure and to avoid a speed-accuracy trade-off, an Efficiency Index was calculated as *percentage of correct items / completion time*. We also ran a secondary analysis investigating reasoning percent correct and completion time in isolation to reveal if errors or slower completion times influenced overall efficiency. Mean (SD) pre- and post-intervention values were reported for these tasks, for the EF tasks, and for self-reported affect (i.e., pleasantness and arousal scores).

Separate 2 x 2 repeated measures ANOVAs (Condition [EC, EC+VF] x Time [pre-, post-]) were used to analyse the Flanker Effect, 2-Back Correct Matches, 2-Back Response Time, verbal reasoning efficiency, nonverbal reasoning efficiency and self-reported arousal and pleasantness.

Dkaidek et al. (2024a) found differential effects of ergometer cycling on young adults' performance on EF tasks; specifically, participants with inferior baseline EF task performance exhibited greater improvements. For this reason, we ran correlational analyses to investigate potential relationships between participants' pre-intervention scores and pre-to-post-intervention change scores on EF and academic tasks. Pre-to-post change scores were calculated as the difference between post-test and pre-test performance; larger change scores signify greater influence of the intervention.

Average scores of the visual foraging task (VFT) were calculated as the percent correct of the completed trials. Exploratory correlations were run between VFT scores and pre-to-post changes in the EF tasks, reasoning tasks and affect to assess if the VFT influences outcomes.

5.4 Results

5.4.1 Cycling Experience Data

Cycling experience data was gathered from each participant. The data revealed that 4 out of 20 of the children took part in formal cycling training prior to taking part in this study. Also, the children have been able to cycle for an average of 2.35 years (SD = 2.74, Range = 0 – 7 years), in which 9 out of 20 reported they have no years of cycling experience. There was a correlation between children with formal cycle training and their number of years cycling, $r(18) = 0.54$, $p = .013$.

5.4.2 Intervention – Manipulation Check

Participants cycled at an average cadence of 58.57 revolutions per minute (SD = 12.92), aiming to reach 60%HR_{max}. However, although the average target heart rate was 119.24 bpm (SD = 0.50, Range = 119-120, N = 20), the actual average was 141.70 bpm (SD = 20.50, Range = 109-180, N = 15) – an intensity closer to 70% HR_{max}. Not all HR data were collected as the monitor did not fit some of the children and, therefore, did not gather any HR data, and a couple of children requested not to wear the monitor (N = 5).

5.4.3 Measures

5.4.3.1 EF Tasks

Table 5.3 shows descriptive statistics for EF task measures.

Table 5.3

EF Tasks Descriptive Statistics, by Condition and Timepoint

	Pre-Intervention				***Post-Intervention***			
	Mean	**Median**	**SD**	**Range**	**Mean**	**Median**	**SD**	**Range**
EC								
Flanker Task								
Flanker Effect (ms)	47.1	36.0	63.9	226	41.7	30.0	48.1	184
2-Back Task								
Correct matches (%)	67.5	67.0	19.1	73.0	71.1	67.0	17.7	59.0
Response Time (ms)	1394	1320	568	2041	1217	1116	464	1429
EC+VF								
Flanker Task								
Flanker Effect (ms)	29.0	30.0	69.3	244	34.7	28.5	51.7	169
2-Back Task								
Correct matches (%)	65.3	61.5	16.0	56.0	73.1	73.5	19.0	56.0
Response Time (ms)	1266	1072	481	1856	1292	1180	548	2126

Note: The Flanker Effect is calculated as response times for incongruent stimuli minus those for congruent ones; hence, lower values represent better inhibitory control.

5.4.3.1.1 Flanker Task

A repeated measures ANOVA revealed no Condition x Time interaction (p = .299) or main effect of Time (p = .915). However, there was a main effect of Condition, F(1,15) = 4.95, η_p^2 = .25, p = .042. Follow-up pairwise comparisons showed that the participants in the EC condition (M = 48.3, SE = 14.1) had greater inhibitory control compared to those in the EC+VF condition (M = 31.1, SE = 14.9).

A negative correlation was found between pre-intervention Flanker Effect scores and pre-to-post-intervention changes in those scores for the EC condition, $r(18) = -.73$, $p < .001$, but not for the EC+VF condition, $r(18) = -.41$, $p = .073$, albeit that it approached significance. Hence, those with greater inhibitory control – i.e., those manifesting lower Flanker Effect values – made greater improvements.

5.4.3.1.2 2-Back Task

A repeated measures ANOVA revealed no Condition x Time interaction for correct matches on the 2-Back Task ($p = .397$) or main effects of Condition, ($p = .455$). However, there was a main effect of Time, $F(1,16) = 7.94$, $\eta_p^2 = .33$, $p = .012$, in which participants had greater working memory performance post-intervention ($M = 72.8$, $SE = 4.43$) relative to pre-intervention ($M = 67.7$, $SE = 4.17$).

No significant correlations emerged between pre-intervention 2-Back Correct Matches and pre-to-post-intervention changes in either the EC condition, $r(17) = -.39$, $p = .097$, or the EC+VF condition, $r(16) = -.04$, $p = .884$.

There was no Condition x Time interaction for 2-Back Task response time ($p = .149$) or main effects of Condition ($p = .59$) or Time ($p = .42$).

No significant correlations emerged between pre-intervention 2-Back RT and pre-to-post-intervention changes in either the EC condition, $r(17) = -.21$, $p = .384$, or the EC+VF condition, $r(16) = -.27$, $p = .278$.

5.4.3.1 Academic Reasoning Tasks

Table 5.4 shows descriptive statistics for reasoning task measures.

Table 5.4

Reasoning Tasks Descriptive Statistics, by Condition and Timepoint

	Pre-Intervention				***Post-Intervention***			
	Mean	**Median**	**SD**	**Range**	**Mean**	**Median**	**SD**	**Range**
EC								
Verbal Reasoning								
Percent Correct (%)	55.3	57.5	24.9	80.0	57.9	57.5	23.0	80.0
Completion Time (s)	507	570	110	290	490	502	115	340
Efficiency Index	0.11	0.11	0.06	0.21	0.13	0.10	0.07	0.22
Nonverbal Reasoning								
Percent Correct (%)	54.6	50.0	20.3	67.0	60.0	67.0	22.7	75.0
Completion Time (s)	410	392	150	422	374	360	122	390
Efficiency Index	0.15	0.14	0.08	0.24	0.17	0.19	0.07	0.24
EC+VF								
Verbal Reasoning								
Percent Correct (%)	47.6	42.5	22.7	85.0	73.9	73.5	18.9	56.0
Completion Time (s)	453	439	144	420	475	487	112	311
Efficiency Index	0.11	0.12	0.05	0.16	0.12	0.11	0.07	0.23
Nonverbal Reasoning								
Percent Correct (%)	49.5	54.0	18.4	75.0	44.7	54.0	22.5	75.0
Completion Time (s)	403	366	135	398	315	316	121	492
Efficiency Index	0.13	0.12	0.06	0.21	0.15	0.16	0.08	0.35

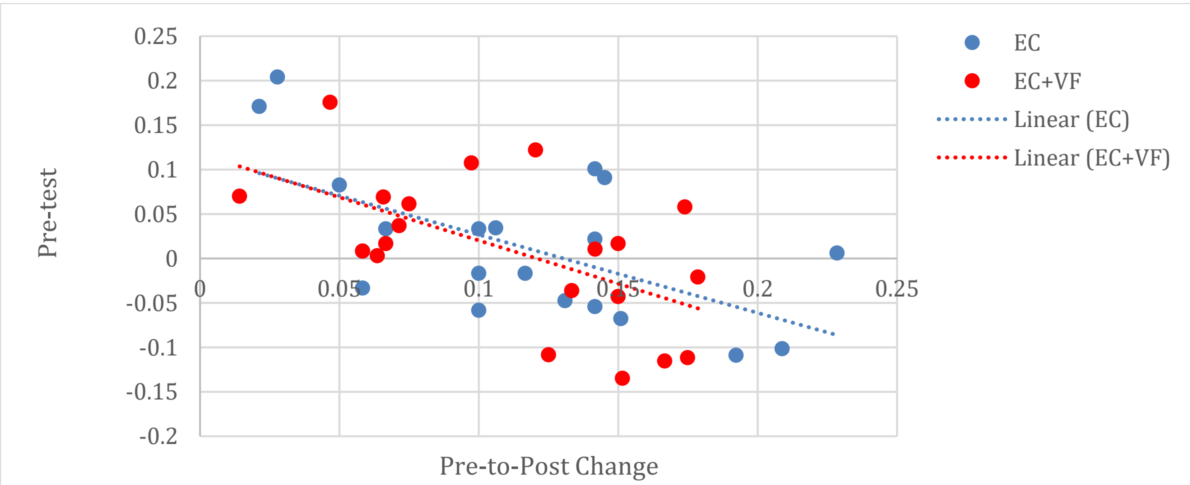
5.4.3.2.1 Verbal Reasoning

A repeated measures ANOVA revealed no Condition x Time interaction for verbal reasoning efficiency (p = .857) nor a main effect of Condition (p = .659) or Time (p = .391). Pre-test verbal reasoning efficiency and pre-to-post-intervention changes in efficiency were correlated in both the EC, $r(18) = -.60$, p = .005, and EC+VF, $r(18) = -.58$, p = .007, conditions. Both relationships are illustrated in Figure 5.5.

When investigating verbal reasoning accuracy, results revealed no Condition x Time interaction, $F(1,17) = 4.13$, $\eta_p^2 = .20$, p = .058, albeit this approached significance for an improvement after the EC+VF condition compared to before, $t(17) = 3.17$, SE = 7.39, p = .033. There was no main effect of Condition (p = .242). However, there was a main effect of Time, $F(1,17) = 6.25$, $\eta_p^2 = .27$, p = .023, revealing an improvement in verbal reasoning task percent correct post-intervention (M = 65.9, SE = 3.54) compared to before (M = 52.4, SE = 4.43), regardless of condition. Considering completion time, there was no Condition x Time interaction (p = .401), nor a main effect of Condition (p = .141), or Time (p = .898).

Figure 5.5

Verbal Reasoning Efficiency: Scatterplot of Pre-Intervention and Pre-to-Post-Intervention Change Scores.



5.4.3.2.2. Nonverbal Reasoning

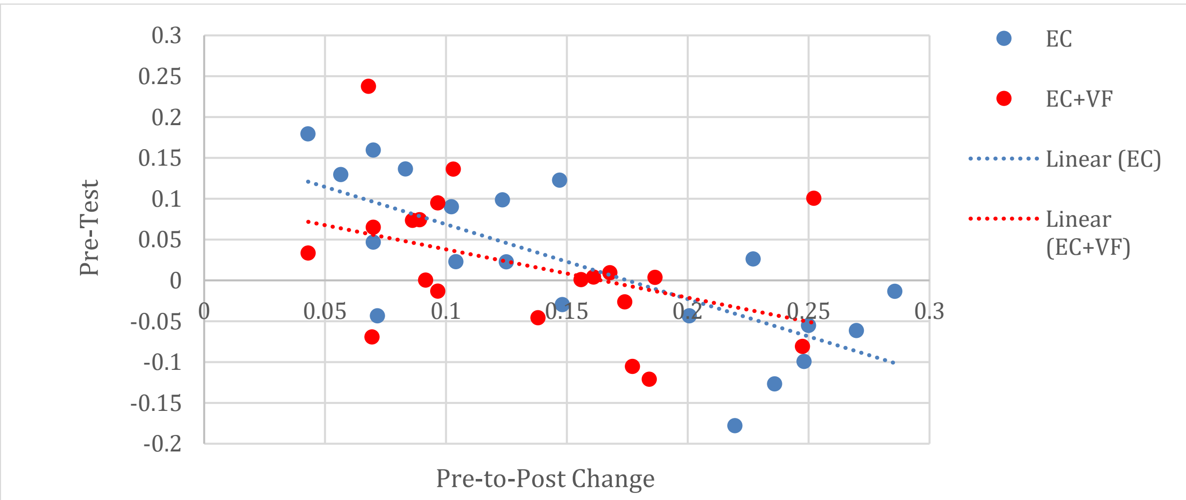
A repeated measures ANOVA revealed no Condition x Time interaction for nonverbal reasoning efficiency (p = .984), nor a main effect of Condition (p = .263), or Time (p = .214).

A correlation was revealed between pre-test and pre-to-post-intervention change scores in the EC condition, $r(18) = -.73$, $p < .001$, but not in the EC+VF condition, $r(18) = -.41$, p = .073, albeit that this approached significance. The correlation is shown in Figure 5.6.

When investigating nonverbal reasoning accuracy, there were no Condition x Time interactions for nonverbal reasoning percent correct (p = .200), or main effect of Time (p = .942). However, there was a main effect of Condition, $F(1,19) = 7.15$, $\eta_p^2 = 0.27$, p = .015, in which participants performed better in the EC condition (M = 57.3, SE = 3.58) compared to the EC+VF condition (M = 47.1, SE = 3.98). Further, considering completion time, there were also no Condition x Time interaction (p = .207), or main effect of Condition (p = .242). However, there was a main effect of Time, $F(1,19) = 12.90$, $\eta_p^2 = .40$, p = .002, revealing quicker completion times after the intervention (M = 345, SE = 26.3), compared to before (M = 406, SE = 22.0), regardless of condition.

Figure 5.6

Nonverbal Reasoning Efficiency: Scatterplot of Pre-Intervention and Pre-to-Post-Intervention Change Scores



5.4.3.1 Affect Grid Data

5.4.3.3.1 Arousal

A repeated measures ANOVA showed no Condition x Time interaction (p = .203), or main effects of Condition (p = .954), or Time (p = .11). Pre-to-post change in arousal levels for the EC and EC+VF conditions were correlated, $r(18) = .63$, $p = .003$, suggesting an increase in arousal regardless of the inclusion of a VFT.

5.4.3.3.2 Pleasantness

A repeated measures ANOVA revealed no Condition x Time interaction (p = .72), or main effects of Condition (p = .124), or Time (p = .449). There was a correlation between pre-to-post subjective pleasantness change in the EC and EC+VF condition, $r(18) = .70$, $p < .001$.

5.4.3.4 Visual Foraging Task (VFT)

The average score during the VFT was 25.8% (SD = 27.1%; Range = 5% - 89%). There were no correlations between VFT performance and pre-to-post changes in EF performance or affect; all p’s > .05.

5.5 Discussion

This study examined the differential effects of an acute bout of ergometer cycling (EC) compared to ergometer cycling and visual foraging tasks combined (EC+VF) on children’s executive function (EF) and academic reasoning task performance and affect. Notably, neither condition elicited significant improvements in any of the measures relative to the other. However, there were main effects of Time for the 2-Back correct matches, verbal reasoning percent correct and nonverbal reasoning completion times. This suggests that ergometer cycling per se may be an effective intervention, irrespective of the VFT, although we must not rule out practice effects.

The absence of a main effect of either intervention on EF task performance, albeit there were moderate improvements in most tasks from pre- to post-intervention (see Table 5.3), could be due to pre-existing individual differences in EFs. EF task performance tended to improve more post-intervention for participants whose pre-intervention scores were lower; such interindividual variability might have masked any differential effects of the two interventions. Specifically, pre-intervention scores for the Flanker Task, verbal reasoning efficiency and nonverbal reasoning efficiency were negatively correlated with pre-to-post changes in those variables. These findings suggest that individuals with poorer reasoning skills might have more to gain from EC interventions than those with superior reasoning skills in terms of their reasoning ability in the immediate term. Conversely, those with better inhibitory control (a lower Flanker scores means improved performance) may experience greater improvements, potentially due to the lower complexity of the task and its reliance on reaction time rather than accuracy. There was also a correlation between participants' pre-intervention verbal reasoning efficiency and pre-to-post change in their efficiency in the EC+VF condition. This suggests that individuals with poorer pre-intervention verbal reasoning efficiency could benefit more from EC+VF interventions than those with superior verbal reasoning ability.

Evaluation of previous research supports such claims. Sibley and Beilock (2007) employed a 30-minute treadmill protocol (at 60-80% HRR) to examine its influence on the reading and operation span. The participants completed the two working memory tasks in two separate sessions, one no-exercise baseline session and an exercise session involving 20 minutes of treadmill running. They concluded that individuals with lower initial performance derived more significant benefits from exercise than those with higher initial performance, potentially due to their greater capacity for improvement. This assertion is supported by Drolette et al. (2014), who found that preadolescent children with lower baseline pre-intervention scores and self-regulatory behaviour demonstrated improved Flanker task accuracy after 20 minutes of treadmill walking, achieving scores comparable to those of the higher-performing group. The variability in pre-test scores, as shown in the range of scores in Table 5.3, potentially demonstrates the presence of ceiling and floor effects: Higher-performing individuals might have had limited room for improvement, whereas lower-performing individuals may have struggled to make progress. These effects may have masked potential Time-by-Condition interactions.

Differences in Flanker Task performance and nonverbal reasoning efficiency in the EC and EC+VF conditions may reflect increased mental fatigue or ego depletion in the latter: performance decreased from pre-to-post-intervention, albeit not sufficiently to yield a significant interaction score. Hence, the additional attentional and cognitive demands of the VFT might have undermined improvements that would otherwise arise from an EC intervention alone. There is a precedent for this: Dkaidek and colleagues (2024a) compared the effects of EC and EC+VF on brain function in healthy adults, and found that participants' cycling cadence and energetic investment were lower in the EC+VF condition than in the EC condition, which suggests that the increased demands in the VFT might have detracted from participants' ability to maintain the required cadence and, therefore, work rate.

Observed reductions in post-intervention task performance may also be explained by ego depletion, as the EC+VF condition required sustained self-control and cognitive effort, reducing available resources for tasks administered post-intervention. Considering the scores of the VFT and the low number of participants with formal cycle training and cycling experience, it is likely that the EC+VF condition was too difficult and effortful for many of the children. Price and Yates (2010) investigated ego depletion in a school setting and found that ego-depleted children opted to complete mathematics questions of lower difficulty levels, whereas the control group began the task at moderate difficulty and progress to take on more difficult questions. The authors used the term *motivational depletion* – a reduced amount of effortful control an individual is willing to use in a subsequent task – as an explanation for the intervention group's inferior performance. In this current study, participants may have concentrated on cycling rather than the VFT or vice versa. Increased effort induced by the concurrent, and for many, both tasks being novel, may have resulted in a state of ego depletion, affecting subsequent task performance.

The main effect of Time suggests that ergometer cycling interventions per se might be effective, seeing as both conditions comprised this element – although we must not rule out practice effects as an obvious explanation (Haith & Krakauer, 2018). However, if we consider the positive correlation between self-reported arousal levels in both conditions and the established relationship between self-reported arousal and cognitive task performance (Byun et al., 2014; Lambourne & Tomporowski, 2010), then we tentatively claim that increases in subjective arousal resulting from ergometer cycling may enhance cognitive performance on both EF tasks and academic reasoning tasks. Indeed, previous research has shown such arousal-performance relationships in inhibitory control (Byun et al., 2014) and memory tasks (Lambourne & Tomporowski, 2010; Tomporowski, 2003). Nonetheless, it would have been preferable to include a control group that received no intervention. However, the logistical constraints of recruiting and testing additional children were considerable, and so a conscious decision was made to forego this.

Unlike the Lode ergometer used by Dkaidek et al. (2024a), the Monark ergometer used in this study does not record cadence levels and energetic investment data. Furthermore, the Monark ergometer requires manual adjustment of intensity levels using weights – but reductions of weighted resistance did not always lower HR sufficiently to achieve the target exercise intensity. The chest strap heart rate monitor did not fit all participants and was uncomfortable for some, meaning five participants did not contribute HR data.

An improvement for future research into the effect of ergometer cycling and visual foraging tasks combined, would be to collect self-report data from participants regarding their subjective mental fatigue, ego depletion and/or task-oriented motivation. For example, given the between-subjects variability in performance of the experimental tasks, collection of self-reported task-oriented motivation data might have helped us to better to understand participants' reasons for taking part in the study, and could have been used as a covariate in analyses. Another development for future research endeavours would be to use a more naturalistic visual foraging task, and one comprising instantaneous feedback, which might be more engaging, and consequently less fatiguing/ego depleting, to better understand the effects of real-world visual foraging behaviour and the subsequent influence on EF task performance.

5.6 Conclusion

This novel study examined the effects of ergometer cycling, with and without a concurrent visual foraging task, on secondary schoolchildren's performance in executive function and academic reasoning tasks. Their working memory accuracy, verbal reasoning percent correct and nonverbal reasoning completion time improved post-intervention, irrespective of condition. Although we must not overlook possible practice effects, it is possible that brief cycling interventions may enhance subsequent executive function and academic reasoning ability. However, it appears likely that pre-existing individual differences in such abilities may mediate any improvements. So, future research should consider such individual differences, along with the addition of a control group, to (dis)confirm the already established effects of ergometer cycling on cognitive function (Dkaidek et al., 2023). Researchers should also consider the cognitive demands of experimental tasks on participants' mental fatigue, which may moderate their performance on subsequent tasks.

CHAPTER 6. NATURALISTIC VISUAL FORAGING DURING STATIONARY CYCLING: THE INFLUENCE OF AGE AND REWARDS ON IN-TASK LEARNING AND SUBSEQUENT COGNITIVE PERFORMANCE

6.1 Abstract

Introduction: Exergaming may be a fun, interactive approach to improve children and young adults' executive functions (EFs). This study aimed to investigate the influence of age and rewards on in-task learning while performing stationary cycling and a naturalistic visual foraging, and on subsequent EF and reasoning task performance.

Method: Twenty-one children aged 11-16 and 21 young adults 18-35 participated in this study. In a mixed design, participants performed stationary cycling while viewing 360-degree real-world point-of-view footage of cycling through an urban environment via a head-mounted display. Participants from each age group were split into two subgroups: (1) one that received immediate auditory feedback when they fixated on target areas (where hazards might emerge); effectively, a visual foraging task and (2) a group that received no auditory feedback; both groups scored points for looking where hazards existed, or might appear. In-task learning was assessed by comparing participants' foraging behaviour in minutes 0-5 (Epoch 1) and 5-10 (Epoch 2) of the intervention. Participants completed EF tasks, verbal and nonverbal reasoning tasks and the Affect Grid pre- and post-intervention.

Results: Our findings demonstrated a Time [Epoch 1, Epoch 2] x Condition [Rewards, no Rewards] interaction, indicating a lack of reward sounds during the intervention resulted in a decline in foraging over time. A main effect of Time was revealed in rightward, leftward, overall foraging and transitions, suggesting changes in foraging behaviour over the course of the intervention. The intervention improved participants' nonverbal reasoning efficiency and heightened subjective arousal, regardless of age and rewards.

Discussion – Combined stationary cycling and naturalistic visual foraging may be an efficient way to improve nonverbal reasoning performance, and given the use of these tasks for diagnostic purposes in selective schools, such benefits may enhance children's academic achievement.

Keywords: Executive Functions, Reasoning, Immersive Reality, Exergaming, Feedback, Children, Adolescents, Young Adults

6.2 Introduction

Dual-task exercise is becoming an increasingly popular tool to enhance cognition in children (Wollesen et al., 2022) and adults (Zheng et al., 2021). Relatedly, immersive reality (IR) has also become widely adopted in fitness (Liu et al., 2022) and education (Oubibi & Hryshayeva, 2024) settings. To date, visual attention processes have predominantly been assessed using two-dimensional visual search tasks (Kristjánsson et al., 2022). However, immersive 360-degree environments can closely mimic the complexity of foraging in the real world and our allocation of visual attention in dynamic and complex environments. A benefit of using IR to encapsulate human behaviour includes a visual search that is guided in a naturalistic setting (Lambourne & Tomporowski, 2010; Li et al., 2016; Võ et al., 2019).

IR may be a viable tool to improve learning during exercise and to avoid dual-task deficits. A dual-task deficit occurs when the task surpasses attentional capacity limits, increasing the likelihood of errors (e.g., Douris et al., 2018; Kunzler & Carpes, 2021). The gamification of tasks, or exergaming, may benefit exercise compliance as integrating IR may shift the participant's attention away from the physical strain to the immersive environment around them, increasing motivation (Anderson-Hanley et al., 2012; Douris et al., 2018). According to the technology-mediated learning (TML) theory (Makransky & Petersen, 2019) adapted by Lin and colleagues (2020), immersive virtual reality (VR) influences learning outcomes through two pathways: affective and cognitive. The affective path focuses on the individual's attitude and mood towards learning, influenced by enjoyment and immersion. The cognitive path focuses on cognitive task performance using active learning (i.e., analysis, memory, and knowledge acquisition; Lin et al., 2020). Considering the positive influence of VR/IR on affect and cognition, this study aims to explore the influence of combined IR and physical exercise on in-task learning and cognition.

IR-based tasks may be coupled with auditory, textual or haptic feedback (Radianti et al., 2020). By using feedback, the researcher is informed as to whether the participants understood the task, if they are continuously learning and whether the interaction with the immersive environment was successful (Radianti et al., 2020). As reward cues attract attention, it is suggested that individuals associate them with learning (Bourgeois et al., 2016). The interaction between attentionally salient stimuli and reward expectation may dictate attentional prioritisation and increase learning (Klink et al., 2017). Instant feedback is suggested to promote learning, in which the reward and the desired behaviour are associated, encouraging the behaviour to be repeated (cf. Bishop et al., 2023). Within this context, the Expected Value of Control (EVC) model states that individuals integrate the reward expectation with task performance and adapt their mental effort accordingly (Frömer et al., 2021). Therefore, reward-based exergaming intervention may be a fun and efficient way to support learning.

Previous evidence supports the beneficial effects of exergaming on executive functions (EFs; Benzing & Schmidt, 2019; Best, 2012; Chen et al., 2023). EFs are a set of mental processes characterised by three core domains – *inhibitory control* (the ability to adapt thoughts, feelings and actions), *working memory* (replacing outdated with new information) and *cognitive flexibility* (our ability to adjust behaviours based on our surroundings; Diamond, 2013). Previous meta-analyses have supported the positive effects of acute aerobic exercise on EFs (Chang et al., 2012; Dkaidek et al., 2023). However, Neibaum and Munkata (2023) suggest that rather than training EFs directly, interventions should adopt contextually relevant tasks that engage EFs. Reasoning is a higher-order EF that plays a role in problem-solving during verbal (e.g., semantic) and nonverbal (e.g., visuospatial) situations (Gómez-Veiga et al., 2018; Greiff & Neubert, 2014). Abstract reasoning may be the key higher-order EF that underpins academic success (Gómez-Veiga et al., 2018). Verbal and nonverbal reasoning examinations are used for entry to selective schools in England in Year 6 (BOND 11+), highlighting the importance of improving such abilities. Therefore, it is beneficial to understand the impact of exergaming on reasoning abilities, and whether it is correlated to other EFs (e.g., inhibitory control and/or working memory).

Previous research has tested predictions of exercise-induced influence on EFs using arousal theories (e.g., Yerkes and Dodson, 1908; Kahneman, 1973). These theories commonly suggest that acute exercise positively influences cognitive performance dependent on the allocation of resources and task demands (Lambourne & Tomporowski, 2010). Alongside arousal, exercise-induced EF improvements have also been associated with pleasantness, which VR/IR may increase through brain dopaminergic system activation (Suwabe et al., 2021; Ochi et al., 2022). Ochi and colleagues (2022) revealed that 10 minutes of exergaming improved mood but not EFs, potentially as exergaming may increase cognitive demands inhibiting improvement as the individual reaches attentional capacity limits – effectively ego depletion. Ego depletion occurs if an individual exerts a surplus of self-control during a primary task, reducing self-control for the subsequent task (Baumeister et al., 2000). However, given the validated measures of affect (e.g., Affect Grid; Russell et al., 1989) and its association with exercise and EF task performance (Lambourne & Tomporowski, 2010), we chose to focus on exercise-induced affect rather than ego depletion, which may be driven by extraneous factors such as individual differences, motivation and enjoyment.

Another important consideration of intervention effectiveness is the age group it is targeting. The effects of exergaming have been assessed across different age groups, children and adolescents (e.g., Chen et al., 2023) and young adults (e.g., Douris et al., 2018). The development of foraging and visual cognitive processes may vary between adolescence and early adulthood (Ólafsdóttir et al., 2019). Ólafsdóttir and colleagues (2019) compared foraging patterns and EF abilities in children aged 4-7 years, 11-12 years and adults aged 20-37 years old. Their findings revealed that older children and adults showed similar foraging ability and efficiency, unlike the younger children. They also demonstrated an association between foraging and both attentional flexibility and working memory, which shows that foraging is a promising method of investigating visual attention whilst engaging EFs. Therefore, as IR serves as a naturalistic foraging scenario, our study will explore the difference between the effect of IR cycling on EFs on older children and young adults.

This study investigates whether IR cycling increases in-task learning during the intervention and if it influences post-intervention EF tasks, reasoning tasks and affect. We aimed to investigate whether the presence of reward sounds and age (i.e., children and young adults) affects EF task and reasoning task performance, as well as affect. Our hypotheses were threefold: [1] that reward sounds would promote increased foraging/ in-task learning relative to a condition without reward sounds, [2] that greater in-task learning resulting from rewards would enhance post-intervention EFs and reasoning performance relative to the other condition, and [3] that adults and children would exhibit similar foraging abilities during the intervention and will both show improved post-intervention EF and reasoning task performance.

6.3 Method

6.3.1 Study Design and Participants

The required sample size was calculated in G*Power 3.1 (Faul et al., 2007) for a within-between measures ANOVA. Estimates were based on the effect sizes used in previous studies in which cycling and cycling + foraging were compared (*d* = 0.52; Dkaidek et al, 2024a; Dkaidek et al., 2024b). The parameters entered were as follows: power (1-β) = 0.80, α = 0.05, Cohen's f > 0.252 for a mixed ANOVA comprising one repeated measures factor (Timepoint [pre-, post]), and two between-groups factors (Rewards Sounds [reward sounds, No Reward Sounds] and Age Group [children and young adults]). This yielded a desired sample of 42 participants.

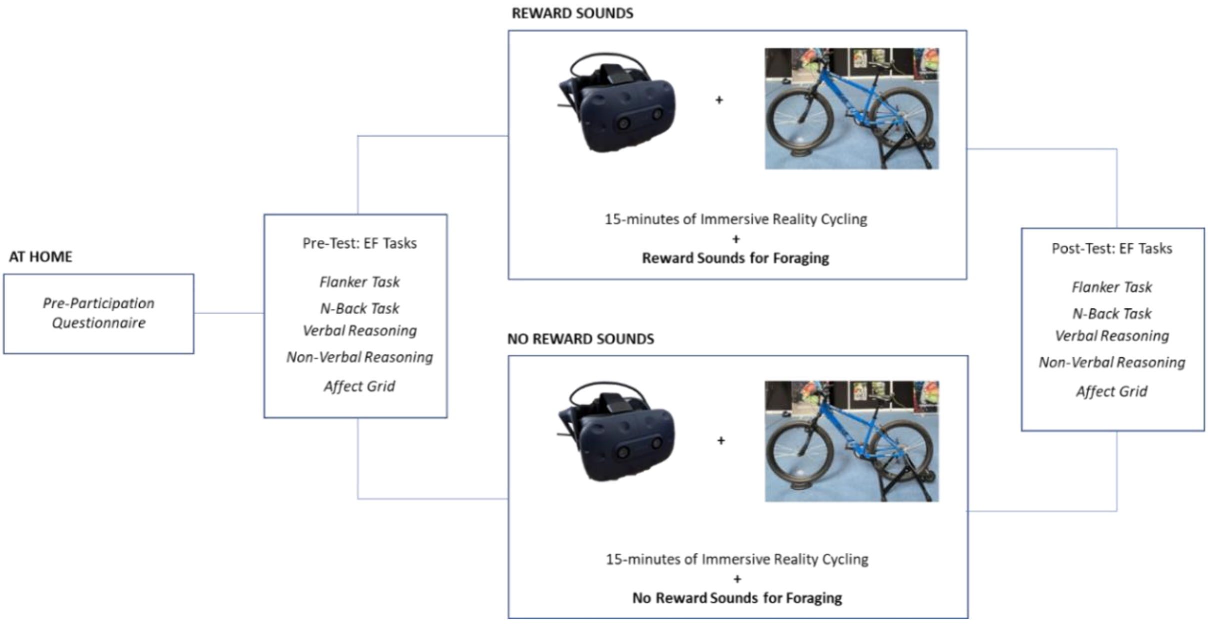
Forty-two participants, 21 children aged 11-16 years (mean age ± SD = 12.89 ± 1.13 years; 11 male, 10 female) and 21 young adults aged 18-35 years (mean age ± SD = 25.33 ± 3.69 years; 11 male, 10 females) took part. All child participants attended a secondary school in London, UK; all adult participants were students at a UK university. All participants reported normal or corrected-to-normal hearing and vision, and had no cardiovascular, neurological, or pulmonary disorders. Ethnicities included Indian (17), White British/Irish (8), White European (5), Bangladeshi (3), Asian-Other (2), White-Other (2), Arab (1), Asian-British (1), Mixed Race (1) and White-Arab (1); one participant did not report their ethnicity. One participant identified themselves as autistic, and another reported diagnoses of autism and attention deficit hyperactivity disorder (ADHD).

Participants self-reported their typical physical activity levels via the Modified International Physical Activity Questionnaire (IPAQ short form, 2016; Booth, 2000; cf. Craig et al., 2003). Using the IPAQ data, average metabolic equivalent (MET) scores were calculated. On average participants exerted 2543.26 ± 2925.59 MET-minutes of vigorous physical activity per week (Range: 0 – 5581.40), 1171.30 ± 1026.29 MET-minutes per week of moderate physical activity (Range: 0 – 4520.93), and 949.61 ± 1170.42 MET-minutes per week of walking (Range: 0 – 2854.88). Accordingly, 23 participants were categorised as exhibiting *high* levels of physical activity, 11 as *moderate* and 8 as *low*.

All participants were randomly allocated into one of two groups, with matching for age, gender and cycling experience: a Reward Sounds group (n = 21; 11 M, 10 F) that heard reward sounds during the VR intervention when they fixated on hazards and a No Reward Sounds group (n = 21; 11 M, 10 F) who also completed the VR intervention but did not hear reward sounds for foraging. All participants were entered into a prize draw to win one of six £25 Amazon Gift Cards (i.e., three for each of the children and adult groups). Figure 6.1 illustrates the study design.

Figure 6.1

Study Design



6.3.2 Equipment and Materials

6.3.2.1 EF Tasks

6.3.2.1.1 The Flanker Task

This task evaluates inhibitory control (Eriksen & Eriksen, 1974). It involved 128 trials, each featuring a centrally presented target arrow flanked by a pair of distracter arrows (cf. Ridderinkhof et al., 2021). Among these trials, 64 were congruent, where the central arrow was identical to the flanking arrows (e.g., <<<<<; leftmost image of Figure 6.2), and 64 were incongruent, with the central arrow differing (e.g., <<><<; as shown in the rightmost image of Figure 6.2). The trials were presented randomly across two blocks of 64 items, separated by a 10-second break. Participants were instructed to press the 'A' key if the target arrow faced the left direction and the 'L' key if the middle arrow faced the right direction (on a standard UK QWERTY keyboard.) A correct response resulted in a green flash at the central fixation point, while an incorrect response resulted in a red flash.

‘Flanker effect’ scores were calculated as the processing speed difference between incongruent and congruent trials. This interference effect is associated with inhibitory control based on individual differences in PFC engagement (Forstmann et al., 2008; Ridderinkhof et al., 2021).

Figure 6.2

Flanker Task Trial Examples – Congruent (left) and Incongruent (right) Stimuli

6.3.2.1.2 The 2-Back Task

This task examines working memory (Kirchner, 1958). The 2-Back Task comprised one block of 25 trials (excluding familiarisation and practice trials), which were presented for 500 ms each, with a new stimulus automatically appearing every 3000 ms. During the task, participants were prompted to press the 'M' key if they thought the current letter matched the one they observed two trials earlier and not to press anything if it differed. The top or bottom of each letter had a surrounding grey border, which flashed green if a correct response was pressed (as shown in the rightmost image of Figure 6.3) or flashed red if the response was incorrect. 'Correct Matches' were measured as the percentage of hits using the following formula: hits/hits + errors.

Figure 6.3

2-Back Task Example

6.3.2.2 Academic Reasoning Tasks

Verbal and nonverbal reasoning were evaluated separately, using tests akin to those used in examinations for admission to selective secondary schools in England (BOND 11+ tests; Oxford University Press, 2020). The completion order for two versions of each of the verbal reasoning tasks (A & B) and nonverbal reasoning tasks (A & B) was counterbalanced within and across participants. Participants were allocated a maximum of 10 minutes for each task, with their accuracy and completion time recorded per task.

6.3.2.2.1 Verbal Reasoning

Twenty questions were posed, comprising the following categories: *Sorting Words, Selecting Words, Anagrams, Coded Sequences* and *Logic*. Table 6.1 provides an example of each category.

6.3.2.2.2 Nonverbal Reasoning

The task consisted of twelve 'multiple-choice' questions. The nonverbal reasoning sections included *Analogies*, *Sequences*, *Similarities*, *Symmetry*, and *Codes*. Table 6.2 illustrates examples of the different question types.

Table 6.1

Verbal Reasoning Categories

Sorting Words	Underline the word in the brackets closest in meaning to the words in capitals. **STALE (fresh stark post stem mouldy)**
Selecting Words	Underline the pair of words most opposite in meaning. **spin, revolve circle, ring revolt, support**
Anagrams	Rearrange the letters in capitals to make another word. The new word has something to do with the first two words. **issue, provide, PIQUE**
Coded Sequences and Logic	Give the two missing numbers in the following sequences. **29 16 ___ 18 17 ___**

Note: From. BOND 11+ 10 Minute Tests; Oxford University Press, 2020.

6.3.2.3 Affect Grid

The Affect Grid, developed by Russell et al. (1989), is a self-report tool used to assess participants' in-the-moment affective responses. The 9-by-9 grid was based on Russell's circumplex model of affect (1980) as a single-item tool incorporating two dimensions split into four quadrants: one-dimension, affective valence ranging from pleasure to displeasure and the other dimension, perceived activation, low to high arousal levels, incorporating four quadrants: *high activation-high valence, high activation-low valence, low activation-low valence and low activation-high valence*. The Affect Grid has been widely used in various sport-related studies (e.g., Bishop et al., 2009, 2014; Dkaidek et al, 2024a). Participants expressed their affective response by placing a cross in the appropriate square in the Affect Grid.

6.3.2.4 Intervention

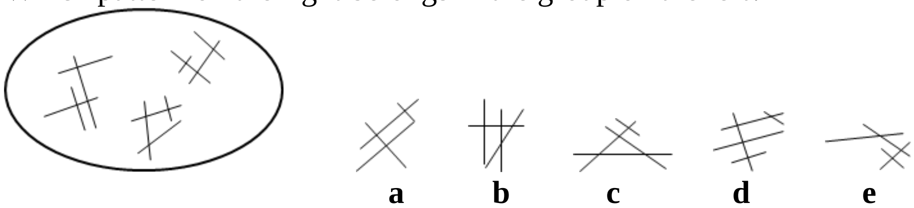
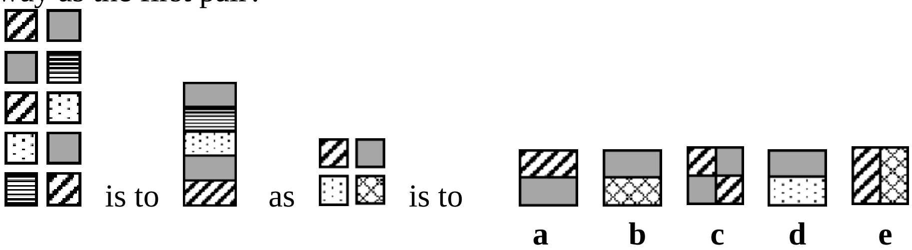
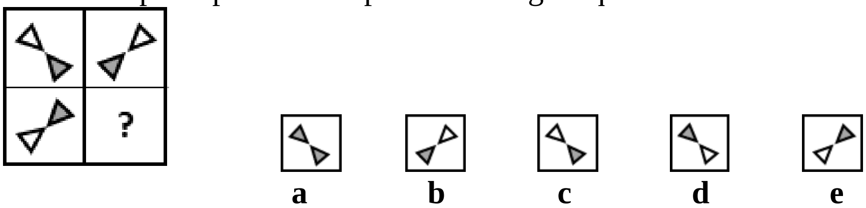
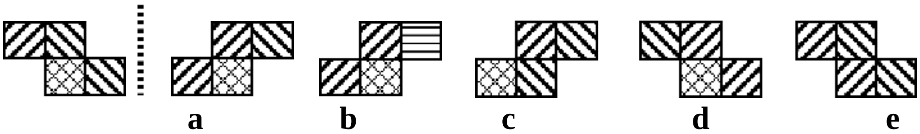
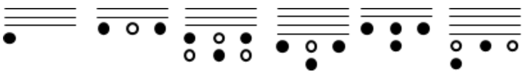
The intervention setup is shown in Figure 6.4. During the intervention, participants sat on a 17-inch all-terrain bicycle with the rear wheel mounted on a cycle trainer and the front wheel on a riser. The handlebars were loosened so the participant could turn them, and the saddle height was adjusted according to the participant’s height and preference. There were crash mats on either side of the bicycle. The participant wore an HTC Vive ProEye (Taoyuan City, Taiwan) head-mounted display (HMD) throughout the protocol.

6.3.2.4.1 360-Degree Immersive Video

The immersive protocol was created by Bishop and colleagues (2023). The video footage was acquired using a GoPro Max 360-degree (GoPro Inc. CA) mounted onto a Hase Trigo cycle (Hase Spezialräder; Waltrop, Germany) at height of 150 cm from the ground. All footage used for the protocol was filmed on roads in London, UK. The protocol was accessed through immersive cycling software created on the Unity application using the OpenXR Plugin, XR Interaction Toolkit packages and Tobii XR SDK. The application allowed gaze tracking, customized fixation targets and reward sounds.

Table 6.2

Nonverbal Reasoning Categories

Similarities	Which pattern on the right belongs in the group on the left? 
Analogies	Which shape or pattern on the right completes the second pair in the same way as the first pair? 
Sequences	Which shape or pattern completes the larger square? 
Symmetry	Which shape on the right is the reflection of the shape given on the left? 
Codes	Which code matches the shape or pattern at the end of each line?  SA RB SC TC RD ? RA TB SB RC TD **a b c d e**

Note: From. BOND 11+ 10 Minute Tests; Oxford University Press, 2020.

Figure 6.4

Intervention Setup

All participants started the session with a 5-minute introductory video to familiarise them with the 360-degree immersive reality footage wearing the HMD. The introductory video had no fixation targets or reward sounds. Following, the participants completed the 10-minute intervention that consisted of fixation targets. Fixation targets were not visible to the participant but could be seen by the researcher via a computer monitor, and covered potential hazards or locations where hazards might appear (e.g., side roads). Targets were located ahead of the rider (e.g., upcoming junctions), to their left and right (e.g., side roads) and behind them (e.g., rearward approaching vehicles). The protocol enabled participants to earn one point for fixating on targets, which was indicative of adaptive foraging behaviour.

For the Reward Sounds group, where reward sounds occurred by fixating on the target zone, the reward sound provided immediate feedback to promote associative learning regarding appropriate looking behaviour and consequently increase motivation (Bishop et al., 2023).

6.3.2.4.2 Heart Rate

Heart rate (HR) was continuously measured throughout the intervention using a Polar Bluetooth Smart chest strap (Polar Electro Oy, Professorintie, 90440 Kempele, Finland). HR_{max} estimates were calculated using Tanaka's (2001) formula: 208-0.7(age). Accumulated evidence supports Tanaka's formula as an appropriate measure to predict children's average HRmax (Mahon et al., 2010; Cicone et al., 2019; Roy & McCrory, 2015).

6.3.3 Procedure

Institutional research ethics committee approval was obtained before commencing data collection. Adult participants provided their informed consent, and child participants and their parents/carers jointly provided their informed consent prior to the child attending. All participants were provided with electronic information sheets prior to providing their consent, and any questions they had after reading those sheets were answered by the researcher to the participant's satisfaction.

Before arriving at the session, participants were asked to complete a health questionnaire and the IPAQ, and to provide demographic information and information pertaining to their cycling experience via an online questionnaire (*Joint Information Systems Committee (JISC) Online Survey Platform*, 2023). Participants under 18 were requested to complete the questionnaire with their parents/carers. Young adult participants volunteered at a time convenient to them, and child participants took part during their school day.

On arrival, participants were asked to sit at a desk where they were invited to ask questions. Once their questions were answered, they were then asked to denote their affective state on a paper copy of the Affect Grid. Thereafter, they completed familiarisation questions for the EF and reasoning tasks until they understood what was required in each task; the researcher invited and answered questions in this regard. The participants also completed five practice trials of the EF tasks and one of each subsection of the reasoning tasks. Once they finished the practice trials, participants completed the pre-test version of each task. For the reasoning tasks, they were asked to complete them as quickly and accurately as possible and that their time to complete each task will be capped at 10 minutes. The running order of the tasks was counterbalanced across participants.

The researcher showed the participant how to put on and adjust the chest strap heart monitor, which the participant then did. Afterwards, the researcher explained the immersive protocol again, told the participant they should notify the researcher if they experience immersion sickness, and answered any questions. The bicycle saddle was adjusted as required and the participant mounted the bicycle. The researcher then measured the participant's resting heart rate before handing them the HMD. The researcher helped the participant adjust the headset to make it comfortable, and the position was optimised.

When the participants were happy to proceed, the researcher asked them to start pedalling and to turn the handlebars when appropriate (e.g., when navigating a turn) during the 5-minute introductory video. The introduction video was standardised across all participants in which No Reward Sounds were given, and it was treated as a familiarisation route. After completing the route, the participant commenced the intervention if they were ready to do so. The researcher provided no feedback regarding performance to either group.

Once the participant completed the intervention, they dismounted and immediately completed the Affect Grid, EF, and reasoning tasks again. If the participant expressed an interest, the researcher let them know how many points they accrued during the immersive task. However, this was not contextualised with information about other participants' scores.

6.3.3.1 Data Analysis

6.3.3.1.1 EF Tasks, Reasoning Tasks and Affect Grid Data

Pre-and post-test data for the Flanker and 2-Back tasks and affective response were expressed as the mean (SD). To mitigate the effects of speed-accuracy trade-offs and because academic reasoning tasks are typically completed under time constraints, an efficiency index was calculated for all reasoning task scores using the following formula: *percentage correct / completion time.* The efficiency index was expressed as the mean (SD).

Separate 2 x 2 x 2 mixed-factorial ANOVAs (Timepoint [Pre, Post], *Condition* [Reward Sounds, No Reward Sounds] x *Age Group* [Children, Young Adults] were run to assess post-intervention EF and academic reasoning task performance and affect. A repeated measures factor of *Timepoint* and between-group factors or *Condition* and *Age Group* were included.

Exploratory correlations were conducted to investigate any effects of individual differences or potential measures that may influence each other. The influence of individual differences in EF and reasoning abilities may become apparent by investigating correlations between pre-test and pre-to-post-change scores.

6.3.3.1.2 Intervention In-Task Learning

Points for target fixations were divided into forward, left, right, and rearward looking (see Figure 6.5 for corresponding zones) and then summed as an overall foraging score. Zones were created as looking around real-world environments requires head turns to explore actively (Haskins et al., 2020).

Points for *transitions* were given when participants switched from one zone to another. For example, forward to leftward to forward is worth two points as the participant transitioned between zones two times. Assessing in-task learning in all zones provides insight into the effectiveness of 360-degree immersive foraging, as real-world foraging requires active forward, right, left and rearward looking (Haskins et al., 2020).

The percentage of collected points for each category, overall foraging and number of transitions were calculated and expressed as the mean. The intervention data were split into two epochs to explore potential learning behaviour during the intervention: the first five minutes of the protocol (Epoch 1) and the second five minutes (Epoch 2). Any significant improvements from Epoch 1 to Epoch 2 were considered evidence of learning.

Overall points for *foraging* (forward, left, right and rearward) and *transitions* were entered as dependent measures in 2 x 2 x 2 mixed-factorial ANOVAs (*Timepoint* [Epoch 1, Epoch 2] x *Condition* [Reward Sounds, No Reward Sounds] x *Age Group* [Children, Young Adults]. The repeated measures factor of *Timepoint* consisted of two Epochs of identical length (5 minutes each) used to assess in-tasking learning throughout the intervention. Between-groups factors of *Condition* and *Age Group* were also included.

Analyses were conducted using IBM SPSS software (IBM Corp., 2023). An alpha level of $p < 0.05$ was used for all statistical comparisons, and all data were checked for outliers and assessed for normality. The Shapiro-Wilk tests revealed violations of normality for multiple measures (See Appendix G); however, no adjustments were made for the violations as they reflected the experimental manipulation or age group differences (see Appendix H).

Figure 6.5

360-degree Footage Scenario (Rightward [red], leftward [red] and Rearward [green] Zones highlighted)

6.4 Results

Two participants' data were excluded from the analysis, as outliers: One exhibited no foraging behaviour (i.e., 0 points were accrued overall; they stared ahead throughout the intervention) and the other completed the reasoning tasks in an impossibly short time (47 seconds).

6.4.1 Intervention – Manipulation Check

The target 60%HR_{max} was 117 bpm (SD = 2.77, Range = 111-120 bpm). However, the average attained value was 97.4 bpm (SD = 16.2, Range = 71-125 bpm). A paired samples t-test revealed a significant difference between the target 60%HR_{max} and the average attained value, $t(25) = 5.74$, $p < .001$, $d = 1.12$. Heart rate data were missing for 12 children, largely because the heart rate monitor did not fit them well (n = 10), although two individuals requested not to wear one.

6.4.2 In-Task Learning

Table 6.3 shows the points obtained during Epoch 1 (i.e., minutes 0-5 of IR cycling) and Epoch 2 (i.e., minutes 5-10 of IR cycling), expressed as means (SDs). Table 6.4 shows the number of transitions during Epoch 1 and Epoch 2, also expressed as means (SDs).

6.4.2.1 Overall Foraging

A mixed-factorial ANOVA revealed a main effect of Timepoint, $F(1,36) = 20.00$, $\eta_p^2 = 0.36$, $p < .001$. Bonferroni Corrected pairwise comparisons revealed that foraging increased in Epoch 2 (M = 36.4, SE = 1.74) relative to Epoch 1 (M = 32.0, SE = 1.39), regardless of Condition and Age Group. However, there were no significant Timepoint x Condition (p = .056) or Timepoint x Age Group (p = .611) interactions. There were also no between-subjects' effects of Condition (p = .625) or Age Group (p = .40).

6.4.2.2 Forward Foraging

A mixed-factorial ANOVA indicated a Timepoint x Condition interaction, $F(1,36) = 7.10$, $\eta_p^2 = .17$, $p = .011$. Bonferroni Corrected pairwise comparisons revealed that the No Reward Sounds group decreased their forward foraging in Epoch 2 relative to Epoch 1, $t(36) = 3.21$, $SE = 1.62$, $p = .017$. The interaction is illustrated in Figure 6.6. There was no Timepoint x Age Group interaction ($p = .725$), nor main effect of Timepoint ($p = .055$), albeit that the latter approached significance. There were also no between-subjects' effects of Condition ($p = .599$) or Age Group ($p = .412$).

6.4.2.3 Rightward Foraging

A mixed-factorial ANOVA showed a main effect of Timepoint, $F(1,36) = 4.23$, $\eta_p^2 = .11$, $p = .047$. Bonferroni Corrected pairwise comparisons revealed a significant increase in rightward foraging in Epoch 2 ($M = 46.6$, $SE = 4.05$) relative to Epoch 1 ($M = 39.3$, $SE = 2.59$). However, there were no significant Timepoint x Age Group ($p = .942$) or Timepoint x Condition ($p = .545$) interactions. There was also no between-subjects' effects of Age Group ($p = .253$) or Condition ($p = .936$).

6.4.2.4 Leftward Foraging

A mixed-factorial ANOVA indicated a main effect of Timepoint, $F(1,36) = .028$, $\eta_p^2 = .13$, $p = .028$, in which Bonferroni Corrected pairwise comparisons showed a significant increase in leftward foraging in Epoch 2 ($M = 36.9$, $SE = 3.39$) relative to Epoch 1 ($M = 29.1$, $SE = 3.70$). However, there was no Timepoint x Condition interaction ($p = .874$) or Timepoint x Age Group interaction ($p = .399$). There was also no between subjects-effects of Condition ($p = .477$) or Age Group ($p = .896$).

6.4.2.5 Rear-view Foraging

No significant Timepoint x Condition (p = .783) or Timepoint x Age Group (p = .920) interactions were revealed. There was also no main effect of Timepoint (p = .375) or between-subjects' effects of Condition (p = .968) or Age Group (p = .201).

6.4.2.6 Transitions

A main effect of Timepoint was revealed for the number of transitions between zones, $F(1,36) = 26.03$, $\eta_p^2 = .42$, $p < .001$. Bonferroni Corrected pairwise comparisons showed increased transitions in Epoch 2 (M = 15.70, SE = 1.27) compared to Epoch 1 (M = 11.40, SE = .80). However, there was no Timepoint x Condition (p = .908) or Timepoint x Age Group (p = .693) interactions. There were also no between-subjects' effects of Condition (p = .683) or Age Group (p = .945).

Figure 6.6

Timepoint [Epoch 1, Epoch 2] x Condition [Reward Sounds, No Reward Sounds] Interaction

Table 6.3

Percentage of Available Points Obtained, by Zone and Age Group

	Forward	**Rightward**	**Leftward**	**Rearward**	**Overall**
Reward Sounds					
Children					
Epoch 1	33.10 (6.19)	45.80 (8.36)	39.40 (11.20)	0.52 (1.16)	33.10 (6.19)
Epoch 2	39.20 (9.39)	45.80 (9.86)	51.50 (22.90)	0.91 (3.02)	39.20 (9.39)
Young Adults					
Epoch 1	27.90 (9.00)	36.50 (13.90)	36.70 (11.20)	0.00 (0.00)	27.60 (9.00)
Epoch 2	34.10 (10.0)	39.50 (12.90)	51.50 (22.90)	0.00 (0.00)	34.10 (10.00)
Overall, Epoch 1	42.10 (11.70)	38.10 (14.10)	26.70 (19.30)	0.27 (0.86)	30.50 (7.99)
Overall, Epoch 2	42.80 (11.60)	47.60 (24.90)	34.90 (21.00)	0.48 (2.18)	56.70 (9.81)
No Reward Sounds					
Children					
Epoch 1	46.60 (7.43)	46.30 (16.20)	31.10 (28.50)	0.32 (0.95)	34.00 (5.79)
Epoch 2	41.30 (6.59)	48.10 (17.60)	35.20 (17.60)	0.56 (1.67)	35.70 (5.92)
Young Adults					
Epoch 1	47.20 (17.80)	35.00 (20.00)	32.00 (25.30)	0.00 (0.00)	33.50 (12.40)
Epoch 2	42.00 (17.90)	43.30 (31.60)	42.50 (24.00)	0.50 (1.58)	36.70 (15.80)
Overall, Epoch 1	44.40 (12.70)	39.20 (16.30)	29.00 (22.60)	0.21 (0.76)	32.00 (8.82)
Overall, Epoch 2	42.30 (12.30)	46.70 (24.80)	36.90 (20.80)	0.50 (1.89)	36.50 (10.70)

Table 6.4

Transitions between Zones, by Condition and Age Group

	Number of Transitions			
	Reward Sounds		**No Reward Sounds**	
	Epoch 1	*Epoch 2*	*Epoch 1*	*Epoch 2*
Children	11.90 (4.06)	15.70 (8.98)	11.00 (5.83)	15.20 (6.51)
Young Adults	9.90 (4.15)	15.00 (6.06)	12.60 (5.99)	16.90 (9.53)

6.4.3 EF Tasks Data

Table 6.5 shows the scores of the EF tasks expressed as the mean (SD).

6.4.3.1 Flanker Task Data

A mixed-factorial ANOVA revealed a Timepoint x Age group interaction, $F(1,33) = 6.29$, $\eta_p^2 = .16$, $p = .017$. Bonferroni-corrected pairwise comparisons indicated no significant difference across the groups, all *p*'s > .05. There was no Timepoint x Condition interaction (p = .836), effect of Timepoint ($p = .902$), effect of Age Group ($p = .443$), or Condition ($p = .866$).

6.4.3.2 2-Back Task Data

A between-subjects effect of Age Group was revealed, $F(1,30) = 15.72$, $\eta_p^2 = .34$, $p = .001$, indicating that the young adult group ($M = 82.5$, $SE = 4.03$) performed better on the 2-Back task compared to the children's group ($M = 59.2$, $SE = 4.28$). A mixed-factorial ANOVA indicated no Timepoint x Condition interaction ($p = .170$) or Timepoint x Age Group interaction albeit approaching significance, $p = .065$. There was also no main effect of Timepoint ($p = .223$), or between-subjects effect of Condition ($p = .762$).

6.4.4 Academic Reasoning Tasks

Table 6.6 shows the academic reasoning task efficiency scores expressed as the mean (SD). A breakdown of the academic reasoning tasks, percent correct and completion time are shown in Appendix I.

6.4.4.1 Verbal Reasoning Task Data

A mixed-factorial ANOVA revealed no Timepoint x Condition (p = .828) or Timepoint x Age Group interaction (p = .52). There was also no main effect of Timepoint (p = .909) or between-subjects' effects of Condition (p = .939) or Age Group (p = .866).

6.4.4.2 Nonverbal Reasoning Task Data

A mixed-factorial ANOVA indicated a significant main effect of Timepoint, $F(1,36) = 7.81$, $\eta_p^2 = .18$, $p = .008$. Bonferroni-corrected pairwise comparisons revealed that post-intervention nonverbal reasoning efficiency (M = 0.18, SE = 0.02) was significantly improved compared to pre-intervention (M = 0.13, SE = 0.01), regardless of Age Group and Condition. No significant interactions were revealed, albeit that the Timepoint x Condition x Age Group interaction approached significance (p = .066). There were no between-subjects effects of Condition (p = .36) or Age Group (p = .55).

Table 6.5

EF Task Performance, by Condition and Age Group

Task	Pre	Post
Flanker Effect (ms)		
Children		
Reward Sounds	57.60 (61.80)	28.50 (28.60)
No Reward Sounds	39.80 (37.20)	32.10 (41.80)
Children Overall	50.10 (52.40)	30.10 (34.20)
Young Adults		
Reward Sounds	22.80 (73.20)	39.90 (37.10)
No Reward Sounds	30.90 (43.10)	40.00 (51.30)
Young Adults Overall	26.90 (58.60)	39.90 (44.30)
Overall	**38.20 (56.20)**	**34.80 (39.10)**
2-Back Correct Matches (%)		
Children		
Reward Sounds	60.70 (16.80)	55.90 (23.70)
No Reward Sounds	55.00 (21.00)	72.80 (22.70)
Children Overall	58.30 (18.30)	64.30 (24.10)
Young Adults		
Reward Sounds	84.00 (18.90)	83.60 (20.10)
No Reward Sounds	81.30 (19.60)	79.30 (17.80)
Young Adults Overall	82.70 (18.80)	81.40 (18.50)
Overall	**70.80 (22.10)**	**73.40 (22.70)**

Note: Flanker Effect is calculated as response times for incongruent minus those for congruent stimuli; hence, lower values demonstrate better inhibitory control.

Table 6.6

Academic Reasoning Task Performance, by Condition and Age Group

Task	Pre	Post
Verbal Reasoning Efficiency		
Children		
Reward Sounds	0.108 (0.058)	0.119 (0.085)
No Reward Sounds	0.117 (0.060)	0.130 (0.081)
Children Overall	0.113 (0.058)	0.124 (0.081)
Young Adults		
Reward Sounds	0.123 (0.070)	0.122 (0.053)
No Reward Sounds	0.118 (0.048)	0.103 (0.055)
Young Adults Overall	0.120 (0.059)	0.112 (0.054)
Overall	**0.116 (0.058)**	**0.118 (0.068)**
Nonverbal Reasoning Efficiency		
Children		
Reward Sounds	0.165 (0.100)	0.174 (0.094)
No Reward Sounds	0.105 (0.046)	0.206 (0.153)
Children Overall	0.138 (0.084)	0.188 (0.121)
Young Adults		
Reward Sounds	0.135 (0.050)	0.189 (0.069)
No Reward Sounds	0.126 (0.035)	0.148 (0.072)
Young Adults Overall	0.131 (0.042)	0.168 (0.072)
Overall	**0.135 (0.066)**	**0.178 (0.100)**

6.4.5 Affect Grid Data

Table 6.7 shows the self-reported Affect Grid data expressed as the mean (SD).

6.4.5.1 Arousal

A mixed-factorial repeated measures ANOVA showed a main effect of Timepoint, $F(1,36) = 9.81$, $\eta_p^2 = .21$, $p = .003$, in which a follow-up Bonferroni Correction showed that post-intervention subjective arousal ($M = 6.67$, $SE = 0.30$) was significantly heightened compared to pre-intervention ($M = 5.69$, $SE = 0.30$), regardless of Age Group and Condition. However, no significant Timepoint x Condition ($p = .435$) or Timepoint x Age Group ($p = .799$), interactions were shown. There were also no between-subjects' effects of Condition ($p = .466$) or Age Group ($p = .610$).

6.4.5.2 Pleasantness

A mixed-factorial ANOVA revealed no interactions between Timepoint x Condition (p = .783) or Timepoint x Age Group (p = .180). There was also no main effect of Timepoint ($p = .08$), or between-subjects effect of Condition ($p = .0.94$); however, a between-subjects effect of age group approached significance, $p = .058$.

Table 6.7

Self-Reported Arousal and Pleasantness Levels, by Condition and Age Group

Affect Grid	**Pre**	**Post**
Subjective Arousal		
Children		
Reward Sounds	6.00 (1.95)	7.45 (0.82)
No Reward Sounds	5.56 (2.13)	6.22 (2.39)
Children Overall	5.80 (1.99)	6.90 (1.77)
Young Adults		
Reward Sounds	5.50 (1.35)	6.50 (1.96)
No Reward Sounds	5.70 (1.95)	6.50 (2.07)
Young Adults Overall	5.60 (1.64)	6.50 (1.96)
Overall	**5.70 (1.80)**	**6.70 (1.86)**
Subjective Pleasantness		
Children		
Reward Sounds	6.55 (2.02)	7.00 (2.14)
No Reward Sounds	7.22 (1.39)	8.22 (1.30)
Children Overall	6.85 (1.76)	7.55 (1.88)
Young Adults		
Reward Sounds	5.60 (2.12)	6.10 (1.91)
No Reward Sounds	6.80 (1.32)	6.50 (1.43)
Young Adults Overall	6.20 (1.82)	6.30 (1.66)
Overall	**6.53 (1.80)**	**6.92 (1.86)**

6.5 Discussion

This study used a brief gamified immersive reality (IR) cycling intervention to elucidate the effects of dual-task cycling exercise on children and young adults' EFs, reasoning skills and affect. All participants performed stationary cycling while foraging using 360-degree real-world POV footage of cycling through an urban environment via a head mounted display (HMD). Children and young adult participants were split into two groups: one that heard reward sounds for fixating on target areas, and one that did not.

We predicted that immediate reward sounds for fixating on target regions (i.e., hazard perception) would increase in-task learning throughout the intervention. Also, that the Rewards Sounds groups would show greater improvements in EF and reasoning task performance as well as greater increases in subjective arousal and pleasantness relative to the No Reward Sounds group. Our findings revealed greater in-task learning, heightened subjective arousal and improved nonverbal reasoning task performance post-intervention, regardless of Rewards or Age Group.

Our findings revealed a Timepoint [Epoch 1, Epoch 2] x Condition [Reward Sounds, No Reward Sounds] interaction, demonstrating that the No Reward Sounds group showed a decline in foraging in Epoch 2 relative to Epoch 1. However, a main effect of Timepoint revealed increased right, left and overall foraging, regardless of Condition and Age Group. Therefore, the decrease may signify a trade-off between forward and right/left foraging because without feedback (cf. Bishop et al., 2023), there was possibly greater exploring autonomy. As suggested by Bishop and colleagues (2023), this trade-off may represent those in real-world cycling as right, left, and rearward looking is essential for successful observation. Further, the number of transitions also did not vary between conditions, suggesting that reward sounds may serve as positive reinforcement, however, they may not guide the participant in changing their behaviour. Foraging and transition increases over the course of the intervention may also reflect increased confidence or arousal levels rather than in-task learning; assessment of in-task arousal and motivation levels would have elucidated this – an oversight in the present study design.

No interactions were revealed in any post-intervention EF or academic reasoning tasks. However, there was a main effect of Timepoint on nonverbal reasoning efficiency, but we cannot rule out practice effects (Haith & Krakauer, 2018). Our findings suggest that nonverbal reasoning efficiency improved post-intervention, regardless of Age Group and Condition. Exercise-induced improvements in nonverbal reasoning performance have been shown previously, however, this was after chronic physical education lessons (Ardoy et al., 2014). There is scarce literature on the association between exercise and nonverbal reasoning; however, given the association between nonverbal reasoning and academic achievement (Brookman-Byrne et al., 2019), there are grounds for further research.

Although there was an effect of the intervention on nonverbal reasoning, the intervention did not influence performance on the two EF tasks. This may be due to ego depletion. During the intervention, participants had to maintain self-control and attention – increased in-task foraging may be a precedent for this. Osgood (2015) posits that ego depletion may reduce an individual’s ability to uphold cognition and arousal when the situation is less stimulating. EF tasks, like the Flanker and 2-Back, include numerous repetitive trials, potentially disrupting the participants’ ability to sustain their attention on the task. On the other hand, the reasoning tasks may require greater focus than the Flanker and 2-Back tasks, are time-sensitive and may be more familiar with classroom-based tasks.

A main effect of Timepoint revealed that arousal levels increased after the IR cycling, regardless of Age Group and Condition. This suggests that the 15-minute IR cycling intervention is sufficient to increase arousal levels irrespective of whether an individual receives feedback or not. As per previous suggestion that arousal levels may mediate cognitive performance (Lambourne & Tomporowski, 2010), we tentatively suggest that exercise-induced arousal levels may have also mediated nonverbal reasoning task improvements; however, as there was no correlation between the two variables, this remains speculative and warrants further research. Increased arousal also may have facilitated foraging during the intervention; however, assessment of affect multiple times during the intervention would be required to draw such conclusions.

Further, a between-subjects' effect of Age Group in the 2-Back Task was found, suggesting that young adults performed better on the 2-Back Task than the children. EFs, including working memory, reportedly peak during young adulthood (Ferguson, Brunsdon & Bradford, 2021). Ferguson and colleagues investigated EF task performance in participants aged 10-86 years old and demonstrated that EFs continue to improve throughout adolescence and peak in young adulthood, followed by declines from around 30-40 years old. Hence, different EF developmental trajectories will likely cause such age group differences.

A stationary bicycle was chosen instead of an ergometer to enable the participant to move the handlebars and increase their immersion. However, due to the lack of resistance manipulation and cadence data on a stationary bicycle, unlike an ergometer, it was difficult to standardise intensity. A heart rate monitor was used in attempt to manipulate intensity levels by instructing participants to cycle faster or slower; however, intensity levels were still considerably under moderate intensity.

Future research should explore more nuanced data, such as gaze data, which may give greater insight into foraging behaviour. Alongside the number of fixations, dwell time is also suggested to help indicate how individuals process the visual information – the attention paid to target fixations compared to environmental distractors (Enders et al., 2021). Further, information on switch costs could elucidate the movement time between targets (Jóhannesson et al., 2016), especially if there is a difference in switch costs between fixation targets in the same zone and when transitioning to a different zone.

Although the children completed this study at their school, participating in experimental research is likely unfamiliar; unlike the young adult participants in higher education, many were psychology or sports science students and were likely to have taken part in lab-based experiments. The novelty of the situation may have been mitigated if we had included a baseline session. Further, the children were likely motivated to experience the immersive reality and, therefore, may not have been fully committed to the experimental tasks. Self-reported data regarding subjective task-oriented motivation would have provided insight into why the participants took part.

6.6 Conclusion

We used a brief 360-degree immersive reality cycling intervention to determine the influence of immediate rewards on foraging behaviour and any effects on children's and young adults' subsequent EFs, academic reasoning and affective state. Our findings indicate that there may be a trade-off between forward, right and left-looking behaviour in the No Reward Sounds groups, possibly as they had more exploring autonomy. Although foraging behaviour generally increased over the course of the intervention, the reasons for this are still unknown (e.g., arousal and/or confidence levels). IR cycling may be an enjoyable way to enhance nonverbal reasoning task performance in children and young adults however this still warrants further research.

CHAPTER 7. GENERAL DISCUSSION

7.1 Overview of Main Objectives

This thesis aimed to investigate the effect of an acute bout of cycling exercise on executive function (EF) in school-aged children and young adults. Moderators, including exercise intensity and duration, were synthesised from previous literature using a meta-analysis and systematic review in Chapter 3 and then applied to empirical studies in Chapters 4-6. Combined ergometer cycling and visual foraging (i.e., dual-task) were introduced in Chapter 4 to reflect the attentional demands of real-world cycling. This thesis, as a whole, reinforces the importance of exercise for cognition, however, the extent of improvements may be contingent on pre-existing individual differences. The findings also highlight that acute exercise interventions may be a time-efficient yet effective way to improve cognitive functions. Overall, an acute bout of cycling may improve brain function, affect, EF performance and in-task learning. Such benefits may also manifest when dual-tasking.

The following subsections synthesise the main findings across the studies, their implications, contributions to theory and the real world, and limitations. Directions for future research are also suggested.

7.2 Summary of Key Findings

7.2.1 The Effects of Acute Cycling Exercise on Brain Function

In Chapter 3, a synthesis of research comprising 293 effect sizes in 17 studies revealed that acute cycling exercise may be a viable method to improve EF response time (RT) if various moderators (*intensity*, *duration*, *task type* and *task onset*) are considered. EFs are mental processes that are reliant on the prefrontal cortex (PFC). Previous research commonly agrees that acute exercise may induce PFC activation (Endo et al., 2013; Li et al., 2005), including during dual-task conditions (Ji et al., 2019; Kimura et al., 2022). In light of the association between exercise-induced PFC oxygenation and enhanced cognitive performance, applying functional Near-Infrared Spectroscopy (fNIRS) data in Chapter 4 was important to understand the underlying mechanisms.

The aim of Chapter 4 was to investigate the differential impacts of ergometer cycling (EC), visual foraging (VF) or both combined (EC+VF) on brain function. fNIRS data revealed greater PFC oxygenation in the EC and EC+VF conditions than the VF condition, with even greater oxygenation in the EC condition relative to EC+VF. Although participants were instructed to cycle at a set cadence in both cycling conditions, there was a greater average cadence and energy investment in the EC condition relative to the EC+VF condition. This may be because, during the EC+VF condition, the VF may have acted as a distraction from the cycling exercise, potentially hindering the latter's performance.

The relationship between PFC oxygenation and gaze fixations in the EC+VF condition may represent the PFC oxygen turnover, as cycling may increase the supply of PFC oxygenation. In contrast, the attentional demands of the complex visual foraging task (VFT) may increase the demand for oxygen supply. This thesis supports that exercise increases PFC oxygenation, of which may be required for cognitive processes not only to improve but to remain intact (Herold et al., 2018).

7.2.2 The Effects of an Acute Bout of Cycling Exercise on Affect

The systematic review and meta-analysis findings support the inverted-U hypothesis, which suggests a relationship between moderate-intensity cycling and task performance mediated by increased arousal. However, the relationship between arousal and EF performance changes is likely not straightforward and may be contingent on other factors, such as task difficulty (Beerendonk et al., 2024). Previous studies suggest that exercise-induced arousal levels may be an underlying mechanism mediating EF enhancements (Byun et al., 2014; Lambourne & Tomporowski, 2010); however, this seems to be the case with response time-based tasks (Lambourne & Tomporowski, 2010). To understand the exercise-arousal relationship, all three empirical studies investigated subjective affect pre- and post-intervention, with varying intervention types and post-task difficulties.

Mixed findings were revealed for affect, in which both EC and EC+VF conditions heightened young adults' arousal levels more than the VF condition. Previous research has also shown heightened exercise-induced arousal after acute exercise interventions (Byun et al., 2014; Hacker et al., 2020; Lambourne & Tomporowski, 2010). However, the increase in arousal levels was not associated with EF task enhancements, despite previous suggestions (Basso & Suzuki, 2017; Lambourne & Tomporowski, 2010). Hacker et al. (2020) found similar findings, suggesting that increased arousal may not mediate improved EFs. There was also an increase in arousal levels in children and young adults' post-intervention after the combined stationary cycling and naturalistic visual foraging (Chapter 6). This finding supports previous research that suggests heightened arousal levels after immersive protocols (Lin et al., 2020). However, it may be tentatively suggested that heightened subjective arousal may have facilitated nonverbal reasoning task improvements, as there was no correlation between the two variables. this remains speculative.

Contrarily, the second empirical study (Chapter 5) revealed no changes in affect post-EC or EC+VF. However, there was a positive correlation between the two conditions' subjective arousal and pleasantness pre-to-post change. As the common factor between the two conditions was cycling, there is likely a relationship between cycling and subjective affect. This thesis partially supports an exercise-arousal relationship, however, the extent of its influence on EF and academic reasoning task performance is still unclear and warrants further research.

7.2.3 The Effects of an Acute Bout of Cycling Exercise on EFs

This thesis presents mixed findings on the influence of an acute cycling exercise on EFs. The meta-analysis and systematic review showed that moderate-intensity cycling improves inhibitory control and task-switching RT, with marginally smaller effects after high-intensity and minimal after low-intensity exercise, however, acute cycling exercise did not affect response accuracy (RA) regardless of intensity. Negligible effects in RA may be partially explained by the catecholamine hypothesis, which states that increases in catecholamines due to acute exercise may positively influence RT but potentially cause neural noise that may negatively impact performance accuracy (Cooper, 1973). This is likely contingent on the chosen EF task because of differences in task complexity, in which low-complexity tasks may cause ceiling effects.

McMorris and Hale's (2012) study suggests that a speed-accuracy trade-off may explain improvements in RT and not RA post-exercise, whereby focusing on improving RT may come at the cost of RA. The authors suggested that this could occur in tasks such as the Flanker Task, in which individuals have to decide a response while also moving and selecting their answer and are likely to favour RT over RA. Findings from Chapter 3 agreed with McMorris and Hale's (2012) suggestion that working memory and inhibitory control tasks may not be sufficiently complex to assess RA. To investigate the influence of more complex tasks, the second two empirical studies in Chapters 5 and 6 included two of the same EF tasks as the first empirical study (i.e., Flanker Task and 2-Back); however, they also included academic verbal and nonverbal reasoning tasks – effectively higher-order EF tasks.

Although the empirical studies did not show direct Time-by-Condition interactions, which would suggest that cycling exercise improves EF task performance, genuine effects may have been masked by baseline individual differences in EF abilities. The findings in Chapter 4 suggest that young adults with lower Flanker Task baseline performance showed greater post-intervention performance improvements than those with higher abilities. This interaction was shown in the EC condition, not the EC+VF or VF conditions. Contrarily, the findings in Chapter 5 revealed that children with higher inhibitory control performance showed greater improvements after the EC condition than those with lower scores. The variation in findings may reflect differences in inhibitory control abilities in children compared to adults and potential floor effects for children with lower inhibitory control scores.

The results in Chapter 5 indicated that children with lower pre-test verbal and nonverbal reasoning performance demonstrated greater improvements post-EC than those with higher pre-test scores. This pattern was also observed in the EC+VF condition concerning verbal reasoning efficiency. This finding supports the claim that lower pre-test performance may improve more post-intervention than higher-ability individuals. Previous studies support these assertions (Drollette et al., 2014; Ishihara et al., 2021), suggesting that future research should consider pre-existing individual differences in EF abilities. However, due to school timetabling constraints, baseline measures were not obtained, and therefore, we cannot rule out practice effects.

Ergometer cycling in isolation benefitted EF performance more than the dual-task condition. There are several potential explanations for this. McMorris's interoception theory (2021) may partially explain improvements in the EC condition relative to the EC+VF condition. This theory posits that fatigue and effort cost perception may influence the benefits on EF (McMorris, 2021). In Chapter 4, the association between PFC activation and the number of gaze fixations in the EC+VF condition may suggest that the VF may have led to more significant effort costs and exceeded available resources. For example, eye movements may increase energetic costs (Moskowitz et al., 2023). Given the increased demands of the EC+VF condition, available cognitive resources, effort, and self-control may be expended, possibly impacting subsequent performance. If this is the case, the participants likely experienced mental fatigue or ego depletion. Another possible explanation is that the VF served as a distractor of the cycling task, hindering the performance of the latter.

The stationary cycling and naturalistic visual foraging intervention improved nonverbal reasoning performance post-intervention, irrespective of Age Group or Condition. Previous studies found similar effects of physical exercise and/or exergaming on nonverbal reasoning-based tasks, such as identifying shapes, coding, rotating and spatial orientation (Ardoy et al., 2014; Fargier et al., 2023; Morawietz & Muehlbauer, 2021). However, as there were no baseline measures, practice effects cannot be ruled out for this finding either.

The findings of this thesis partially support previous assertions that acute exercise improves EF task performance. Although there were mixed findings, there seems to be a common theme of individual differences influencing the extent of improvements. There also seems to be greater potential improvement in more complex tasks, such as reasoning tasks, compared to simpler tasks, such as Flanker and 2-Back tasks. Overall, acute cycling exercise has the potential to be a useful method for improving EF task performance; however, individual differences, effort costs and task difficulty should be considered.

7.2.4 In-Task Learning

The findings in Chapter 6 revealed increased foraging and transitions across zones (forward, right, left and rearward) throughout the stationary cycling and naturalistic visual foraging intervention, regardless of rewards or age. However, forward zone points decreased in the No Reward Sound group over the course of the intervention. As foraging still increased overall, this may suggest a trade-off between forward and left/right foraging (cf. Bishop et al., 2023) in the No Reward Sounds group. Such trade-offs accurately represent real-world cycling which requires successful, active observation (Bishop et al., 2022, 2023) – awareness of surroundings and other road users. Observation is a key skill for safe cycling, as per the Bikeability Cycle Training Delivery Guide (The Bikeability Trust, 2024), which, apart from looking ahead, also includes checking around corners, looking down the roads they are passing, rearward checks and looking around for signs and other road users.

7.2.5 Exercise-Induced Brain Changes: A Holistic View

The holistic impact of exercise stems from neurophysiological changes (e.g., PFC activation [fNIRS; Section 2.2.3.3]) as assessed in this thesis, but also by the neurochemical responses it elicits, including changes in the level of cortisol, neurotrophins (BDNF, vascular endothelial growth factor and insulin-like growth factor), neurotransmitters (dopamine, serotonin, and norepinephrine; Section 2.2.3.1) and neuromodulators (endogenous opioids and endocannabinoids). Although assessing these responses in this thesis was not possible, they may help partially explain some findings.

7.2.5.1 HPA Axis Response

The meta-analysis (Chapter 3) indicated that exercise at a moderate intensity for at least 10 minutes enhances subsequent cognitive task performance. Previous reviews demonstrated adverse effects on task performance when exercise lasted less than 10 minutes (Chang et al., 2012). Therefore, one of the eligibility criteria in the meta-analysis and systematic review (Chapter 3) was that the experimental studies utilised a cycling duration ranging from 10-60 minutes. The Hypothalamic-Pituitary-Adrenal (HPA) axis response to acute exercise may partially explain these parameters.

Moderate-intensity exercise may elicit an HPA axis response, which induces heightened arousal levels and improves task performance compared to vigorous-intensity exercise (Basso & Suzuki, 2017). During exercise, the anterior pituitary gland secretes adrenocorticotropic hormone (ACTH), triggering the adrenal glands' release of cortisol to maintain homeostasis (Basso & Suzuki, 2017; Budde et al., 2015). The sympathetic nervous system and the HPA axis systems regulate the central physiological stress response through intensity-dependent stimulation, with cortisol increasing after 10 minutes or more of exercise at around or above 60% $\dot{V}O_2max$ (Hill et al., 2008; Zschucke et al., 2015; Basso & Suzuki, 2017). Prior research suggests that cortisol influences memory, learning, and mood, potentially due to the presence of cortisol receptors found in brain regions such as the PFC, amygdala and hippocampus - areas that support memory and learning (Heffelfinger & Newcomer, 2001; Basso & Suzuki, 2017).

In Chapter 4, the dual-task condition may have required more effort than ergometer cycling in isolation. While acute exercise generally decreases stress-related blood pressure by suppressing the stress response in the sympathetic nervous system (Brownley et al., 2003), this may not apply to dual-task conditions - the heightened stress response while dual-tasking may hinder the benefits of exercise on task performance. For example, Becker and colleagues (2023) found an elevated sympathetic nervous system and lower parasympathetic nervous system response during a dual-task condition compared to a single-task condition. However, gamified dual-task interventions like exergaming may not have the same effect. Marques and colleagues' systematic review reported that exergames positively impact emotional experience, including reduced stress, potentially leading towards a more positive mood (Marques et al., 2023).

7.2.5.2 Neuromodulatory Changes

Corresponding with changes in HPA axis hormones, acute exercise-induced intensity-dependent neuromodulatory increases, including endogenous opioids and endocannabinoids, are associated with mood improvements (Basso & Suzuki, 2017; Raichlen et al., 2013). The endogenous opioid system regulates rewards, pain modulation, automatic control and stress response (Boecker et al., 2008), and endocannabinoids possibly alter mood states by reducing pain sensations and altering cognitive and emotional processes (Dietrich & McDaniel, 2004). The interplay of these neurochemicals may also partially explain heightened arousal levels in Chapters 4 and 6 and any changes in task performance throughout the thesis. Further, Chapter 4 posited that increased PFC blood oxygenation may result from macroscopic vasodilation, potentially linked to the endocannabinoid system's adaptive exercise response during exercise, which promotes vasodilation, enhancing blood flow during exercise (Bhattacharya et al., 2023).

7.2.5.3 Neuromodulatory Responses and Individual Differences

McMorris' (2021) interoception theory suggests that neuromodulator increases depend on factors such as motivation and fitness levels (Section 2.2.3.2), a concept that may extend beyond neurotransmitters. However, further research is required to confirm this claim. Existing literature supports this claim, as previous studies have highlighted the influence of individual differences on acute exercise's impact on the endocrine system (Mennitti et al., 2024).

Acute exercise influences circulating hormone concentrations based on exercise intensity and duration (Borer, 2003; Mennitti et al., 2024). These exercise-induced hormone concentrations (e.g., cortisol, insulin and testosterone) regulate physiological processes such as energy metabolism, hydration levels and tissue growth (Mennitti et al., 2024). Individual differences - such as age, nutritional status, genetics, sex, drug use, fitness levels, energy availability, and developmental stage - affect the hormonal response to exercise (Mennitti et al., 2024). For example, sex and gender differences influence estrogen and testosterone variations (Kudielka & Kirschbaum, 2005), and puberty and menopause may influence the endocrine response to exercise (Carmichael et al., 2021; Rubin, 2020).

The acute exercise-induced changes in various neurochemicals highlight the complexity of the brain's response to exercise. As exercise becomes routine, repeated neurophysiological changes occur, engaging feedback and long-term brain plasticity (Basso & Suzuki, 2017). Over time, these processes may alter baseline levels and lead to anatomical, structural, and physiological changes following exercise.

7.3 Overall Contributions to the Field

7.3.1 New Synthesis of Literature

First, the meta-analysis and systematic review provided an up-to-date literature synthesis. The review helped identify moderators that may have improved EFs in previous literature. This meta-analysis and systematic review provided a breakdown of moderators differing in empirical studies to analyse acute exercise's most consistent, strong, positive effects. For example, moderate intensity may be optimal for subsequent EF performance, supporting the inverted-U hypothesis. Doing so revealed a set of ‘optimal’ parameters, which may be helpful for further research into dual-task paradigms and other cycling-based interventions to enhance cognitive performance.

The findings in Chapter 3 suggest that an acute bout of cycling may enhance young adults’ EF task performance. These EFs play a critical role in everyday life, facilitating emotional regulation, decision-making, and the ability to pay attention and retain information (Diamond, 2013). Considering the relationship between EF performance and academic success (Howie & Pate, 2012), findings may promote cycling commutes to school and university, however, further research is required.

7.3.2 Novel Visual Foraging Task

A new visual foraging task (VFT) was created based on previous research on visual foraging (Kristjánsson et al., 2014). To optimise the task, 11 pilot testing phases were conducted to ensure difficulty level, and adjustments to the size of shapes, display settings, and clarity. The intended aim of the task was to engage the three core EFs: *working memory* is required to maintain a mental representation of the target stimulus (e.g., a red triangle) to search effectively, *inhibitory control* is necessary to ignore distractor stimuli with one matching feature (e.g., red circles when searching for red triangles), and *task-switching* is required to change one’s attentional set from one trial to the next. The VFT allows the researcher to determine the level of difficulty and EF demands. Future studies may adopt this VFT, which aims to mimic the complexity of the real-world visual search through dynamic, multitarget, conjunctive foraging. Previous research has reported that mentally demanding tasks that engage EFs are most effective in dual-task paradigms (Guo et al., 2020; Ji et al., 2019).

7.3.3 Immersive Reality

To investigate naturalistic visual foraging, the study in Chapter 6 used a protocol from Bishop et al.'s (2023) study. Bishop and colleagues (2023) investigated if explicit instructions before a gamified cycling immersive task would encourage 11-14-year-olds' adaptive-looking behaviour. They also assessed the impact of auditory rewards on looking behaviour – participants accrued points for fixation on target stimuli (hazard perception). Their findings suggest that the explicit learning group gained more points in the initial stages of the intervention, but by the end, the implicit group matched their performance. Such findings may reflect the effectiveness of their gamified approach, as even without explicit instruction, the participants figured out how to receive rewards and adaptively look around while on-road cycling. Unlike Bishop and colleagues' (2023) findings, the findings in Chapter 6 reveal that auditory rewards did not improve looking behaviour (increase foraging), however, the lack of auditory rewards negatively impacted forward foraging over the course of the intervention. Further, the findings in Chapter 6 reveal the potential beneficial effects of the immersive reality protocol on nonverbal reasoning performance.

7.3.4 Acute Cycling Exercise and Academic Performance

The meta-analysis and systematic review focused on EF measures, such as the Flanker, n-Back and Stroop tasks, as they are the most commonly used to assess exercise-induced changes in EF task performance. However, EF task measures may be considered low-complexity tasks, resulting in a speed-accuracy trade-off and likely not capturing EFs in real-world settings (McMorris & Hale, 2012; Niebaum & Munakata, 2023). A speed-accuracy trade-off may possibly explain improvements in RT and not RA in the meta-analysis and a lack of significant interactions in Chapter 4.

Chapters 5 and 6 included children as participants, therefore, it was important to consider a validity issue, which is that many EF tests were originally developed for adults and then applied to children (Souissi et al., 2022). Due to the greater familiarity of academic-based tasks for children and the contribution higher-order EFs have on academic subjects such as science and maths (Brookman-Byrne et al., 2019), the decision to include academic reasoning tasks was made. The reasoning tasks were developed for children aged 11+. They may be considered ecologically valid as the papers were similar to examinations used for children to enter selective secondary schools in England (BOND 11+). The findings of this thesis demonstrate the potential for acute exercise to enhance reasoning performance, providing a basis for future research; however, with limited research in the field, this still requires further scrutiny.

7.4 Limitations and Recommendations for Future Research

7.4.1 Generalisability of Findings

In Chapter 3, the systematic review and meta-analysis' inclusion criteria comprised studies published in English and with participants aged 18-35 who have no medical complexities or diagnosed impairments. This criterion limits the generalisability of these findings. The empirical studies in this thesis include UK-based individuals aged 18-35, 11-16 years old or both - limiting the generalisability of these findings to individuals outside of these cohorts. Further, while findings in Chapter 6 show the potential for improved exercise-induced nonverbal reasoning performance, the task used to assess reasoning performance matches the England National Curriculum (*BOND 11+*), therefore may not be applicable to individuals who do not attend a school in England. These limitations emphasise the need for further research of exercise-induced enhancements outside of the cohorts in this thesis.

7.4.2 Individual Differences.

Across all studies, individual differences were addressed to an extent; however, they could have been explored in more detail. The meta-analysis and review did not account for fitness levels, sex, or perceived exertion, which were all accounted for the empirical studies. Baseline data were gathered in the first empirical study (Chapter 3), but this was not the case for the second and third empirical studies, due to limited participant availability. This made it impossible to rule out practice effects to explain main effects of Time. Also, EF measures may be affected by general intelligence or cognitive ability (Souissi et al., 2022). This may have also been addressed using baseline measures and/or by gathering information on classroom performance prior to the intervention.

7.4.3 Motivation Levels

It is plausible that motivation was high in young adult samples, as they were enrolled in higher education, many of whom were also psychology students. However, taking part in an experimental study may be unfamiliar for children. It was also likely that the children were motivated to participate to experience immersive reality and/or be absent from their daily classes. Consequently, they might not have been fully committed to completing the experimental tasks. Motivational factors may account for effort perception, mental fatigue, and ego depletion, none of which were assessed in this thesis. It would be beneficial for future studies to explore whether motivation levels are linked to effort and the impact of cycling interventions on EF tasks.

7.4.4 Acute Cycling Exercise and Long-Term Benefits

The EF and reasoning tasks were administered immediately post-intervention, as per findings in Chapter 3 – largest effect sizes elicited when the EF tasks were completed immediately (0-9 minutes) after exercise. Although less, the findings in Chapter 3 suggested RT improvements when the task was administered after a short (10-19 minutes) and moderate (20-29 minutes) delay post-exercise. In this thesis, retention data was not gathered to avoid participant attrition and due to constraints in school timetabling. A cycling commute or break may improve cognitive functions, potentially enhancing classroom performance, however, it is important for future research to investigate the lasting effects of such enhancements.

7.5 Practical Applications

Although the findings of this thesis were mixed, some support that an acute bout of cycling exercise may be an effective method to improve brain function. These findings suggest that incorporating 15 to 20 minutes of cycling into your daily routine may enhance EFs. First, the meta-analysis and review aligned with previous theories and studies that moderate-intensity exercise can be a short and practical approach to enhance EFs, which serve essential functions in our daily lives. Given the relationship between EF abilities and academic attainment (Latino & Tafuri, 2023), cycling may be promoted as an encouraged mode of active travel and/or incorporated into physical activity lessons to support learning and academic success in the classroom.

The first two empirical studies (Chapters 4 & 5) suggest that individuals with lower baseline/pre-test scores in the EF and/or reasoning tasks showed greater improvements in the tasks post-intervention compared to the higher-attaining individuals. I therefore tentatively suggest that an acute bout of cycling exercise may be a helpful way to improve EFs and reasoning abilities in the immediate term, particularly for individuals with lower EF abilities.

Chapter 6 aimed to resemble outdoor cycling and navigation through 360-degree immersive, real-world footage using an HMD. Findings revealed that IR cycling may be an effective and fun way to improve nonverbal reasoning performance. As the field of exergaming is growing quickly, this study helped to support the potential benefits of exergaming, especially when considering the excitement around immersive/virtual reality in adolescent age groups – where there seems to be a decline in physical activity levels (Kann et al., 2018). Exergaming may reduce this decline while improving affect and cognitive performance.

In addition to promoting cycling to improve brain function, individuals must be trained to cycle safely. As shown in our dual-task exercise findings, attentional demands of visual foraging while concurrently cycling may be reducing attention to the latter. Effectively, engaging in visual foraging while exercising is crucial in real-world settings, such as navigating during cycle commutes.

Given the potential beneficial effects of acute exercise on EFs and academic reasoning tasks and the amount of time children spend at school, promoting exercise in education settings is important. This thesis suggests that a short cycling bout may improve some aspects of brain function, which may help encourage individuals to choose cycling as a mode of active travel to work, university or school. The positive influence of cycling on brain health is one of the many holistic benefits of cycling and exercise that also expand to physical health (Oja et al., 2011), mental health (Logan et al., 2023), environmental impact (Brand, 2021), chronic disease prevention (Logan et al., 2023), economic advantages (Gravett & Mundaca, 2021), social and community benefits, and inclusivity (Cook et al., 2022).

7.6 Conclusion

An acute bout of cycling exercise may enhance subsequent executive function (EF) task performance; however, moderating variables must be considered. Moderate-intensity cycling interventions for 21 to 30 minutes, predominantly in the inhibitory control component of EF, may yield the greatest benefits after ergometer cycling. Pre-existing individual differences in EF abilities may mediate enhancements. Young adults with lower baseline inhibitory control benefitted more from ergometer cycling than those with higher abilities.

This trend was also seen in children's reasoning performance. Conversely, children with higher inhibitory control abilities exhibited more pronounced improvements after ergometer cycling than those with lower abilities, suggesting age-related differences in inhibitory control abilities.

Ergometer cycling posited greater EF and reasoning task improvements than concurrent ergometer cycling and visual foraging. The additional attentional demands of visual foraging while ergometer cycling may have decreased focus on the latter. This was suggested based on the young adult participants' physical output and the relationship between prefrontal cortex (PFC) activation and gaze behaviour, which may reflect an oxygen turnover. However, nonverbal reasoning improved after naturalistic visual foraging while stationary cycling, regardless of age or auditory rewards. Although there have been no direct comparisons between the visual foraging task and immersive reality foraging, it is tentatively suggested that the latter may have reduced dual-task deficits and mental fatigue due to greater immersion and enjoyment. Further research is required to support this claim. Additionally, post-intervention tasks were not influenced by rewards, but in-task foraging was. Forward foraging declined without reward sounds, but overall foraging increased, suggesting a trade-off between forward and right/left foraging. This trade-off reflects real-world cycling observation, which is essential for safe cycling.

The main contribution of this thesis to the literature is that acute cycling exercise can potentially improve brain function when the appropriate moderators and secondary tasks are selected. Considering the numerous benefits of exercise demonstrated over the years, this thesis addresses the complexity of outdoor exercising while still in a lab-based setting by exploring the impact of complex visual searches during ergometer/stationary cycling on PFC oxygenation, affective response, physical output, and looking behaviour. Given the importance of reasoning in academic achievement, findings in this thesis advocate for further investigation into how acute cycling exercise could positively influence performance in reasoning and other academic-based tasks.

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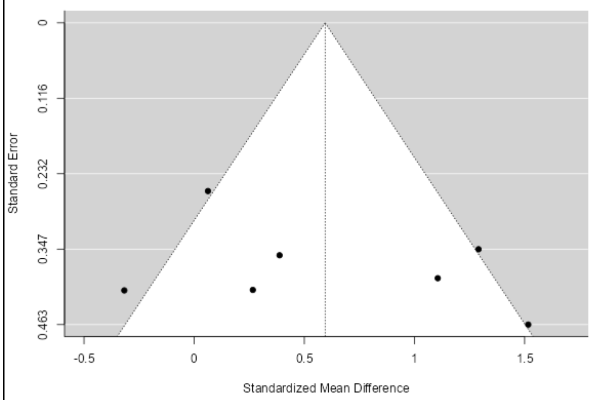
APPENDICES

APPENDIX A: Chapter 3 Funnel Plots

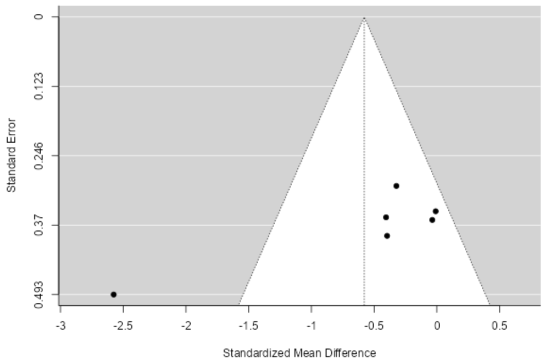
Moderators

Duration

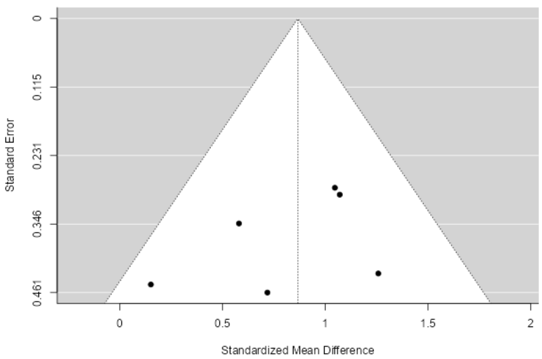
10-20 minutes RT



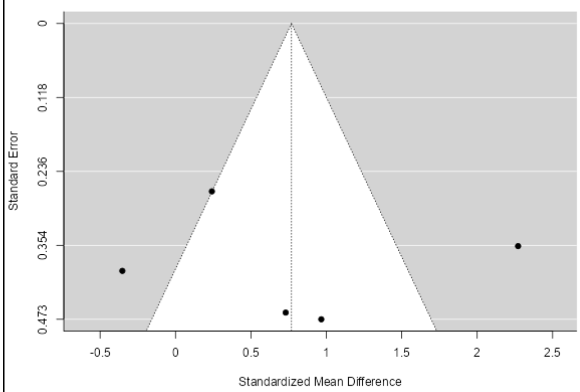
10-20 minutes RA



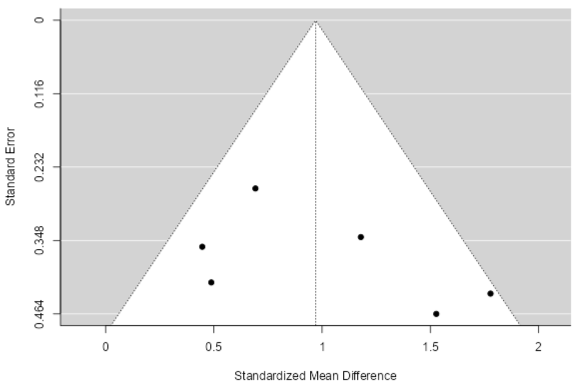
21-30 minutes RT



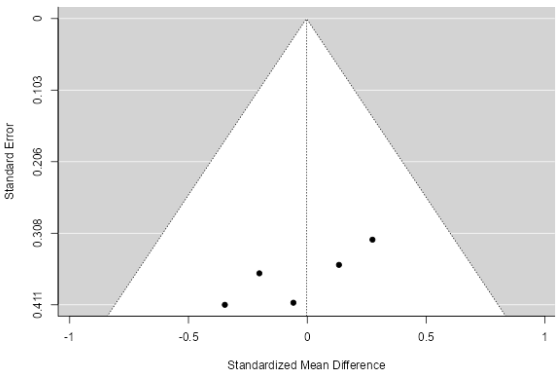
21-30 minutes RA



31-40 minutes RT



31-40 minutes RA



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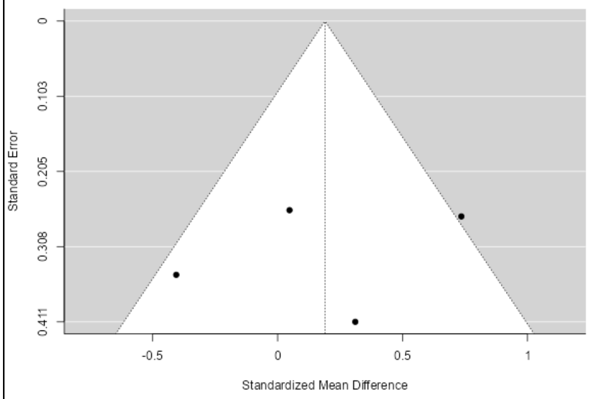
<tr><td>
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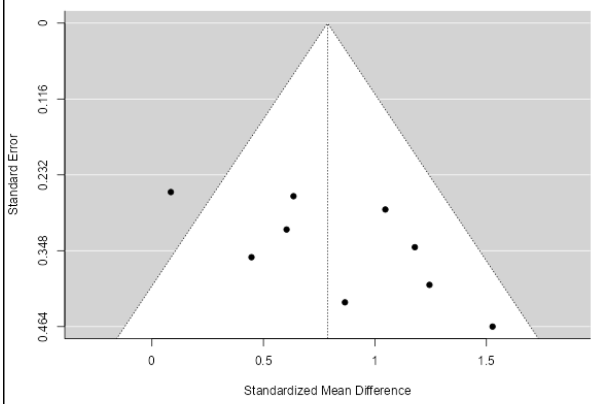
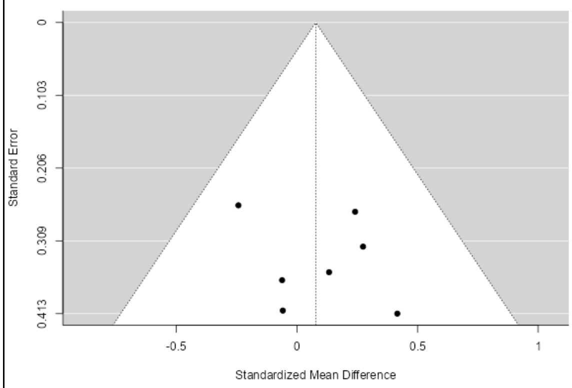
<tr><td>
</td><td>
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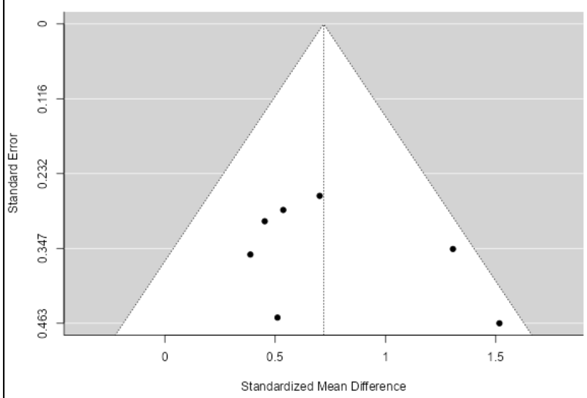
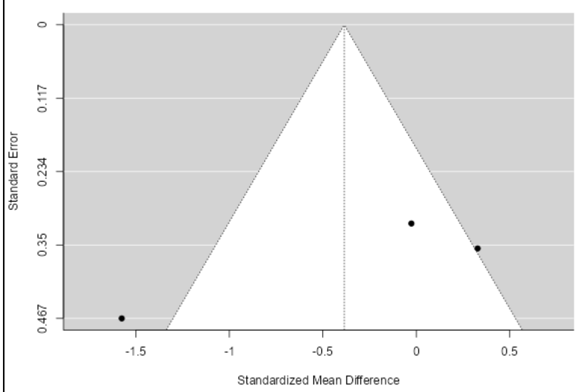
<tr><td>
</td><td>
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<tr><td>Inhibitory Control RT</td><td>Inhibitory Control RA</td></tr>
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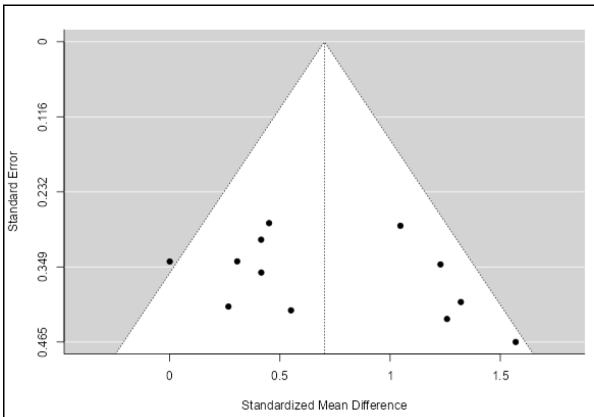
<td>
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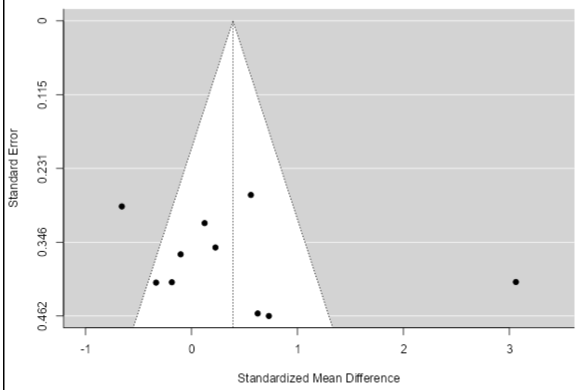
<td>
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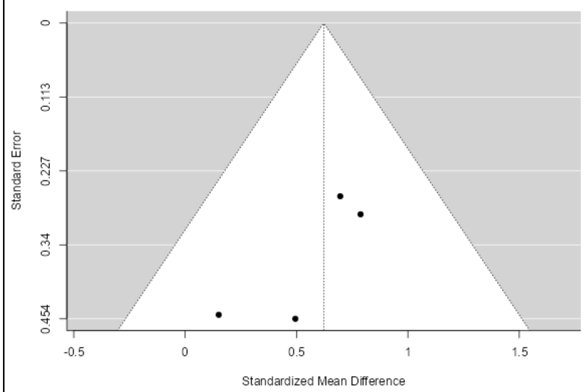
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<td>Cognitive Flexibility RA
Not enough data (n = 2)</td>
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<td colspan="2">EF Task Onset</td>
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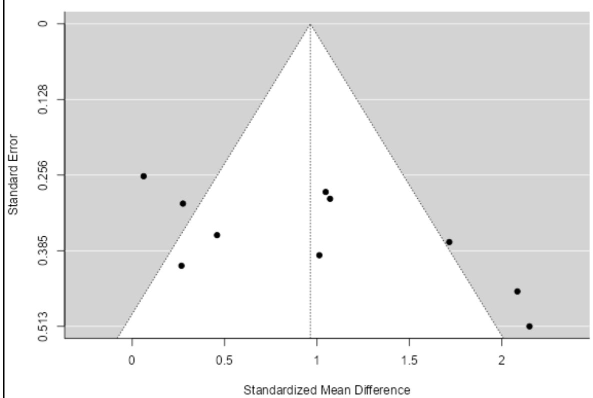
<tr>
<td>0-9 minutes post RT

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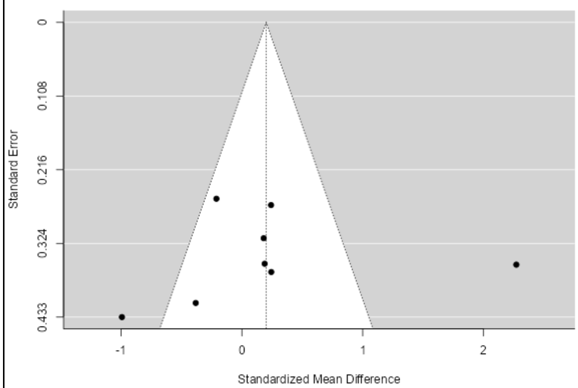
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<tr>
<td>10-19 minutes post RT</td>
<td>10-19 minutes post RA</td>
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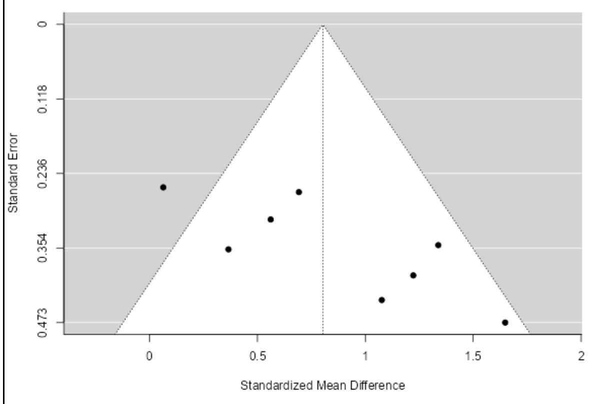
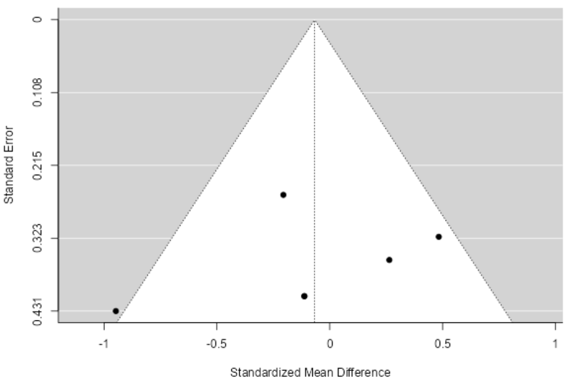
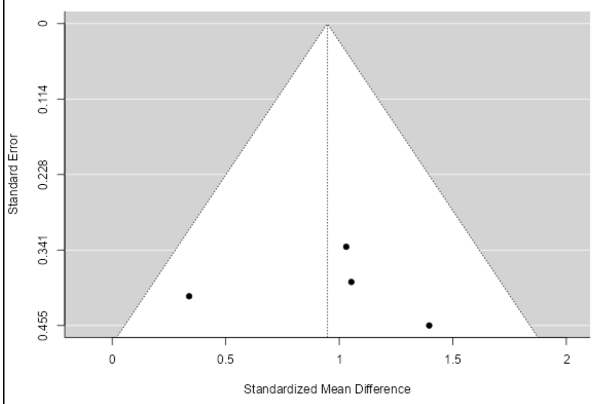
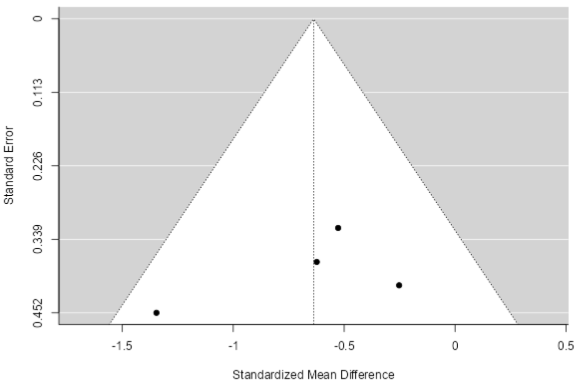




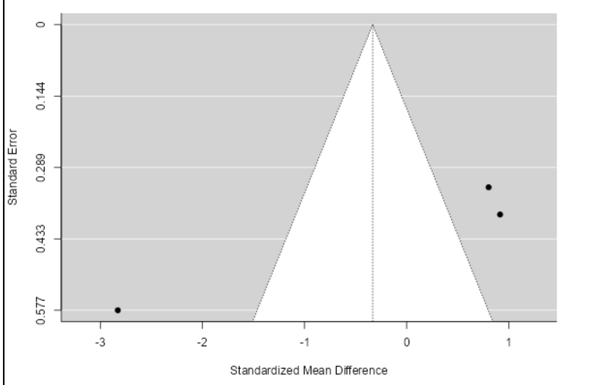
20-29 minutes post RT



20-29 minutes post RA



>30 minutes post RT



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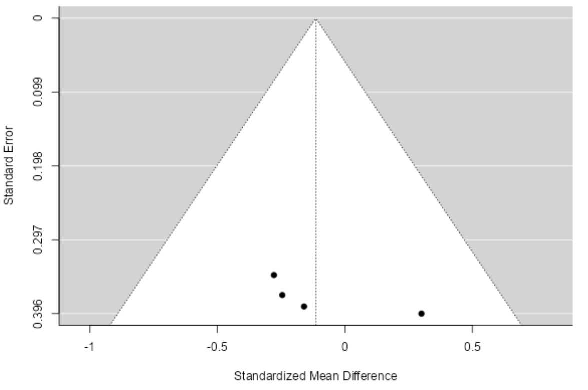
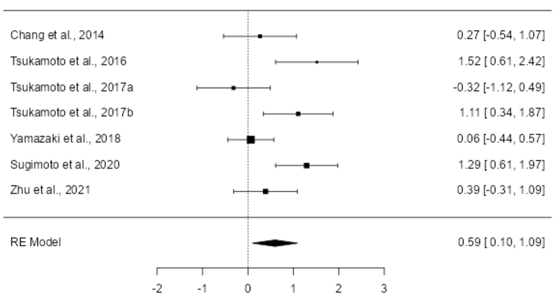


APPENDIX B: Chapter 3 Forest Plots

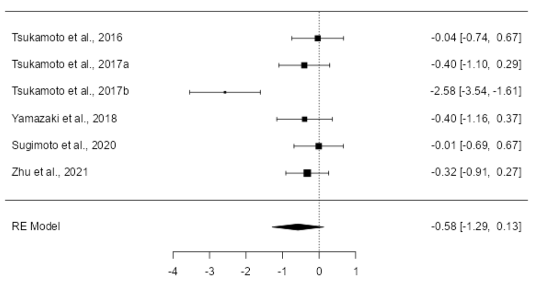
Moderators

Duration

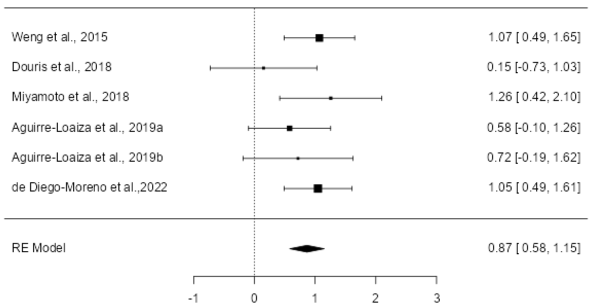
10-20 minutes RT



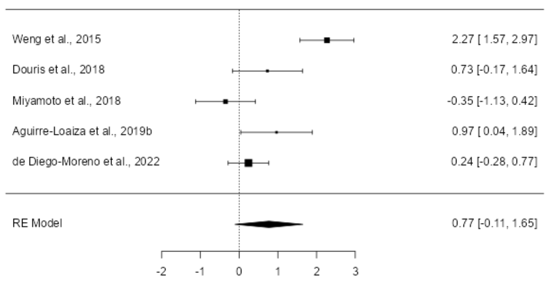
10-20 minutes RA



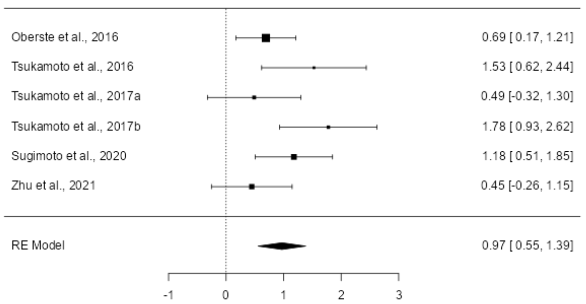
21-30 minutes RT



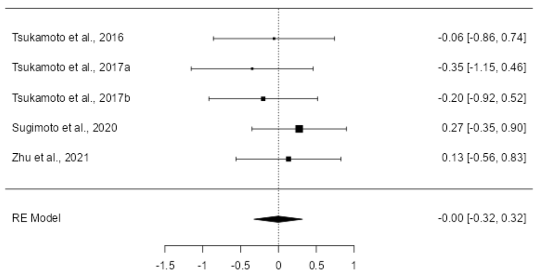
21-30 minutes RA



31-40 minutes RT

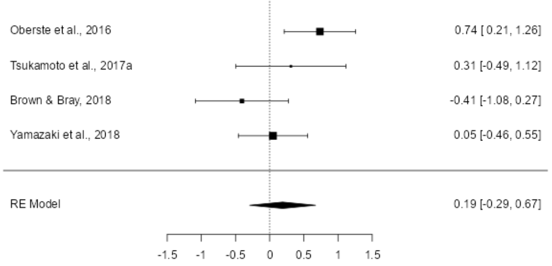


31-40 minutes RA



Intensity

Low Intensity RT

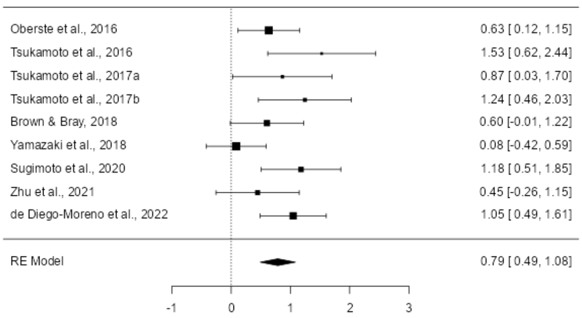


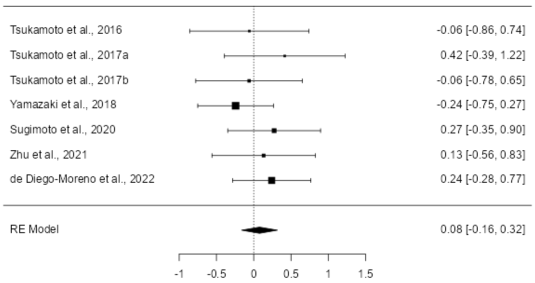
Low Intensity RA

Not enough data (n = 2)

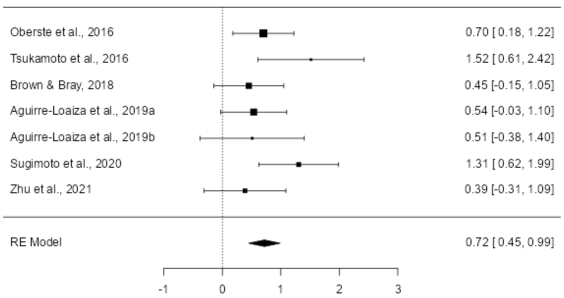
Moderate Intensity RT

Moderate Intensity RA

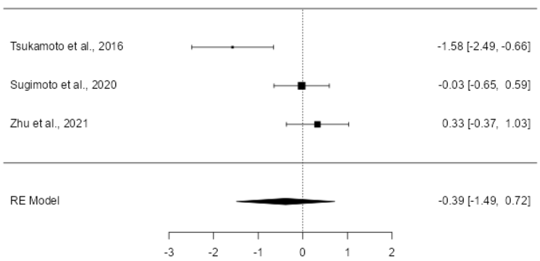




High Intensity RT

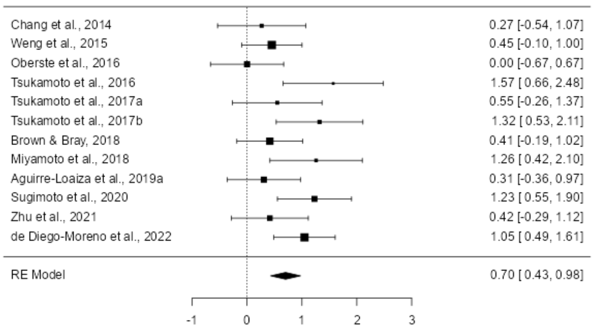


High Intensity RA

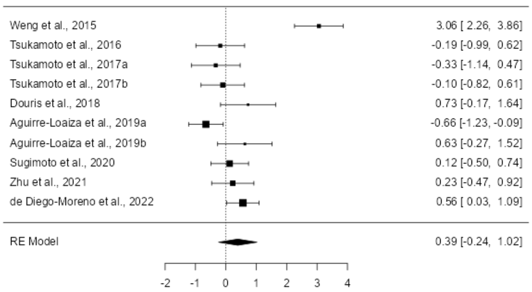


EF Task Type

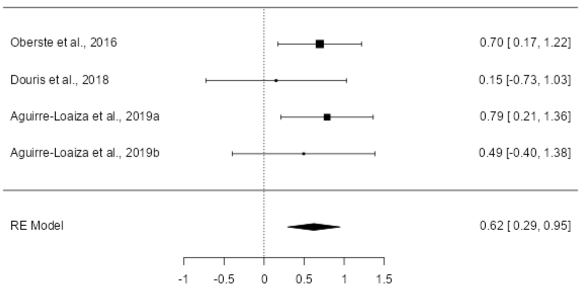
Inhibitory Control RT



Inhibitory Control RA



Cognitive Flexibility RT



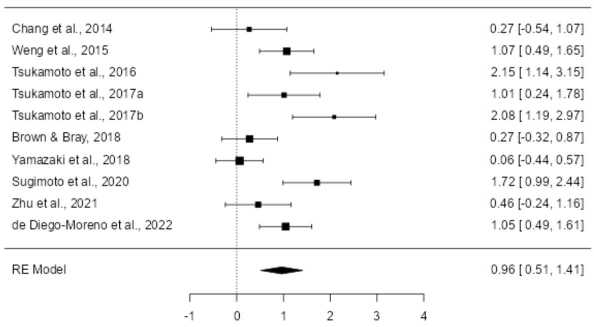
Cognitive Flexibility RA

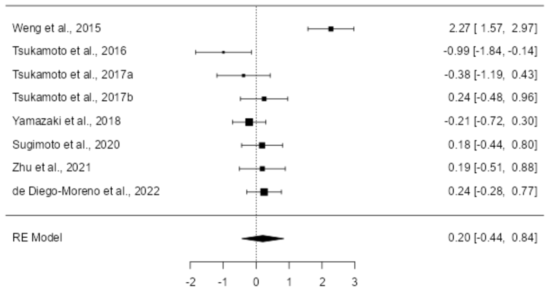
Not enough data (n = 2)

EF Task Onset

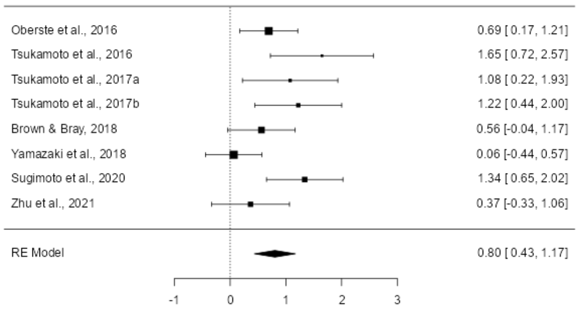
0-9 minutes post RT

0-9 minutes post RA

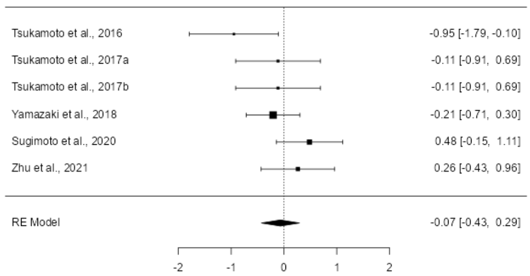




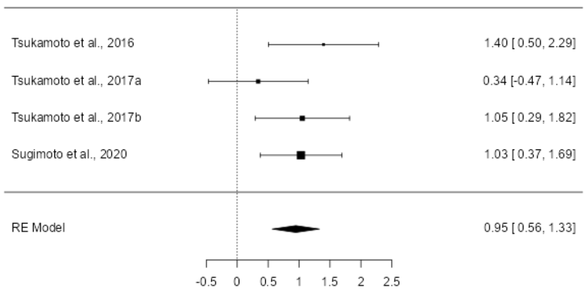
10-19 minutes post RT



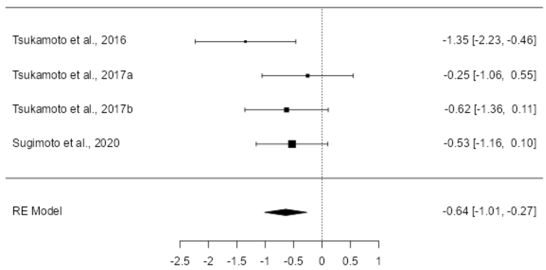
10-19 minutes post RA



20-29 minutes post RT



20-29 minutes post RA



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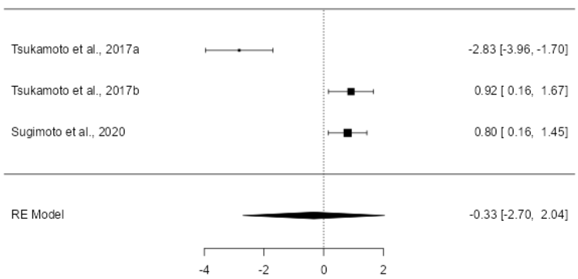
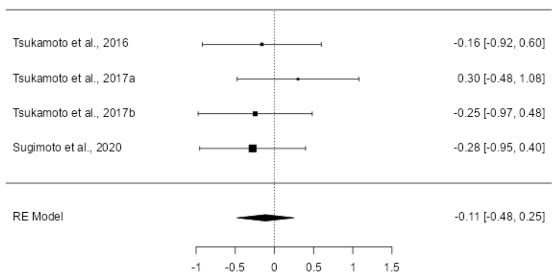


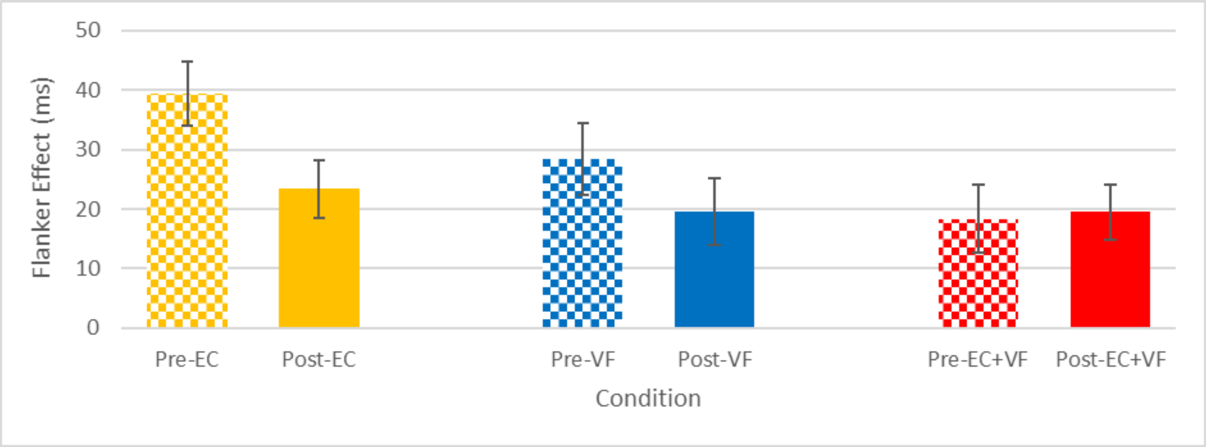
>30 minutes post RA

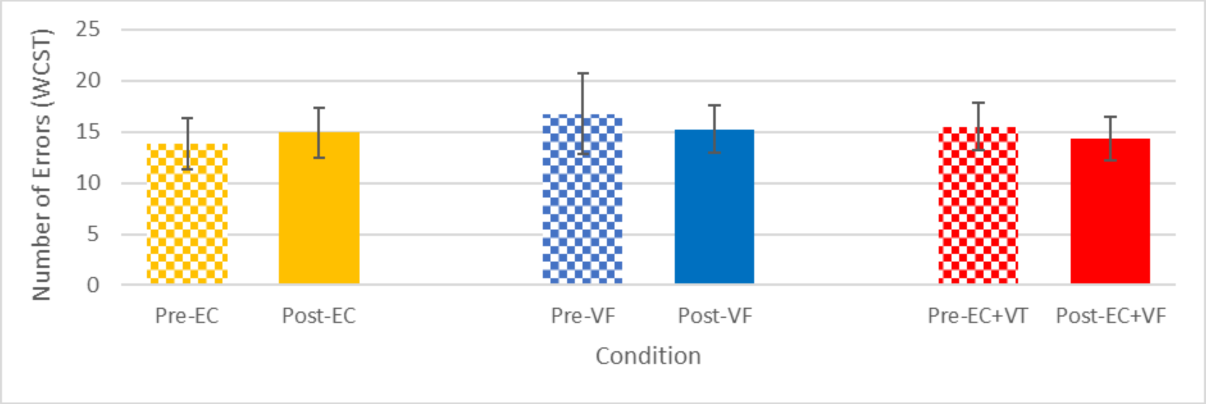


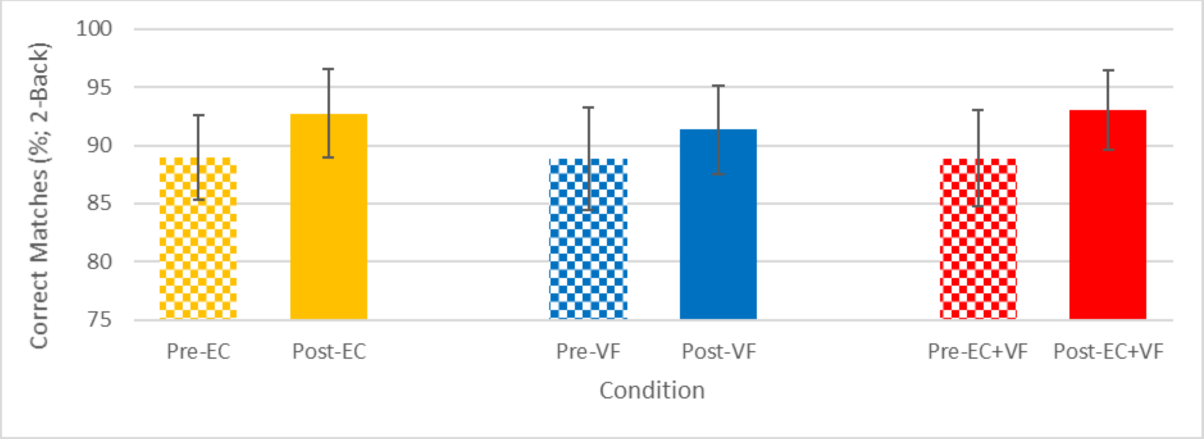
APPENDIX C: Chapter 4 Physiological Measures during $\dot{V}O_{2max}$ testing

		N	Missing	Mean	Median	SD	Min.	Max.
Borg's RPE	Pre	27	0	7.32	6.00	2.12	6.00	13.00
	Post	27	0	16.44	17.00	2.71	7.00	20.00
Lactate (mmol/L)	Pre	22	5	1.35	1.18	0.63	0.53	3.15
	Post	23	4	7.56	7.60	2.59	3.12	14.70
Heart Rate (bpm)	Pre	27	0	75.52	73.00	11.80	57.00	104.00
	Post	27	0	178.33	181.00	12.10	150.00	197.00

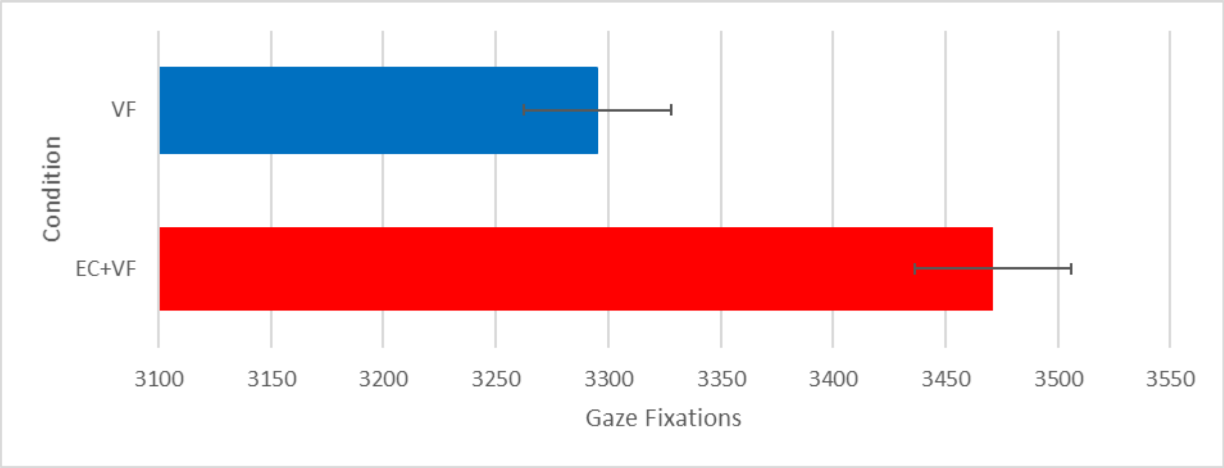
APPENDIX D: Chapter 4 Mean (± SE) EF Task Scores, pre- and post- intervention, by Condition.



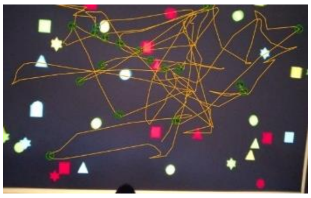
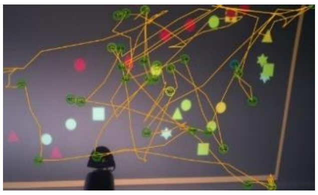
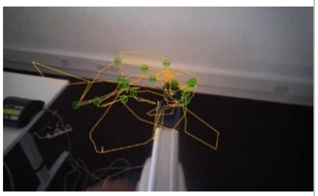
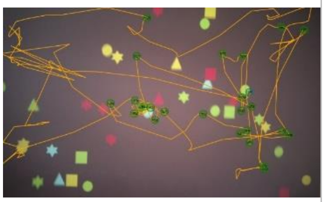




APPENDIX E: Chapter 5 Mean (± SE) Gaze Fixations, by Condition.



APPENDIX F: Chapter 4 Sample Gaze Maps, by Condition. Maps represent Session 2, Trial 3, of the VFT for EC+VF and VF. The EC maps represent the halfway point of the intervention.

	EC+VF	VF	EC
Participant A			
Participant B			
Participant C			

APPENDIX G: Chapter 6 Descriptive Statistics, by subgroup

	Shapiro-Wilk					
	W	**p**	**Skewness**	**SE**	**Kurtosis**	**SE**
			In-Task Learning			
Overall Epoch 1	.96**	.179**	-.76	.37	1.21	.73
Age Groups						
Children	.97**	.84**	.47	.51	-.15	.99
Young Adults	.96**	.52**	-.60	.51	.02	.99
Condition						
Reward Sounds	.96**	.98**	-.07	.50	-.44	.97
No Reward Sounds	.97**	.34**	-1.50	.52	3.88	1.01
Overall Epoch 2	.97**	.337**	-.54	.37	.93	.73
Age Groups						
Children	.99**	.987**	.16	.51	.18	.99
Young Adults	.96**	.625**	-.52	.51	.28	.99
Condition						
Reward Sounds	.99**	.989**	-.21	.50	-.05	.97
No Reward Sounds	.94**	.312**	-.76	.52	1.64	1.01
Forward Epoch 1	.95**	.095**	-.77	.37	1.23	.73
Age Groups						
Children	.97**	.71**	.55	.51	.27	.99
Young Adults	.95**	.34**	-.58	.51	-.17	.99
Condition						
Reward Sounds	.99**	.977**	-.19	.50	.18	.97

No Reward Sounds	.88	.022	-1.48	.52	3.80	1.01
Forward Epoch 2	.94	.048	-.75	.37	1.23	.73
Age Groups						
Children	.98**	.964**	-.06	.51	.26	.99
Young Adults	.94**	.240**	-.63	.51	.28	.99
Condition						
Reward Sounds	.95**	.310**	-.65	.50	.62	.97
No Reward Sounds	.92**	.122**	-.84	.52	1.97	1.01
Right Epoch 1	.91	.003	-.08	.37	-.28	.73
Age Groups						
Children	.88	.015	-.18	.51	-.21	.99
Young Adults	.90	.047	.22	.51	-.20	.99
Condition						
Reward Sounds	.86	.006	.48	.50	.05	.97
No Reward Sounds	.91**	.088**	-.44	.52	-.32	1.01
Right Epoch 2	.84	< .001	.36	.37	.01	.73
Age Groups						
Children	.72	< .001	.79	.51	-.21	.99
Young Adults	.87	.010	.42	.51	-.11	.99
Condition						
Reward Sounds	.81	< .001	.67	.50	.28	.97
No Reward Sounds	.86	.011	.08	.52	-.01	1.01
Left Epoch 1	.84	< .001	1.25	.37	1.93	.73
Age Groups						

Children	.82	.002	1.43	.51	2.17	.99
Young Adults	.87	.014	.84	.51	1.24	.99
Condition						
Reward Sounds	.84	.003	1.08	.50	1.83	.97
No Reward Sounds	.86	.008	1.23	.52	1.66	1.01
Left Epoch 2	.96**	.194**	.34	.37	-.04	.73
Age Groups						
Children	.94**	.237**	.82	.51	.81	.99
Young Adults	.93**	.181**	-.22	.51	-.43	.99
Condition						
Reward Sounds	.95**	.280**	.61	.50	1.58	.97
No Reward Sounds	.87	.027	.07	.52	-1.26	1.01
Rear Epoch 1	.29	< .001	3.35	.37	9.74	.73
Age Groups						
Children	.43	< .001	2.12	.51	2.78	.99
Young Adults	N/A	N/A	N/A	N/A	N/A	N/A
Condition						
Reward Sounds	.34	< .001	2.97	.50	7.56	.97
No Reward Sounds	.24	< .001	4.36	.52	19	1.01
Rear Epoch 2	.29	< .001	4.11	.37	17.6	.73
Age Groups						
Children	.35	< .001	3.44	.51	11.9	.99
Young Adults	.24	< .001	4.47	.51	20.0	.99
Condition						

Reward Sounds	.23	< .001	4.58	.50	21.0	.97
No Reward Sounds	.36	< .001	2.80	.52	6.51	1.01
			EF Tasks			
Flanker Effect Pre-	.92	.010	1.17	.38	1.86	.74
Age Groups						
Children	.89	.026	1.54	.52	3.32	1.01
Young Adults	.92**	.081**	1.26	.51	2.07	.99
Condition						
Reward Sounds	.91**	.067**	1.09	.50	1.06	.97
No Reward Sounds	.95**	.454**	.73	.54	.72	1.04
Flanker Effect Post-	.95**	.081**	.82	.38	1.69	.75
Age Groups						
Children	.98**	.937**	-.02	.51	-.38	.99
Young Adults	.89	.034	1.16	.54	2.12	1.04
Condition						
Reward Sounds	.92**	.09**	1.09	.52	3.22	1.01
No Reward Sounds	.96**	.582**	.68	.52	1.10	1.01
2-Back Correct Matches Pre-	.93	.023	-.30	.38	-1.05	.74
Age Groups						
Children	.95**	.332**	< -.01	.52	-.36	1.01
Young Adults	.82	.002	-1.11	.51	-.01	.99
Condition						
Reward Sounds	.94**	.175**	-.08	.50	-1.08	.97

No Reward Sounds	.91**	.07**	-.48	.54	-1.16	1.04
2-Back Correct Matches Post-	.92	.014	-.84	.40	.39	.79
Age Groups						
Children	.96**	.661**	-.59	.56	.55	1.09
Young Adults	.86	.012	-1.05	.54	.078	1.04
Condition						
Reward Sounds	.92**	.137**	-.84	.55	.53	1.06
No Reward Sounds	.92**	.158**	-.65	.55	-.67	1.06
			Academic Reasoning Tasks			
Verbal Reasoning						
Efficiency Pre-	.85	.006	.49	.37	-.31	.73
Age Groups						
Children	.96**	.607**	.05	.51	-.89	.99
Young Adults	.91	.067**	.95	.51	.19	.99
Condition						
Reward Sounds	.96**	.415**	.47	.50	-.23	.97
No Reward Sounds	.95**	.339**	.63	.52	-.43	1.01
Efficiency Post-	.93	.018	.72	.37	-.25	.73
Age Groups						
Children	.93**	.184**	.48	.51	-.74	.99
Young Adults	.85	.006	1.07	.51	.01	.99
Condition						
Reward Sounds	.93**	.153**	.87	.50	.46	.97

No Reward Sounds	.91**	.069**	.59	.52	-.91	1.01
Percent Correct Pre-	.96**	.169**	-.12	.37	-1.03	.73
Age Groups						
Children	.93**	.135**	-.13	.51	-1.37	.99
Young Adults	.96**	.469**	.01	.51	-1.17	.99
Condition						
Reward Sounds	.94**	.242**	-.10	.50	-1.28	.97
No Reward Sounds	.97**	.761**	-.04	.52	-.69	1.01
Percent Correct Post-	.96**	.112**	.10	.37	-.66	.73
Age Groups						
Children	.95**	.342**	-.09	.51	-1.12	.99
Young Adults	.85	.005	.77	.51	-.04	.99
Condition						
Reward Sounds	.94**	.206**	.11	.50	-.71	.97
No Reward Sounds	.97**	.781**	.10	.52	-.42	1.01
Completion Time Pre-	.72	< .001	-1.45	.37	1.32	.73
Age Groups						
Children	.83	.003	-.97	.51	.04	.99
Young Adults	.56	< .001	-2.02	.51	3.00	.99
Condition						
Reward Sounds	.72	< .001	-.99	.50	-.56	.97
No Reward Sounds	.69	< .001	-2.09	.52	4.48	1.01
Completion Time Post-	.79	< .001	-.86	.37	-.61	.73
Age Groups						

Children	.91**	.052**	-.06	.51	-1.32	.99
Young Adults	.59	< .001	-2.00	.51	3.25	.99
Condition						
Reward Sounds	.80	< .001	-.54	.50	-1.36	.97
No Reward Sounds	.76	< .001	-1.31	.52	.71	1.01
Nonverbal Reasoning						
Efficiency Pre-	.92	.010	1.07	.37	2.14	.733
Age Groups						
Children	.92**	.099**	.95	.37	.51	.73
Young Adults	.96**	.510**	.37	.51	1.87	.99
Condition						
Reward Sounds	.93**	.136**	.69	.50	.83	.97
No Reward Sounds	.93**	.179**	.26	.52	-1.05	1.01
Efficiency Post-	.91	.003	1.44	.37	3.75	.73
Age Groups						
Children	.87	.013	1.52	.51	2.91	.99
Young Adults	.98**	.889**	-.03	.51	-.86	.99
Condition						
Reward Sounds	.96**	.424**	.42	.50	-.34	.97
No Reward Sounds	.84	.004	1.85	.52	4.86	1.01
Percent Correct Pre-	.96**	.111**	-.40	.37	-.59	.73
Age Groups						
Children	.95**	.296**	.05	.51	-.96	.99
Young Adults	.92**	.117**	-.55	.51	.74	.99

Condition						
Reward Sounds	.93**	.154**	-.68	.50	-.23	.97
No Reward Sounds	.94**	.247**	-.10	.52	-.69	1.01
Percent Correct Post-	.97**	.284**	-.18	.37	-.52	.73
Age Groups						
Children	.95**	.379**	-.28	.51	-.17	.99
Young Adults	.95**	.370**	-.63	.51	-.02	.99
Condition						
Reward Sounds	.95**	.394**	-.41	.50	-.68	.97
No Reward Sounds	.96**	.624**	.06	.52	.07	1.01
Completion Time Pre-	.89	.001	-.46	.37	-1.05	.73
Age Groups						
Children	.95**	.395**	.45	.51	-.43	.99
Young Adults	.76	< .001	-1.65	.51	2.96	.99
Condition						
Reward Sounds	.88	.019	-.41	.50	-1.34	.97
No Reward Sounds	.89	.019	-.30	.52	-1.27	1.01
Completion Time Post-	.89	< .001	-.36	.37	-1.27	.73
Age Groups						
Children	.85	.005	.10	.51	-1.76	.99
Young Adults	.89	.025	-.35	.51	-1.26	.99
Condition						
Reward Sounds	.90	.034	-.16	.50	-1.39	.97
No Reward Sounds	.87	.013	-.63	.52	-.99	1.01

Affect Grid						
Arousal Pre-	.96**	.192**	.06	.37	-.60	.73
Age Groups						
Children	.93**	.149**	.13	.51	-1.22	.99
Young Adults	.97**	.639**	-.16	.51	.56	.99
Condition						
Reward Sounds	.41**	.95**	.13	.50	-.59	.97
No Reward Sounds	.96**	.595**	.05	.52	-.59	1.01
Arousal Post-	.90	.002	-.85	.37	.12	.73
Age Groups						
Children	.88	.015	-.1.03	.51	.52	.99
Young Adults	.93**	.150**	-.75	.51	.12	.99
Condition						
Reward Sounds	.87	.008	-1.24	.50	1.52	.97
No Reward Sounds	.92**	.116**	-.50	.52	-.59	1.01
Pleasantness Pre-	.89	.001	-.99	.37	.75	.73
Age Groups						
Children	.87	.011	-1.30	.51	1.78	.99
Young Adults	.88	.020	-.85	.51	.77	.99
Condition						
Reward Sounds	.86**	.006**	-.92	.50	-.23	.97
No Reward Sounds	.92**	-.92	.50	-.23	.97	.86
Pleasantness Post-	.88	< .001	-.92	.37	.07	.73
Age Groups						

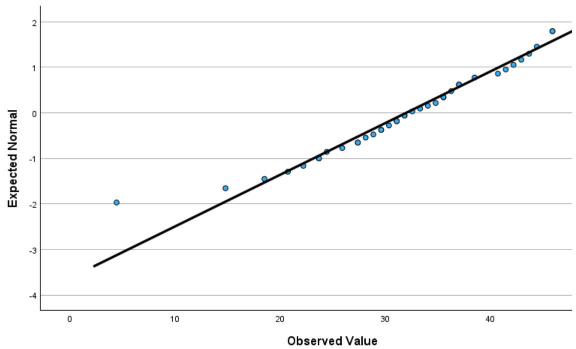
Children	.75	< .001	-1.86	.51	3.33	.99
Young Adults	.93**	.161**	-.46	.51	-.70	.99
Condition						
Reward Sounds	.90	.041	-.80	.50	-.27	.97
No Reward Sounds	.86	.010	-.94	.52	.15	1.01

Note: ** means the data was normally distributed

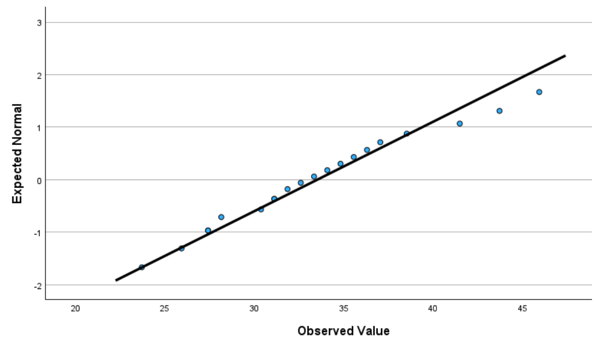
APPENDIX H. Chapter 6 Q-Q Plots, by subgroup

In -Task Learning

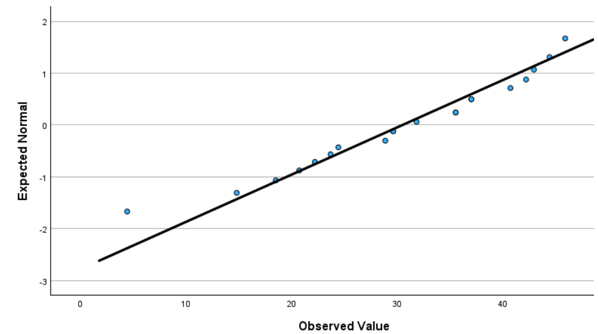
Overall Epoch 1



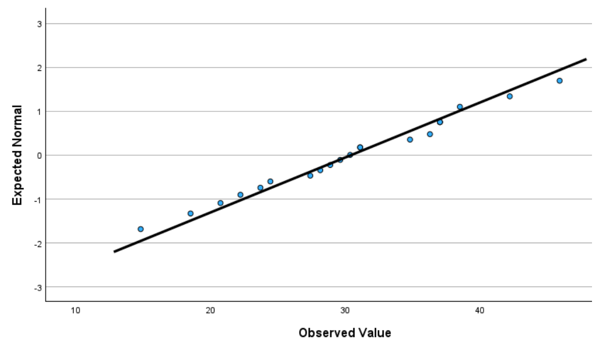
Children



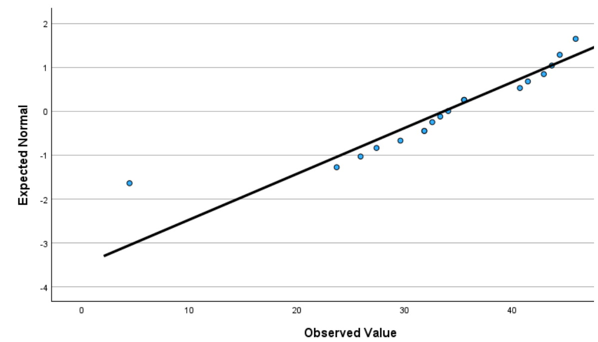
Young Adults



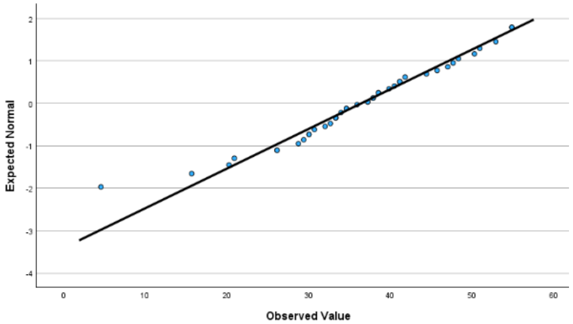
Rewards



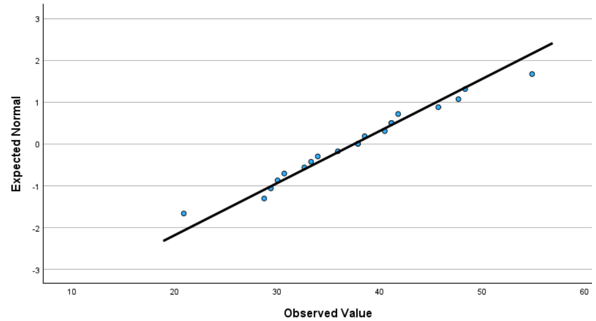
No Rewards



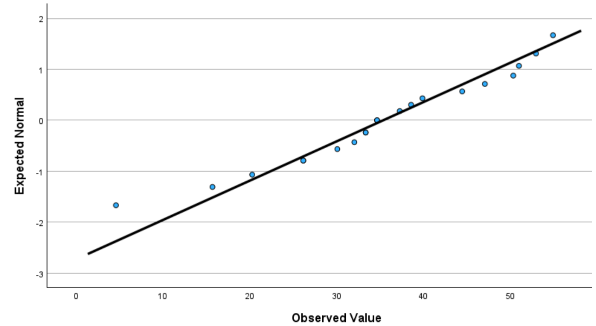
Overall Epoch 2



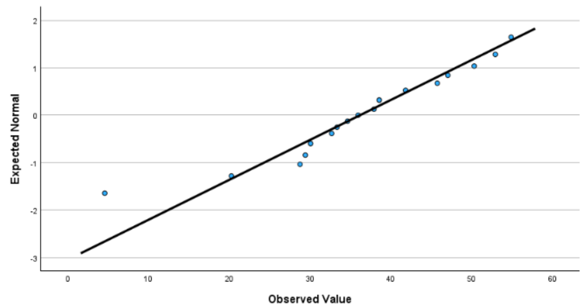
Children



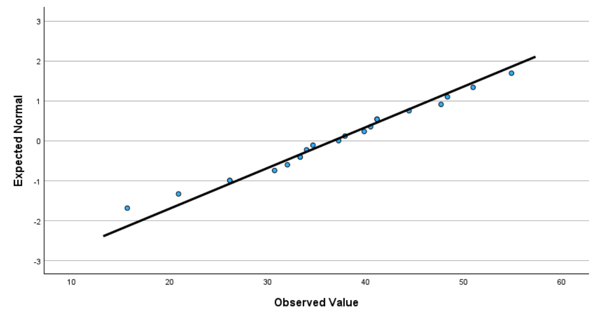
Young Adults



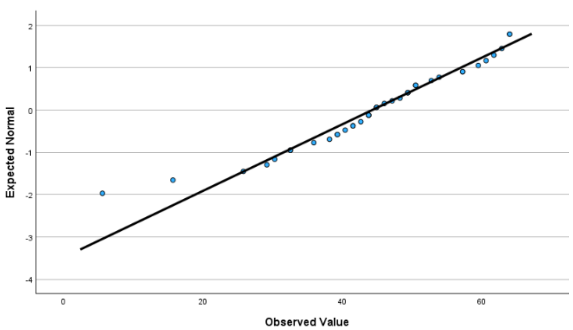
Rewards



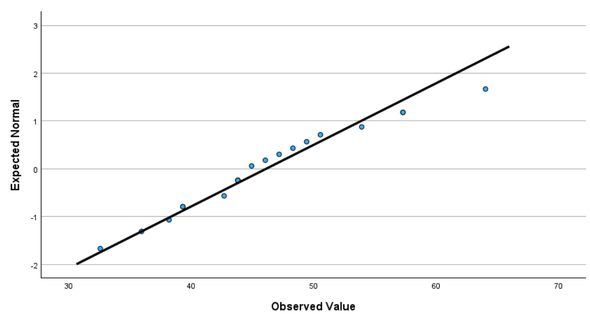
No Rewards



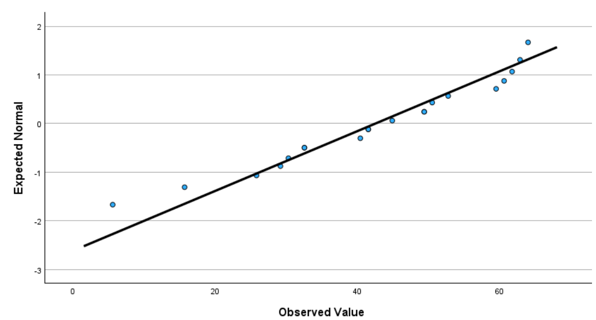
Forward Epoch 1



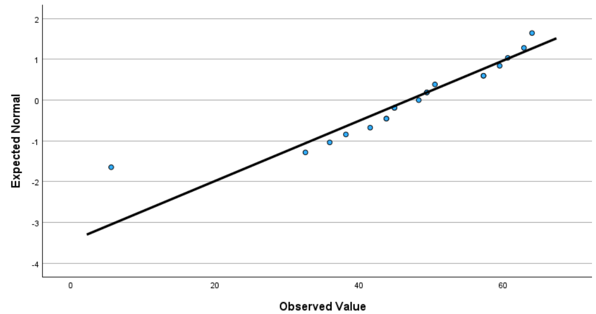
Children



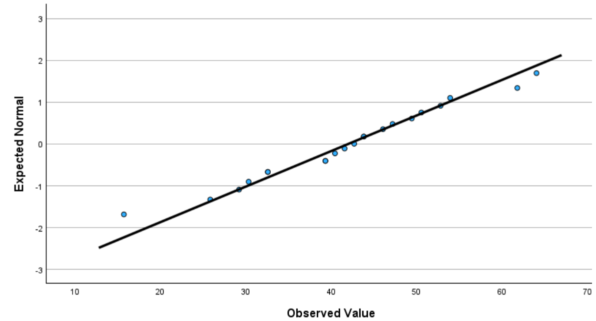
Young Adults



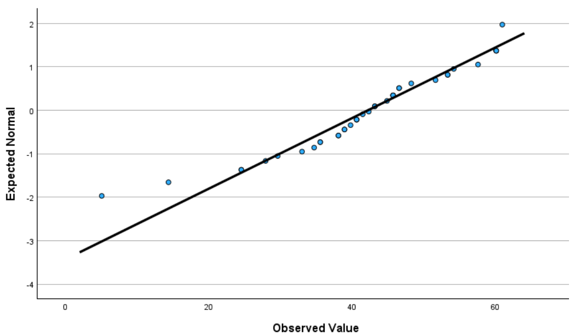
Rewards



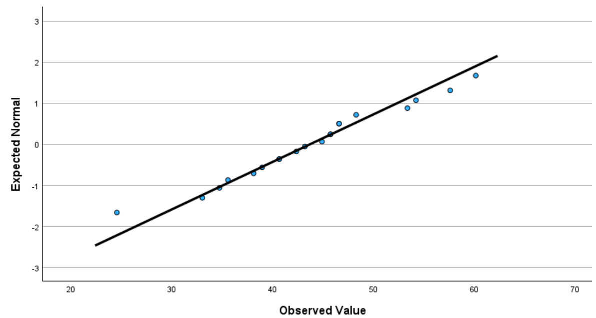
No Rewards



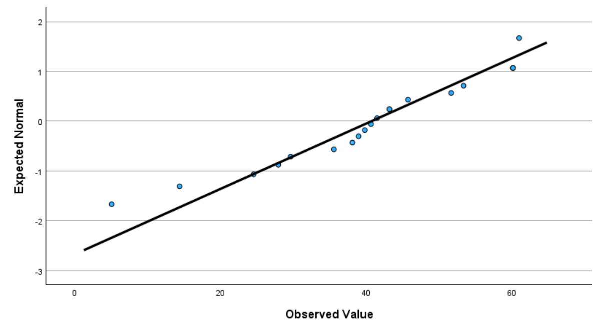
Forward Epoch 2



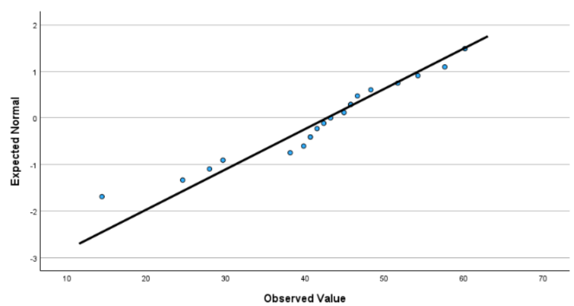
Children



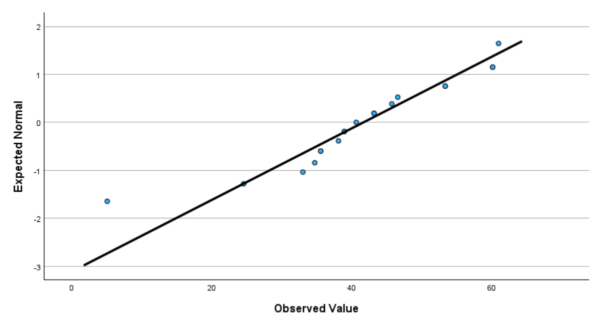
Young Adults



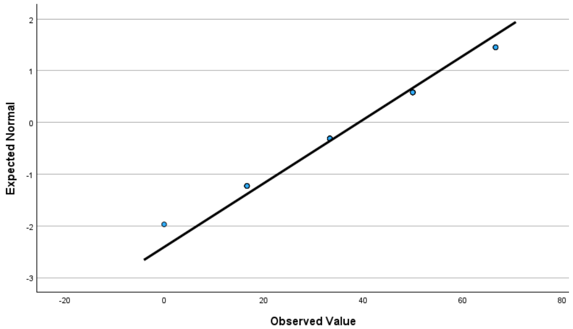
Rewards



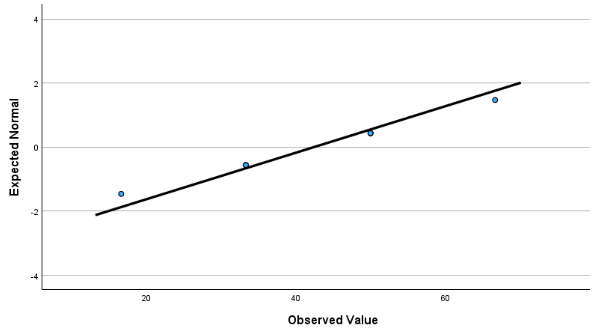
No Rewards



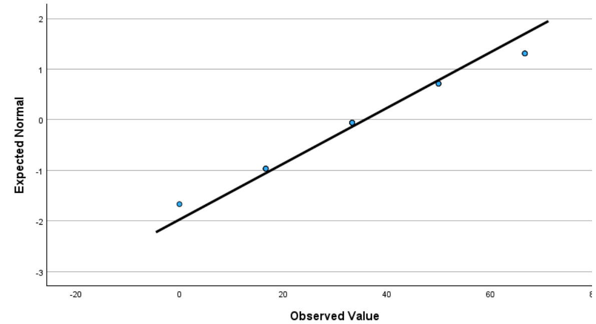
Right Epoch 1



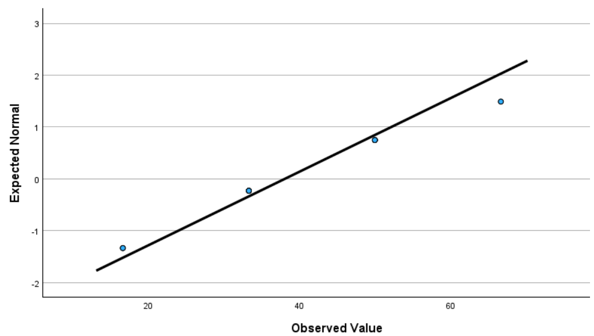
Children



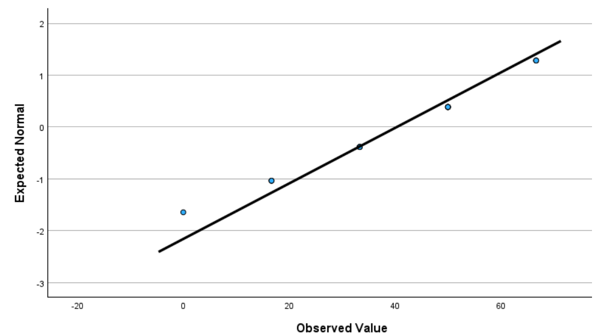
Young Adults



Rewards



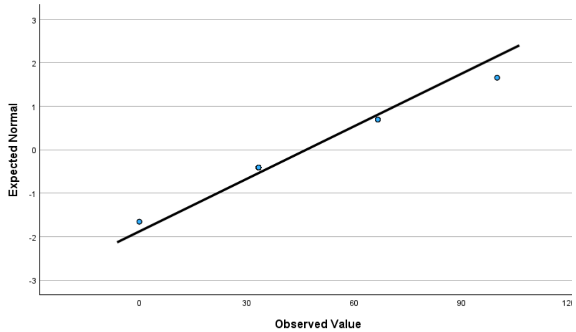
No Rewards

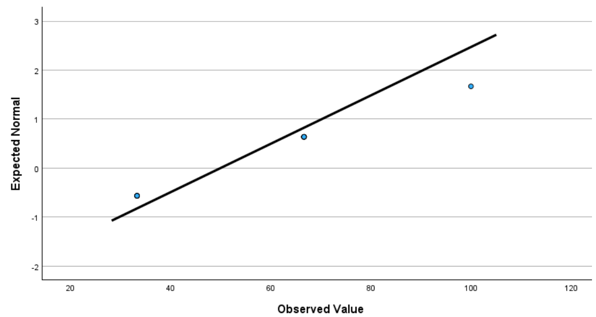


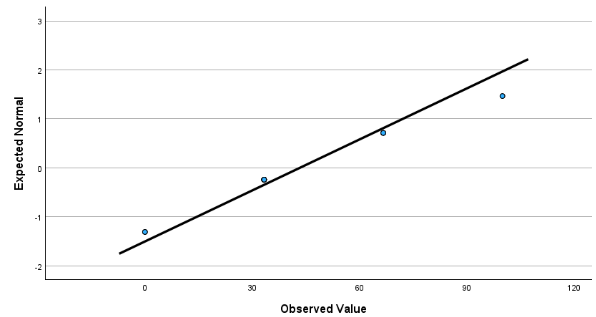
Right Epoch 2

Children

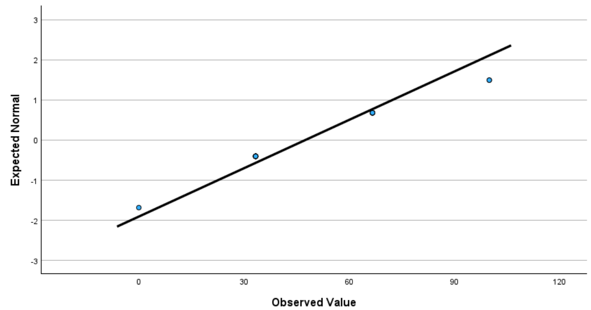
Young Adults

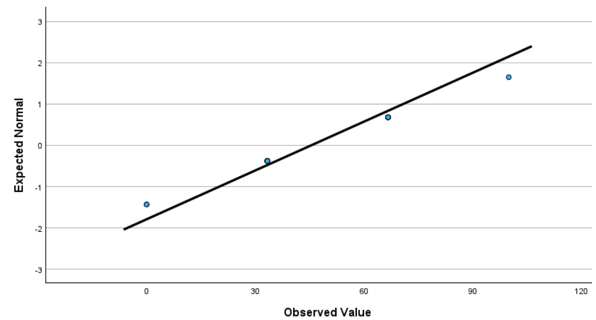




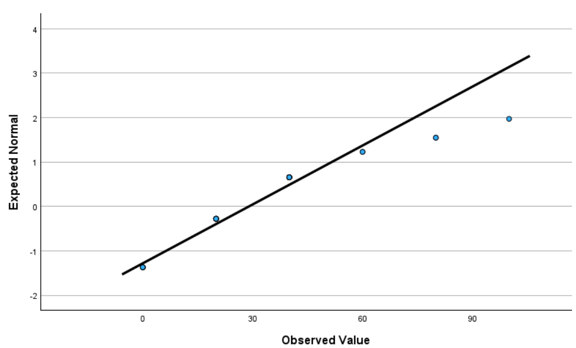


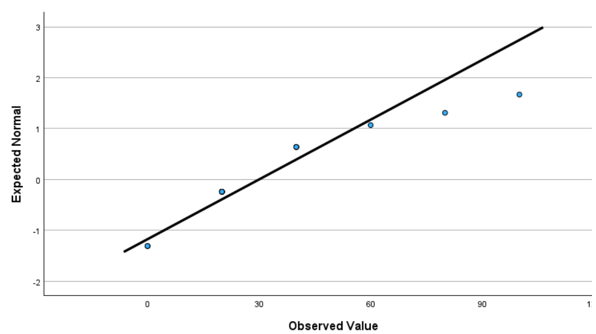
Rewards ***No Rewards***

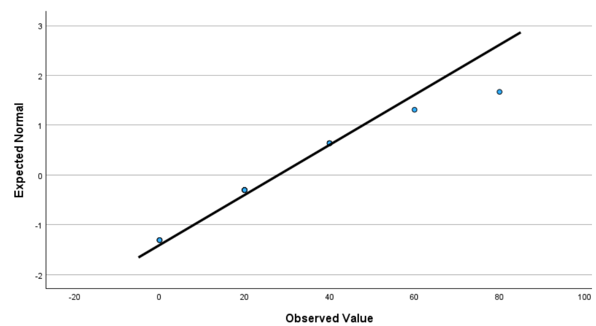




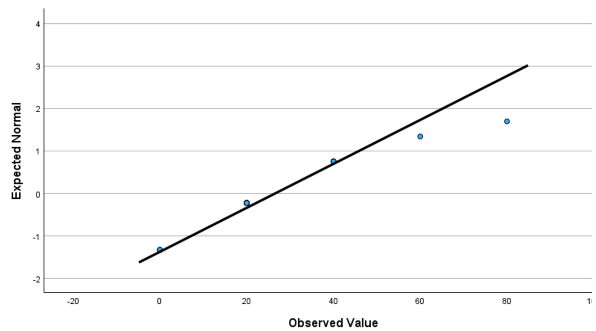
Left Epoch 1 ***Children*** ***Young Adults***

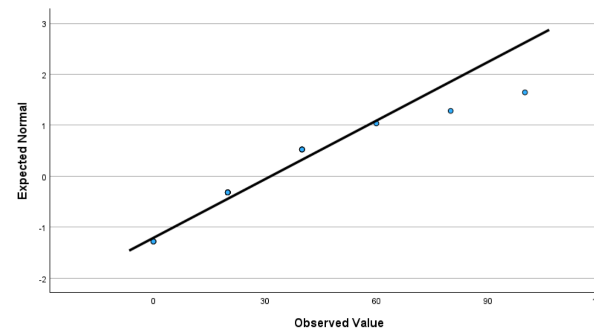






Rewards ***No Rewards***

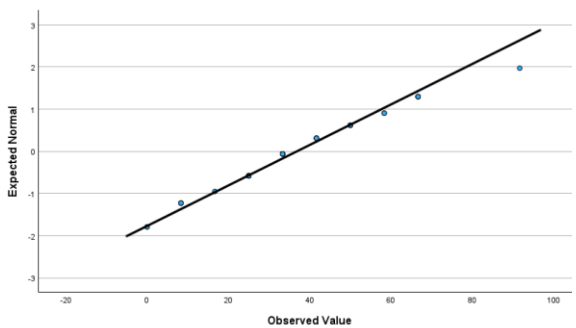


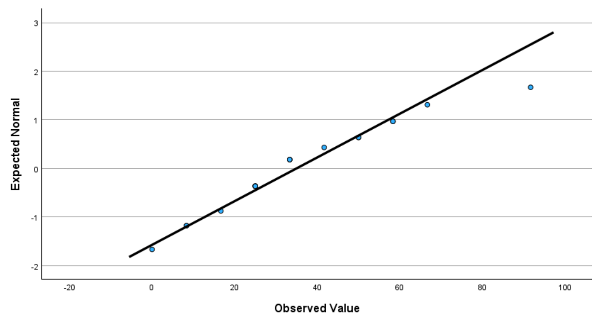


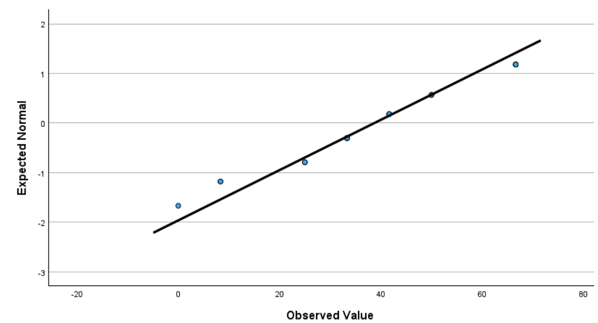
Left Epoch 2

Children

Young Adults

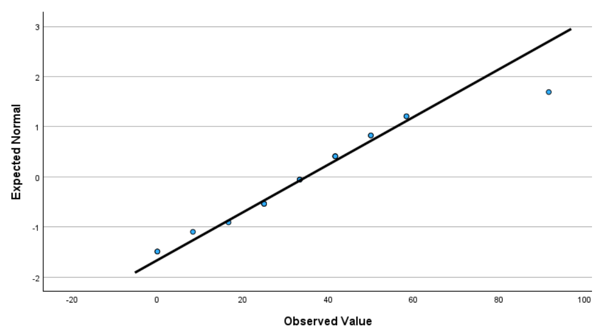


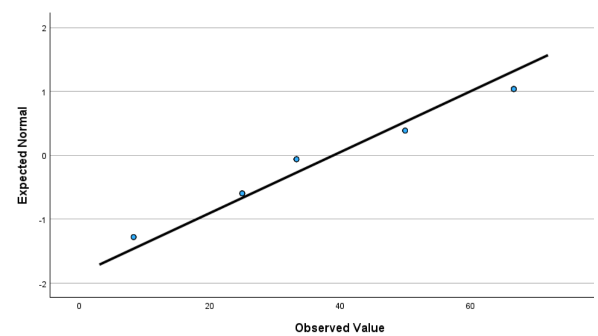




Rewards

No Rewards

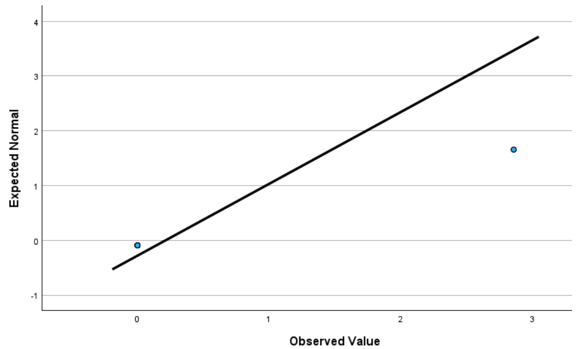


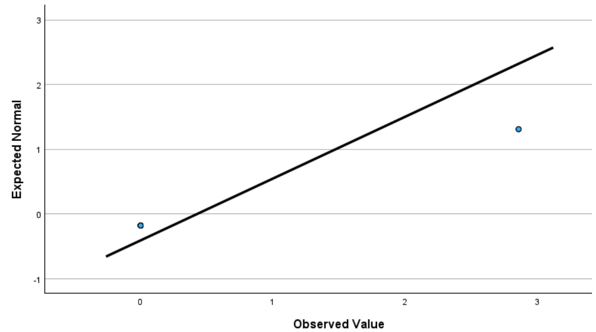


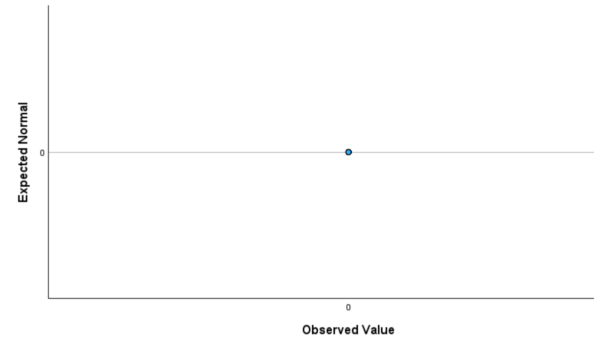
Rear Epoch 1

Children

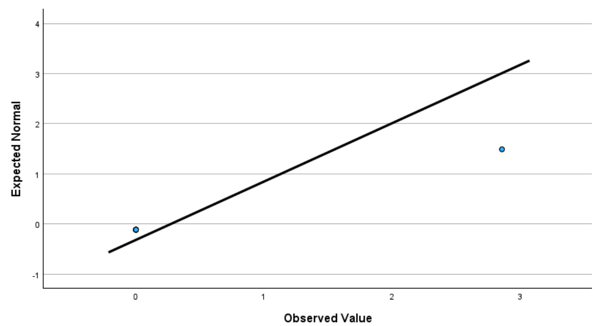
Young Adults



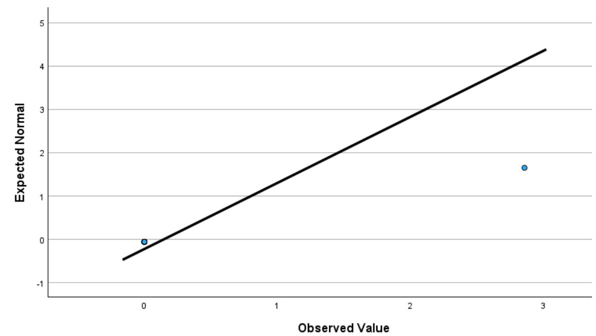




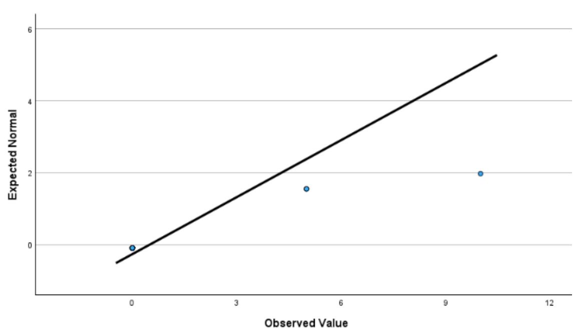
Rewards



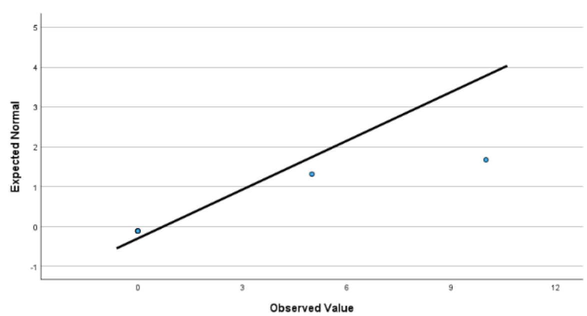
No Rewards



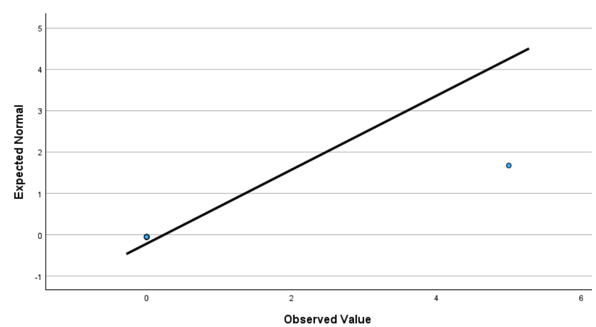
Rear Epoch 2

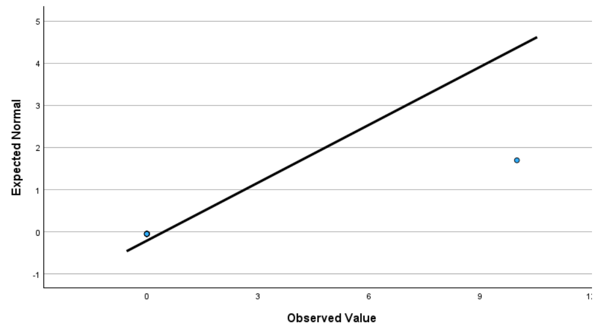
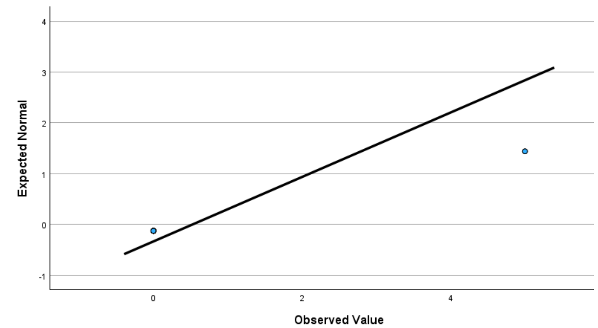


Children

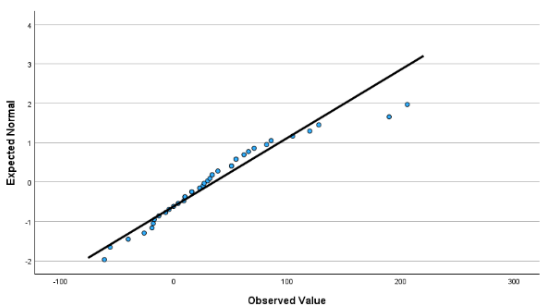
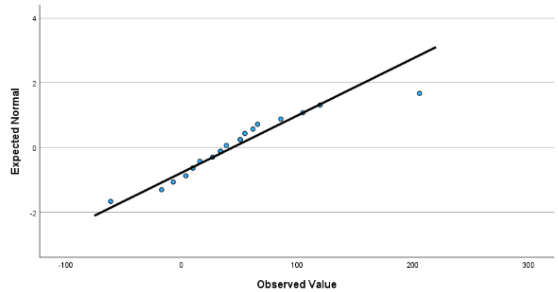
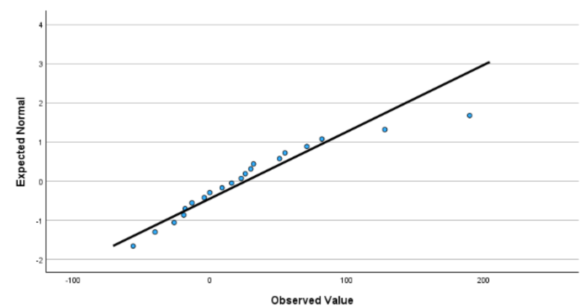
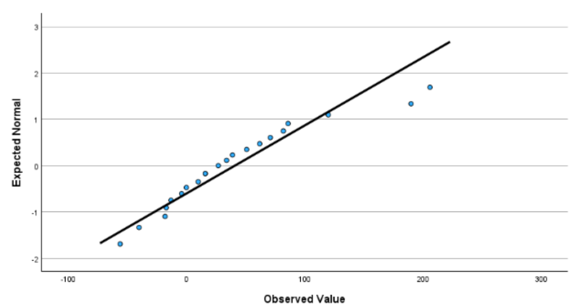
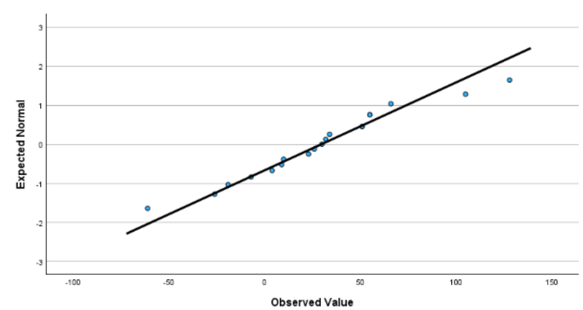


Young Adults

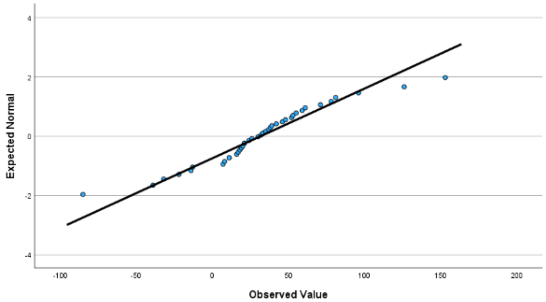


	Rewards	***No Rewards***
		

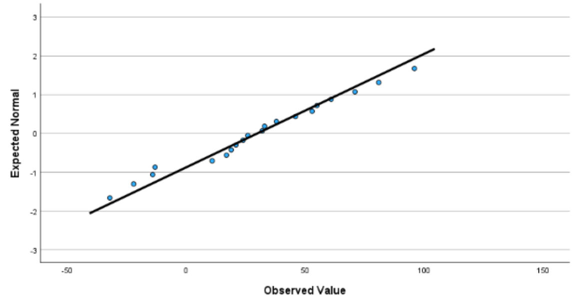
EF Tasks

Flanker Pre	***Children***	***Young Adults***
		
	Rewards	***No Rewards***
		

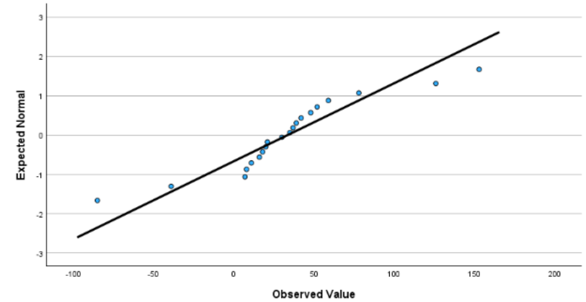
Flanker Post



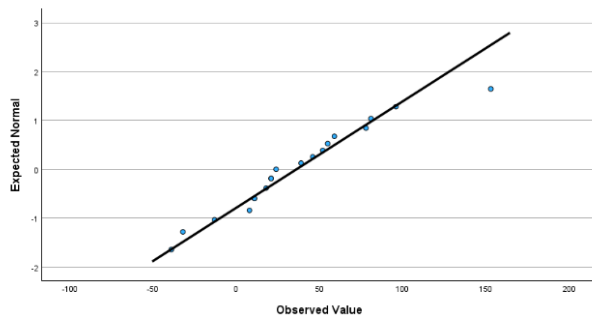
Children



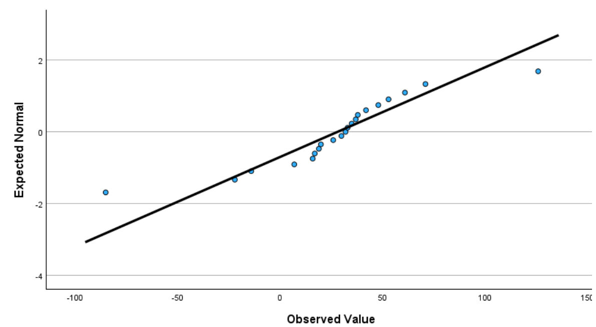
Young Adults



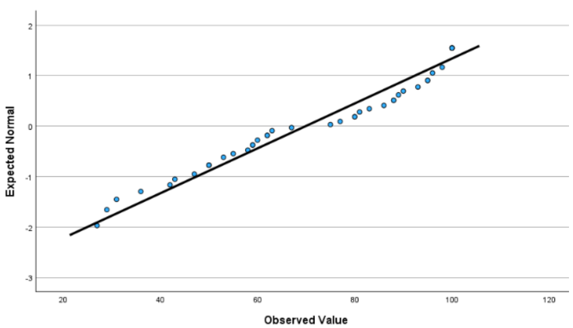
Rewards



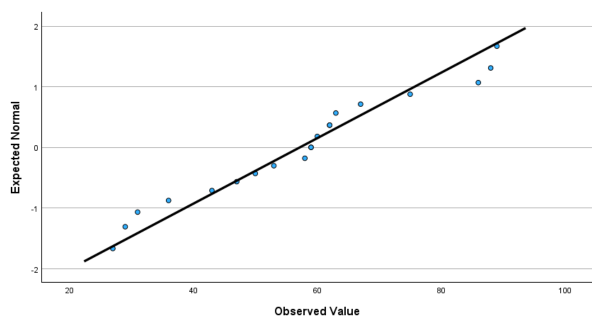
No Rewards



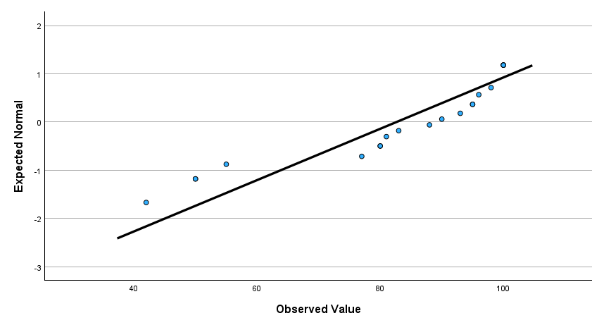
2-Back Pre

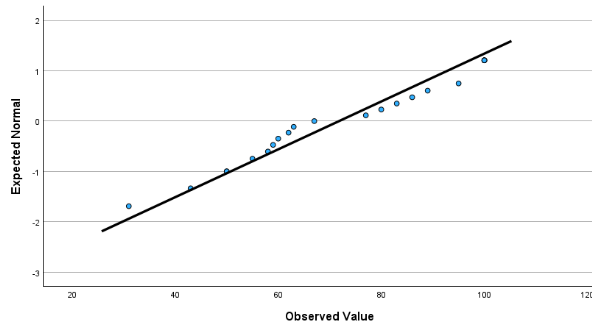
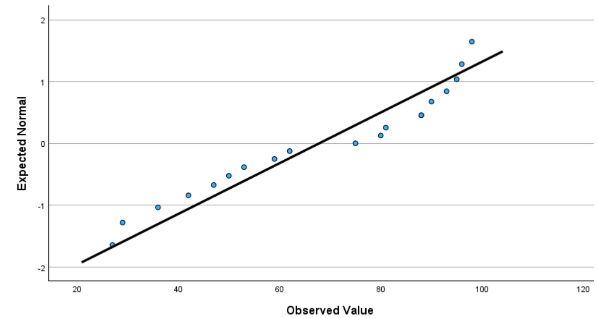
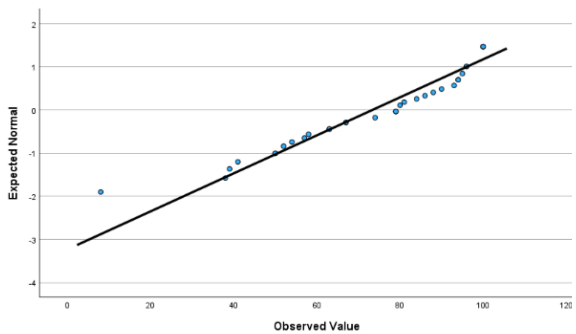
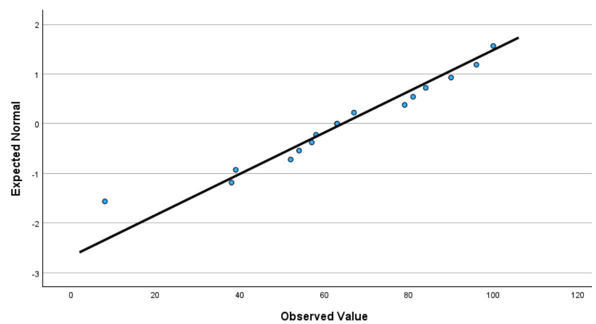
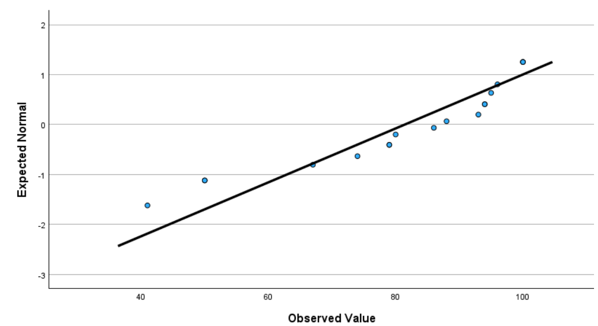
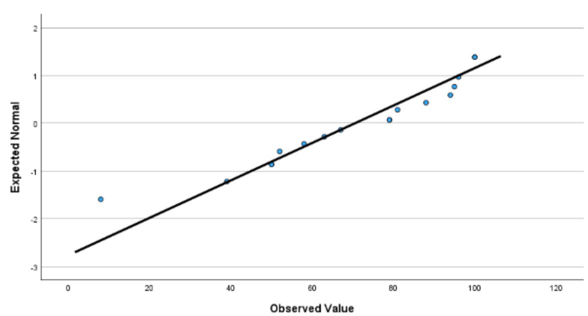
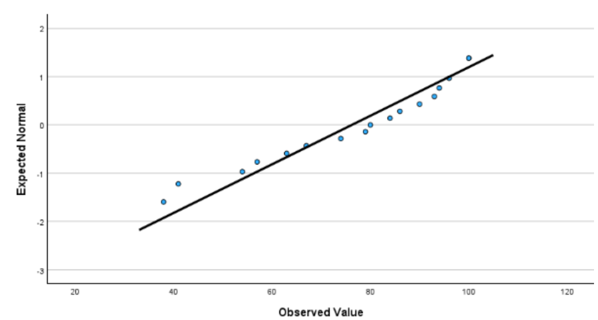


Children



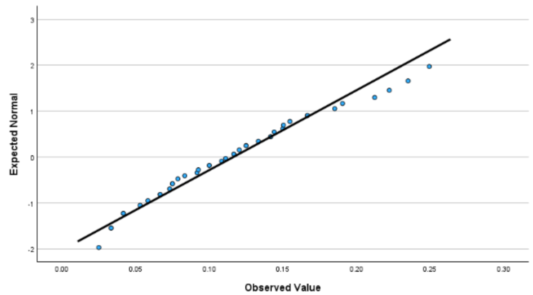
Young Adults



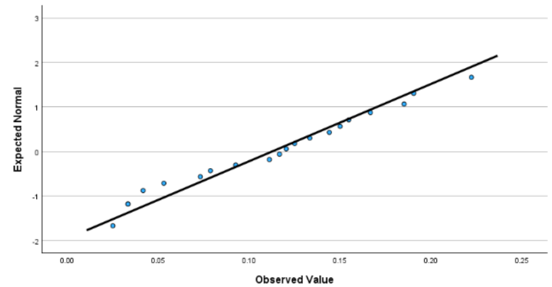
	Rewards	***No Rewards***
		
2-Back Post	***Children***	***Young Adults***
		
	Rewards	***No Rewards***
		

Academic Reasoning Tasks

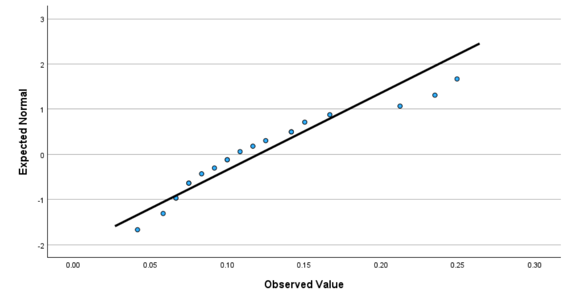
Verbal Efficiency Pre



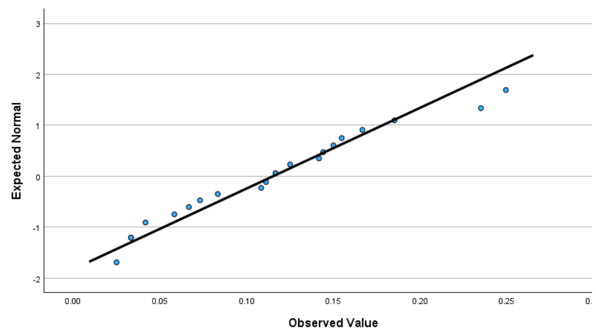
Children



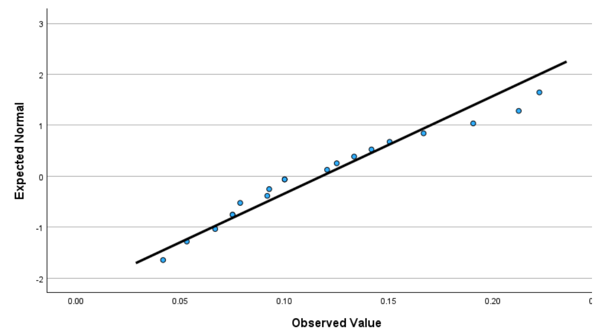
Young Adults



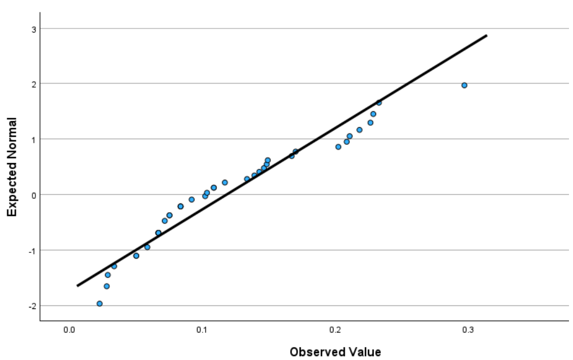
Rewards



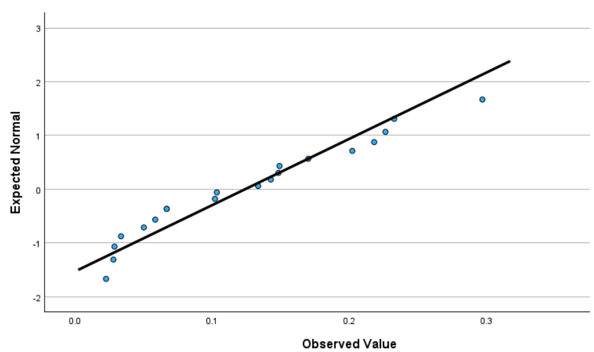
No Rewards



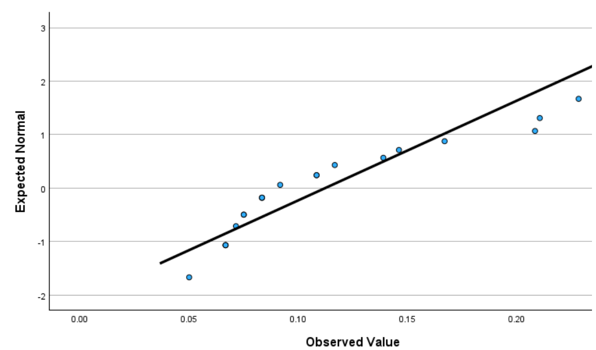
Verbal Efficiency Post

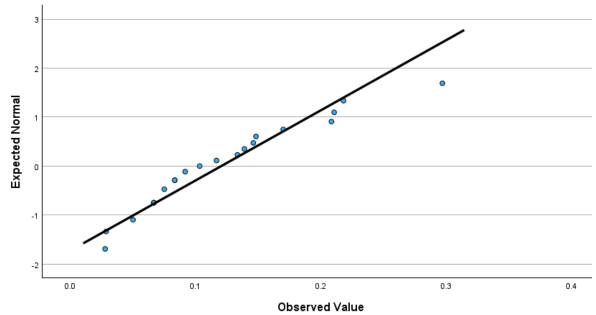
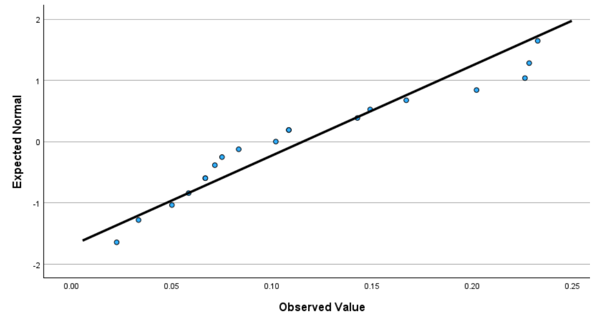
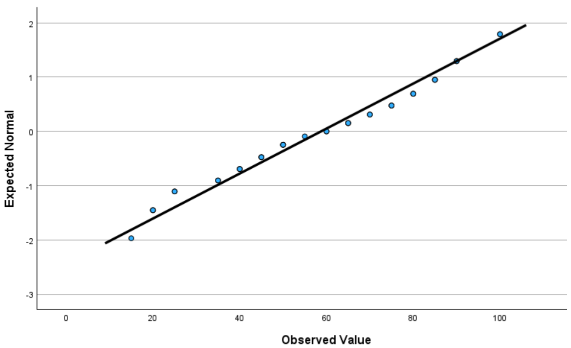
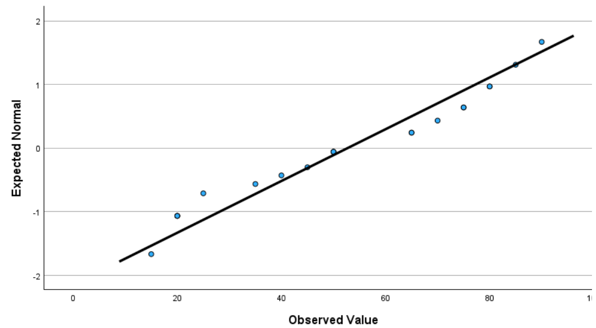
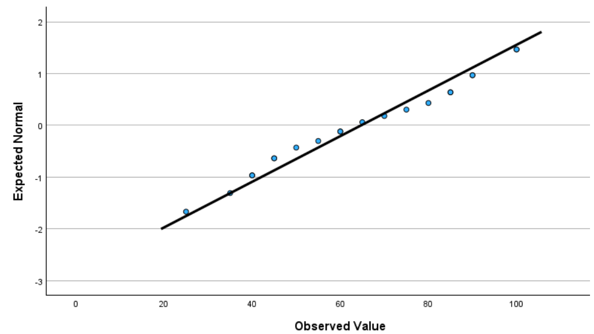
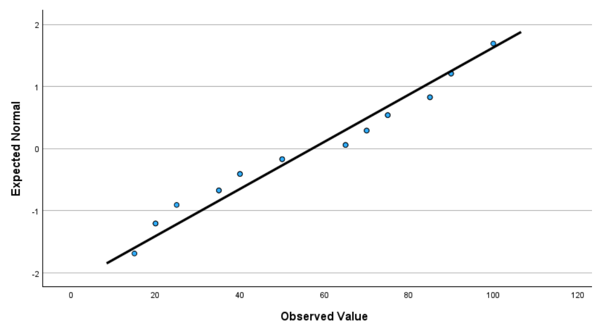
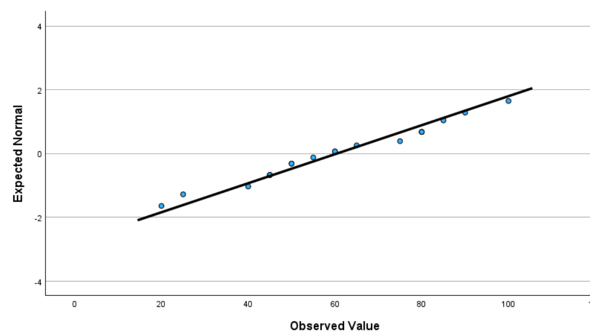


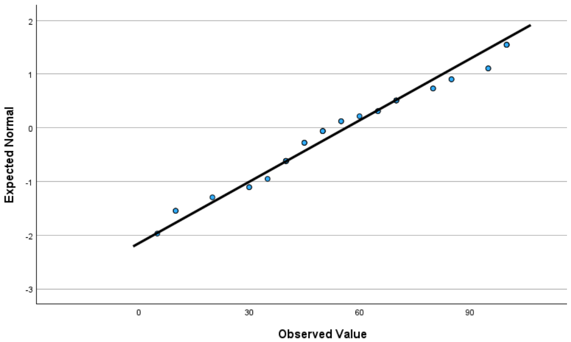
Children

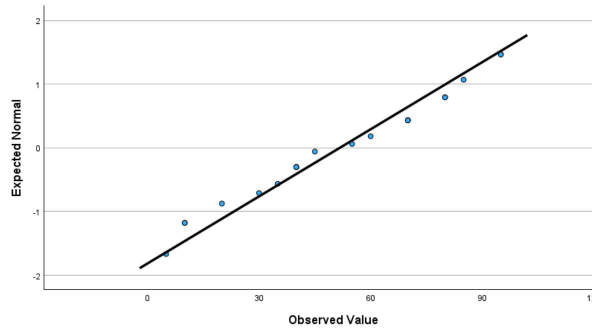


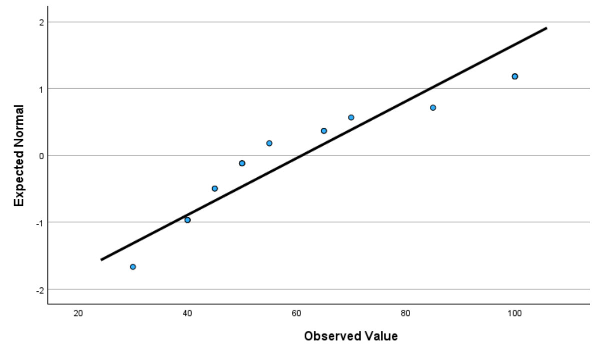
Young Adults



	Rewards	***No Rewards***
		
Verbal Percent Correct Pre	***Children***	***Young Adults***
		
	Rewards	***No Rewards***
		
Verbal Percent Correct Post	***Children***	***Young Adults***

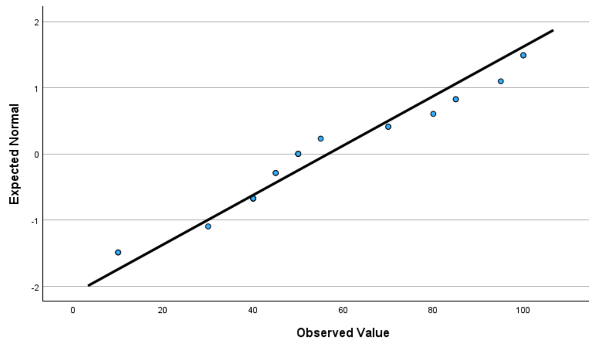


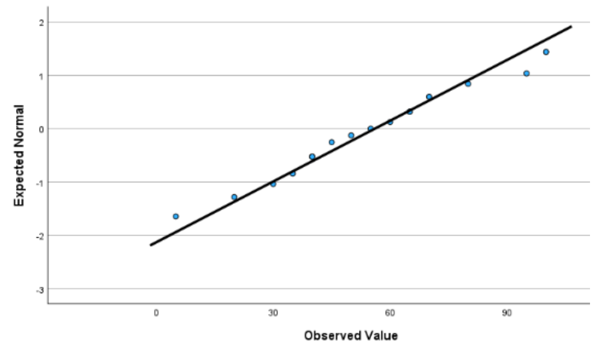




Rewards

No Rewards

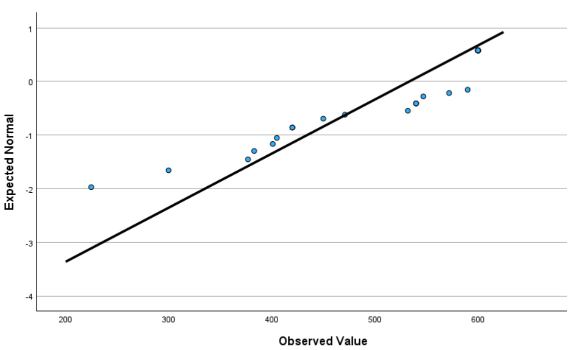


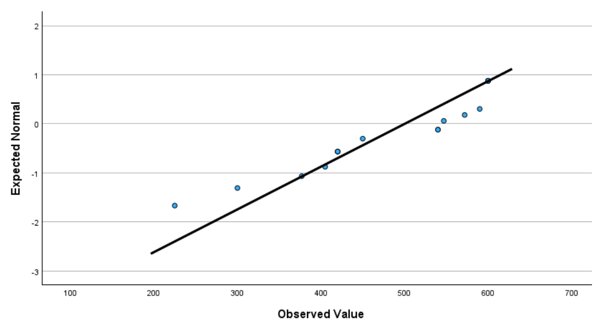


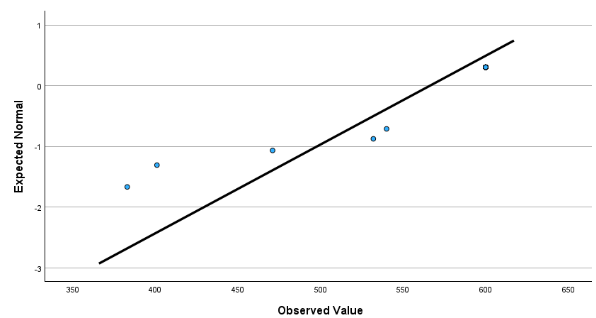
Verbal Completion Time Pre

Children

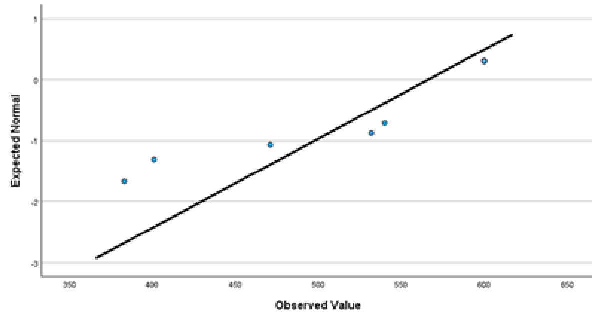
Young Adults







Rewards



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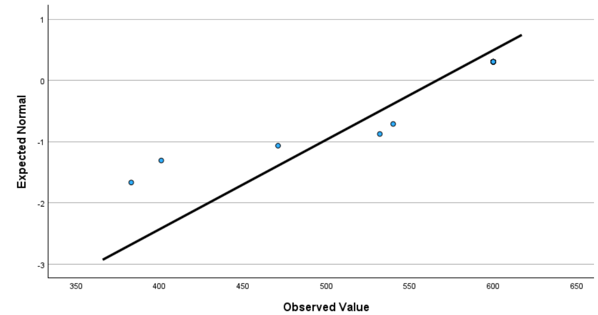
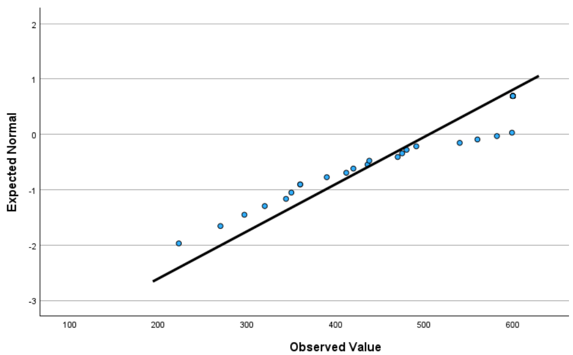
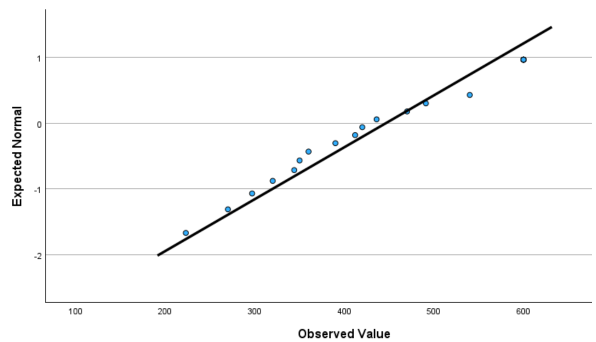


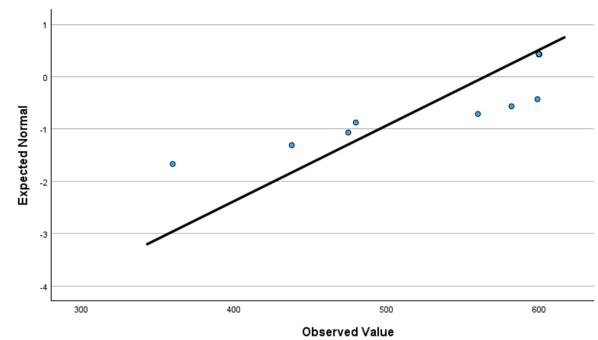
Verbal Completion Time Post



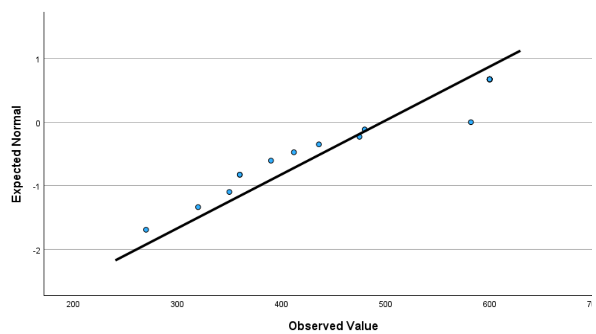
Children



Young Adults



Rewards



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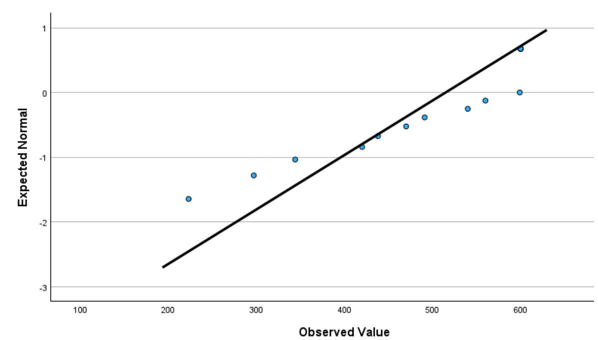
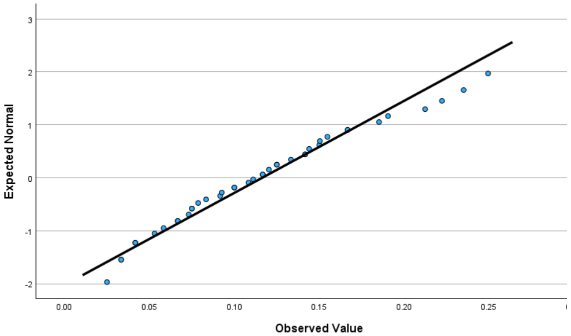
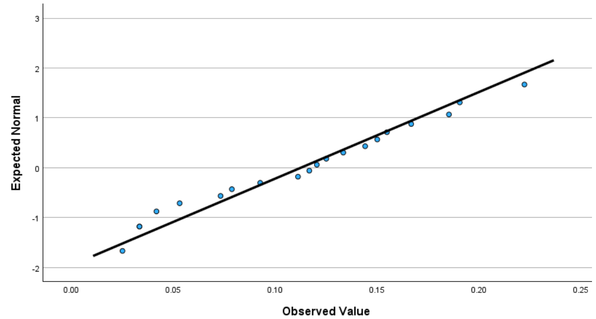


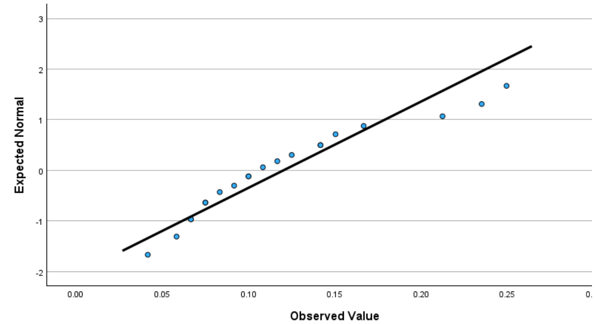
Nonverbal Efficiency Pre



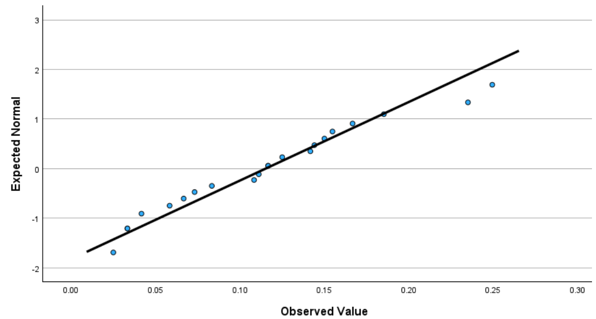
Children



Young Adults



Rewards



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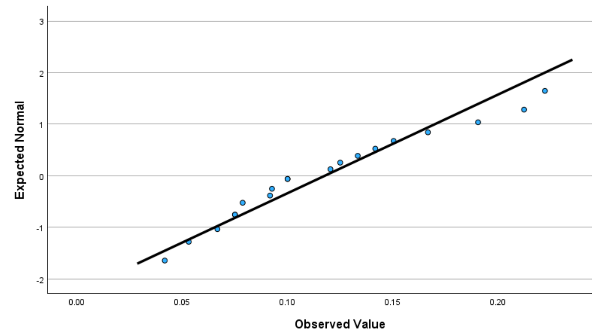
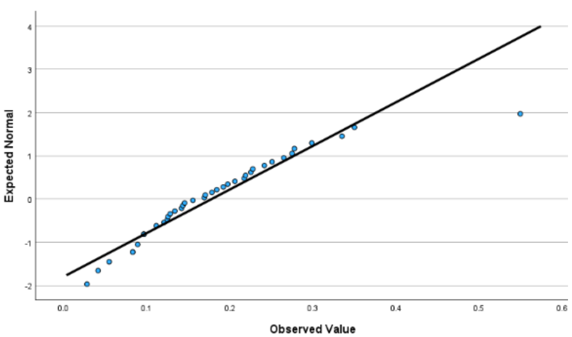
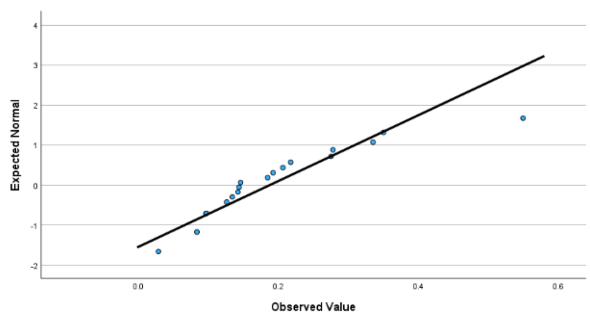


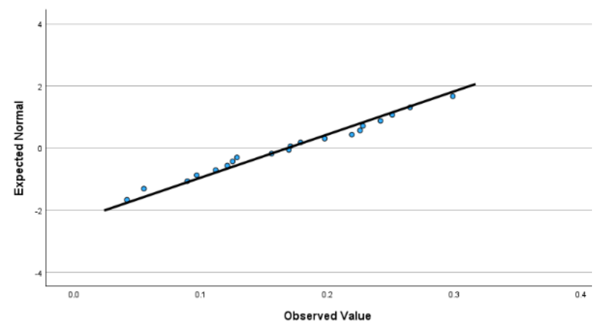
Nonverbal Efficiency Post



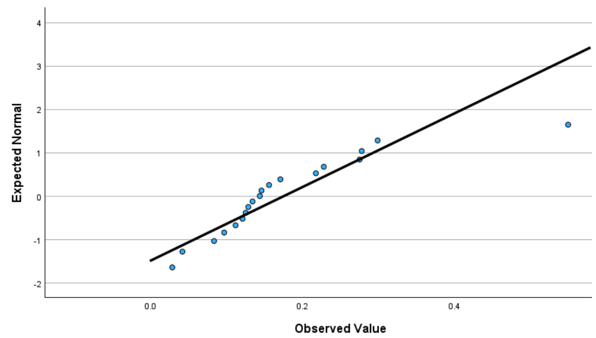
Children



Young Adults



Rewards



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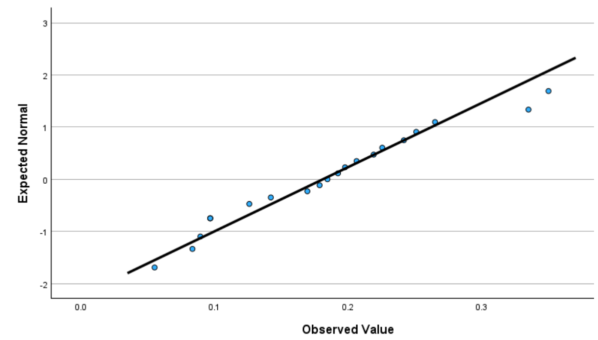
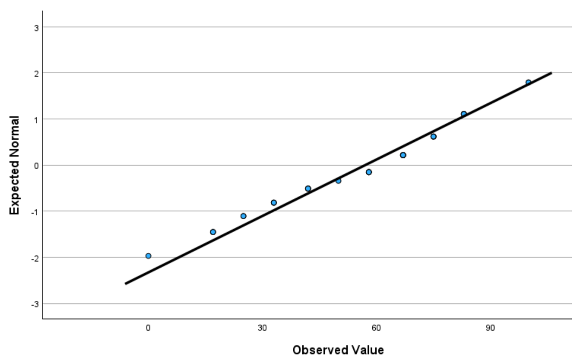
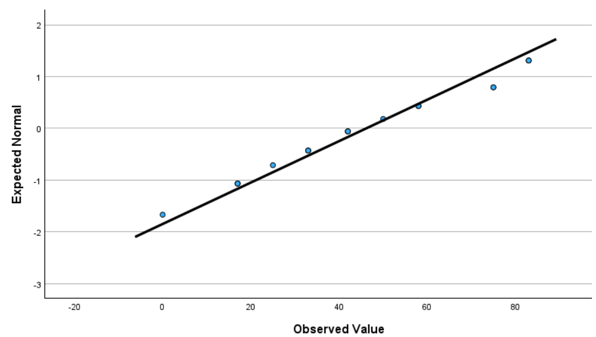


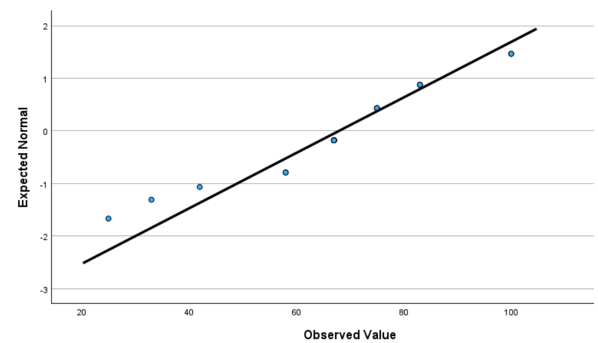
Nonverbal Percent Correct Pre



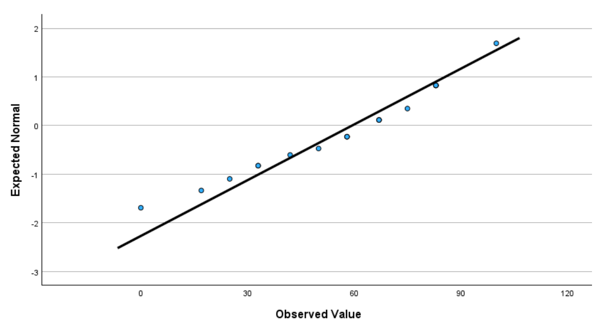
Children



Young Adults



Rewards



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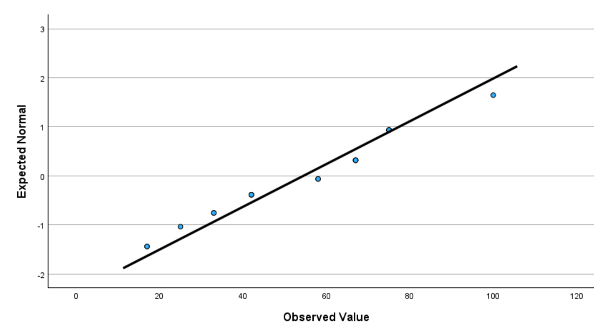
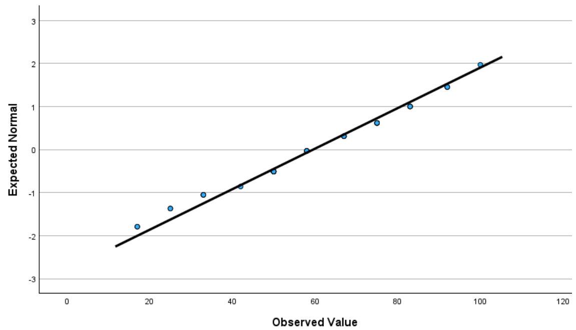


Nonverbal Percent Correct Post



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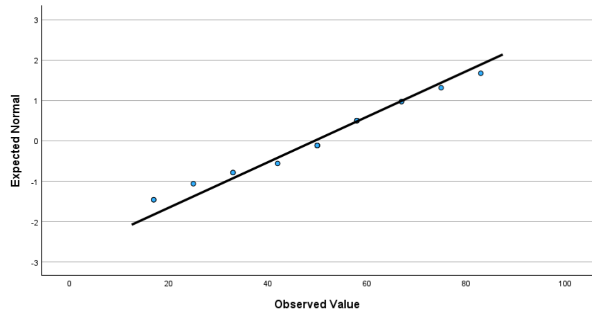
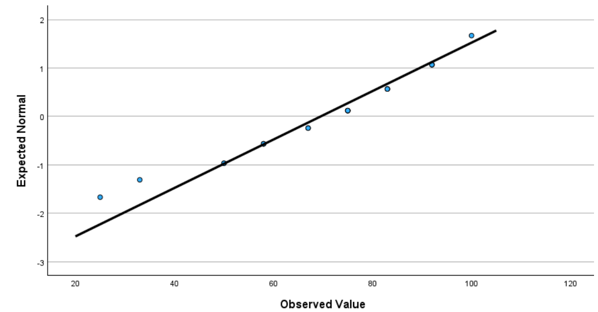
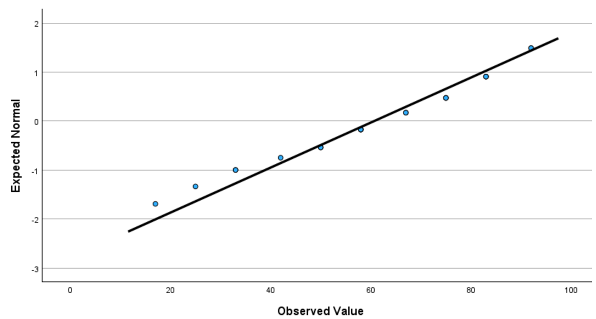


Young Adults



Rewards



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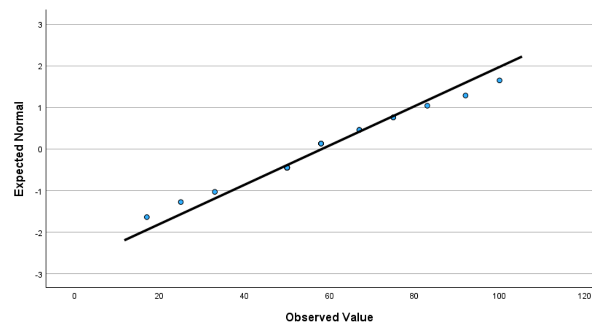
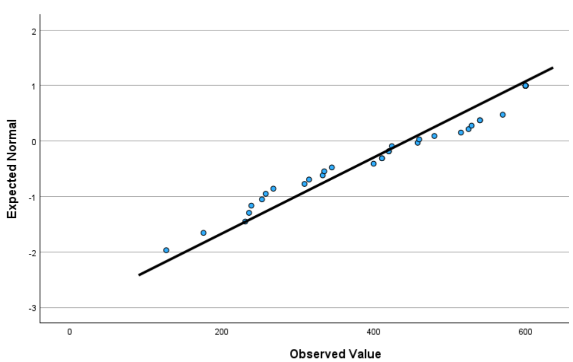


Nonverbal Completion Time Pre



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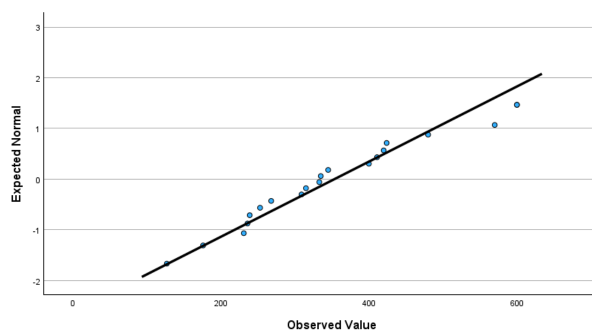
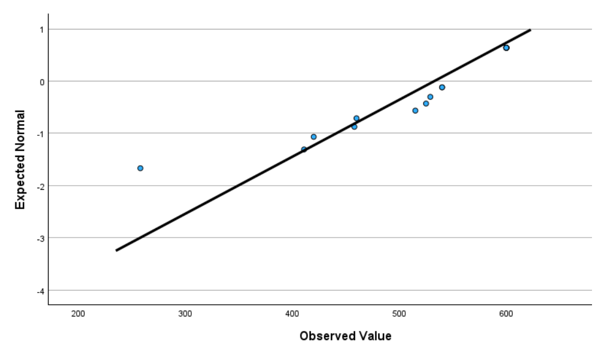
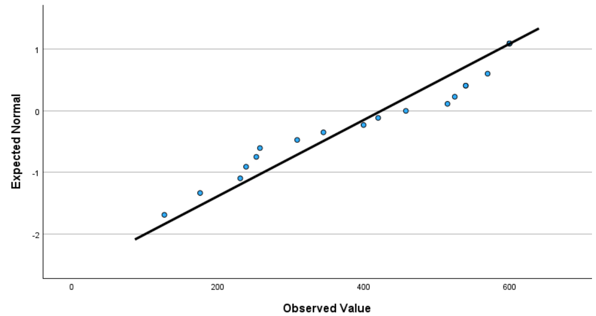


Young Adults



Rewards



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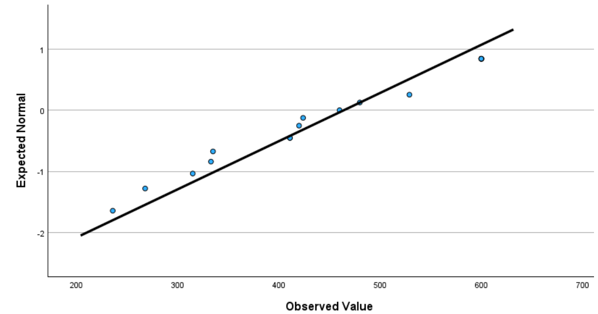

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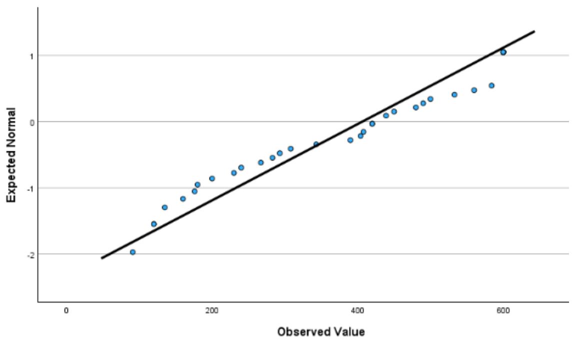
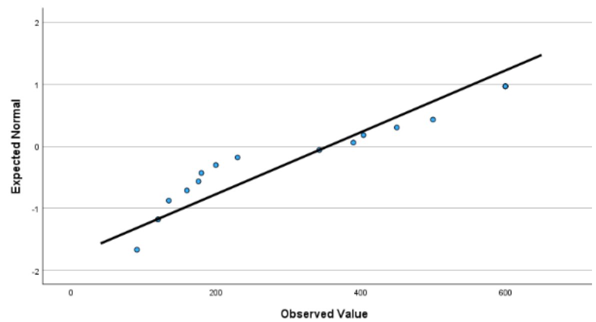
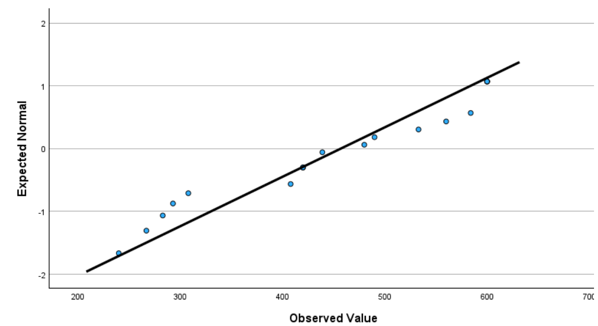


Children



Young Adults



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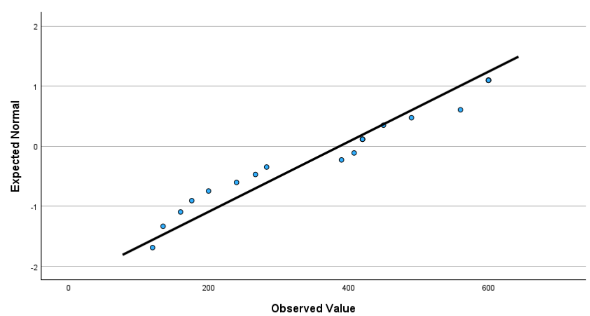
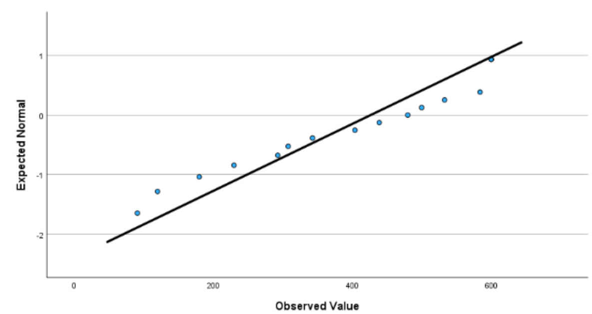
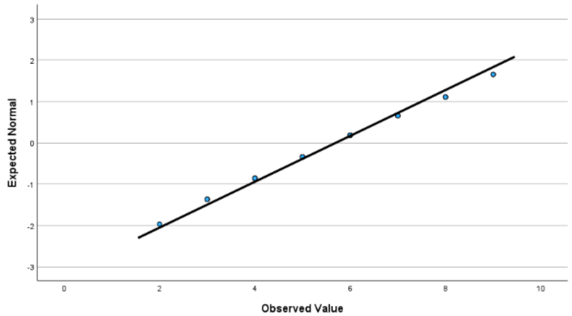
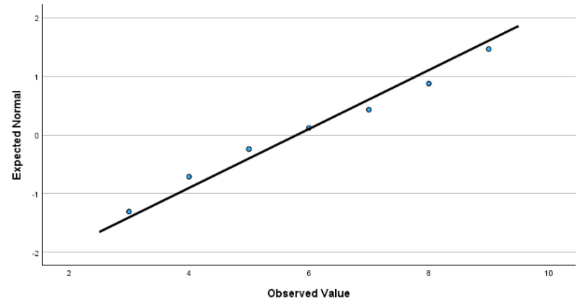
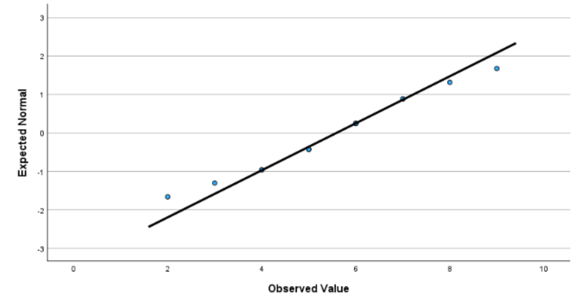
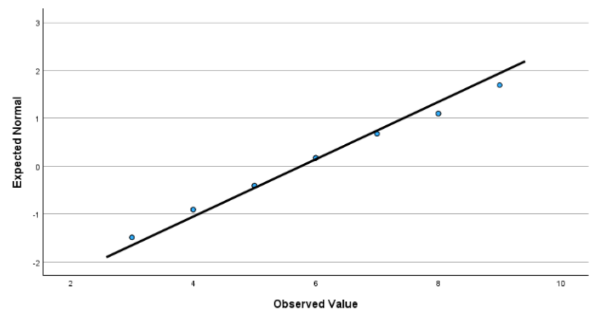
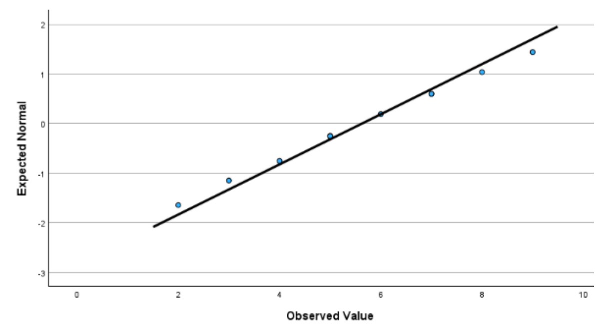
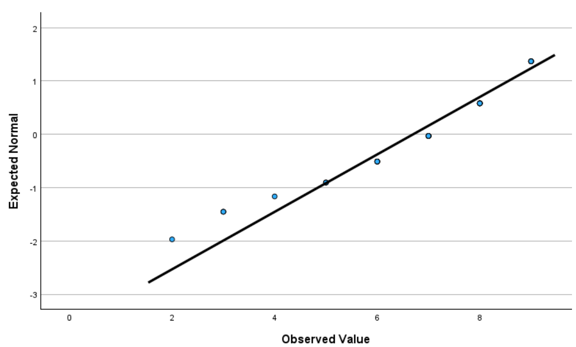
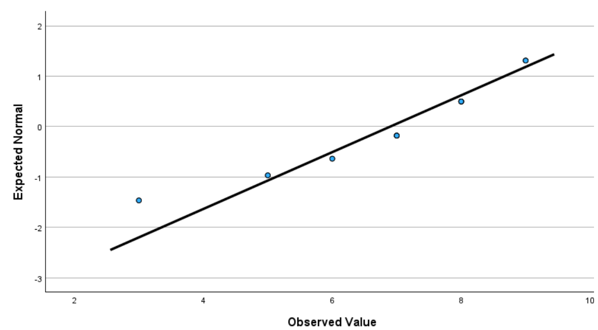
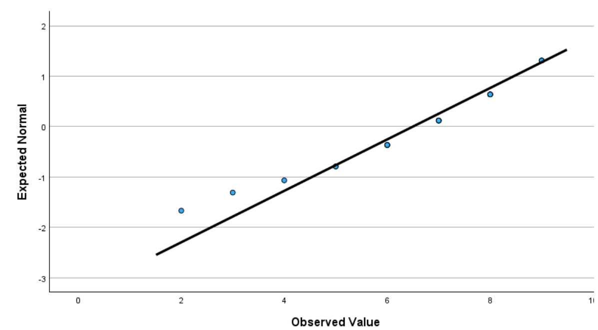
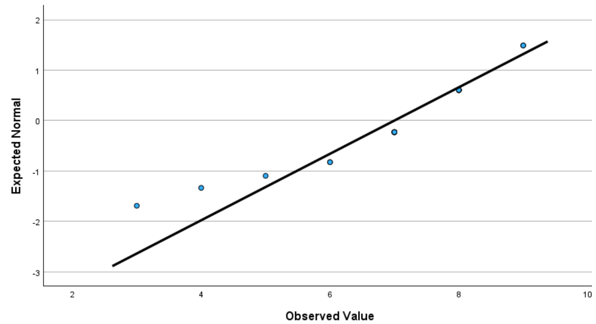


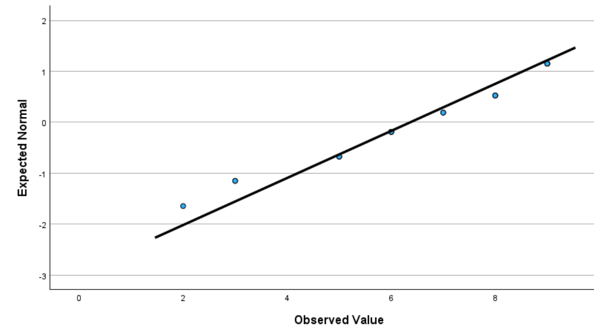
No Rewards



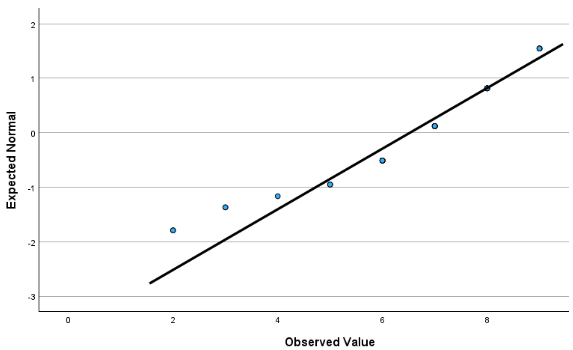
Affect Grid

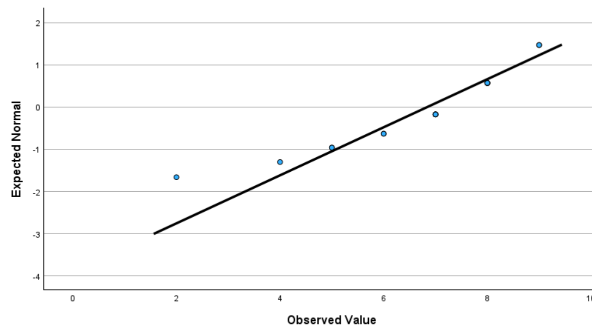
Arousal Pre	***Children***	***Young Adults***
		
	Rewards	***No Reward***
		
Arousal Post	***Children***	***Young Adults***
		
	Rewards	***No Rewards***

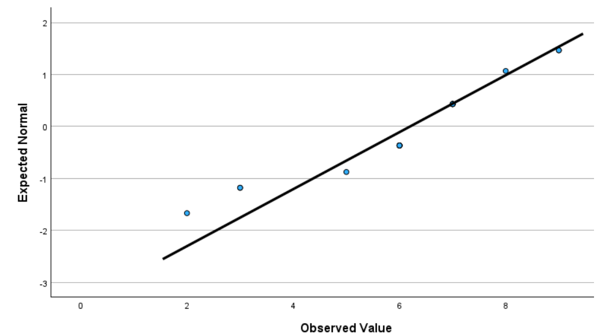




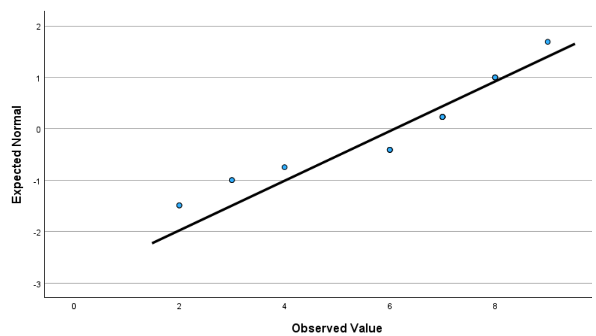
Pleasantness Pre	***Children***	***Young Adults***

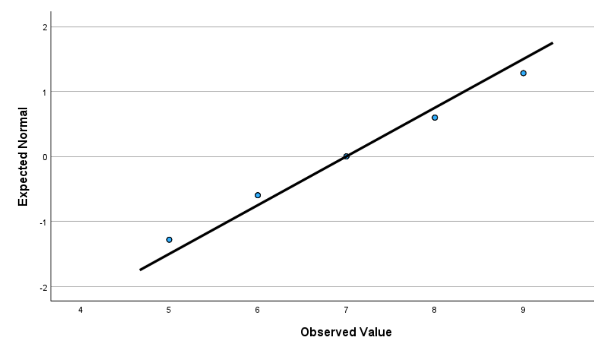




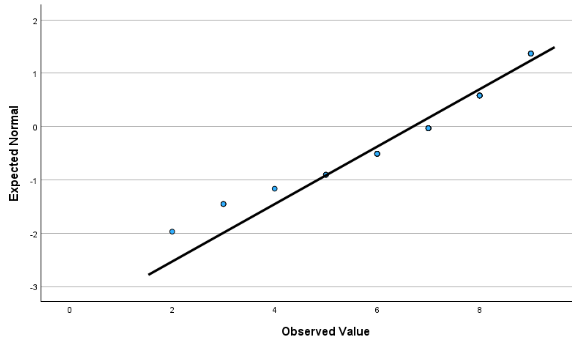


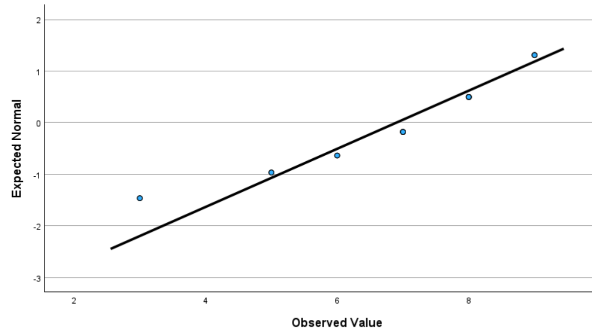
	Rewards	***No Rewards***

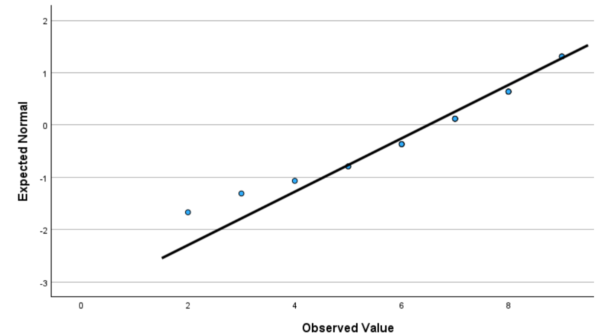




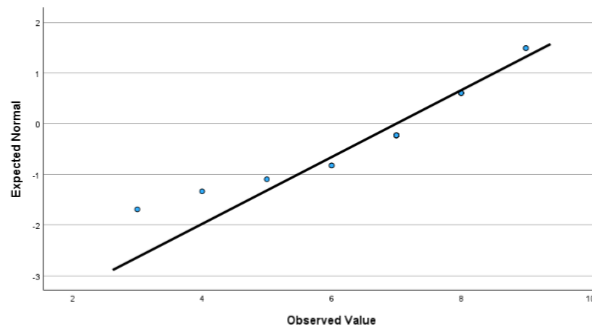
Pleasantness Post	***Children***	***Young Adults***

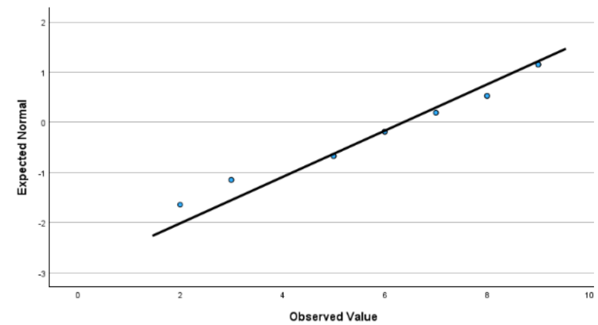






	Rewards	***No Rewards***





APPENDIX I: Reasoning Performance, by Condition and Age Group

Task	Pre	Post
Verbal Reasoning Percentage Correct (%)		
Children		
Reward Sounds	51.40 (27.20)	49.50 (29.10)
No Reward Sounds	54.40 (22.40)	54.40 (29.20)
Young Adults		
Reward Sounds	63.50 (25.20)	64.50 (22.80)
No Reward Sounds	66.00 (21.20)	57.50 (25.00)
Overall	58.80 (24.10)	56.40 (26.20)
Verbal Reasoning Time Taken (s)		
Children		
Reward Sounds	503 (107)	449 (128)
No Reward Sounds	497 (130)	443 (133)
Young Adults		
Reward Sounds	558 (87.80)	550 (83.40)
No Reward Sounds	574 (45)	580 (51.30)
Overall	533 (99.1)	505 (117)
Nonverbal Reasoning Percentage Correct (%)		
Children		
Reward Sounds	52.90 (28.10)	51.50 (20.60)
No Reward Sounds	38.00 (19.00)	47.20 (14.40)
Young Adults		
Reward Sounds	66.60 (23.20)	70.80 (19.10)
No Reward Sounds	69.30 (14.70)	68.30 (21.80)
Overall	57.10 (24.50)	59.50 (21.20)
Nonverbal Reasoning Time Taken (s)		
Children		
Reward Sounds	350 (171)	366 (211)
No Reward Sounds	358 (80.50)	341 (198)
Young Adults		
Reward Sounds	506 (106)	411 (121)
No Reward Sounds	560 (70.20)	504 (121)
Overall	443 (146)	406 (173)

APPENDIX J: Chapter 4 Ethics Letter

University Research Ethics Committee
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

2 March 2023

LETTER OF APPROVAL

APPROVAL HAS BEEN GRANTED FOR THIS STUDY TO BE CARRIED OUT BETWEEN 28/03/2022 AND 31/12/2023

Applicant (s): Miss Tamara Dkaidek

Project Title: The Effect of an Acute Bout of Cycling on Brain Function

Reference: 32748-A-Feb/2023- 43987-1

Dear Miss Tamara Dkaidek

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- **The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.**
- **Please ensure that you monitor and adhere to all up-to-date local and national Government health advice for the duration of your project.**

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to any conditions that may appear above.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- If your project has been approved to run for a duration longer than 12 months, you will be required to submit an annual progress report to the Research Ethics Committee. You will be contacted about submission of this report before it becomes due.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Dr Derek Millard-Healy

Chair of the University Research Ethics Committee

Brunel University London

APPENDIX K: Chapter 5 Ethics Letter

College of Health, Medicine and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

26 May 2023

LETTER OF APPROVAL

APPROVAL HAS BEEN GRANTED FOR THIS STUDY TO BE CARRIED OUT BETWEEN0 26/05/2023 AND 31/12/2023

Applicant (s): Ms Tamara Dkaidek Dr Daniel Bishop , Dr Andre Szameitat

Project Title: The Effect of Combined Moderate Intensity Cycling and a Visual Foraging Task on Cognition

Reference: 42007-MHR-May/2023- 44830-2

Dear Ms Tamara Dkaidek

The Research Ethics Committee has considered the above application recently submitted by you.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- C1 - The PAR-Q questionnaire only includes participant and investigator's names and signatures. Please ensure parents/guardian's name and signature are also be included and obtained.
- **The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.**
- **Please ensure that you monitor and adhere to all up-to-date local and national Government health advice for the duration of your project.**

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to any conditions that may appear above.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- If your project has been approved to run for a duration longer than 12 months, you will be required to submit an annual progress report to the Research Ethics Committee. You will be contacted about submission of this report before it becomes due.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Louise Mansfield

Chair of the College of Health, Medicine and Life Sciences Research Ethics Committee (DLS)

Brunel University London

APPENDIX L: Chapter 6 Ethics Letter

College of Health, Medicine and Life Sciences Research Ethics Committee (DLS)
Brunel University London
Kingston Lane
Uxbridge
UB8 3PH
United Kingdom

www.brunel.ac.uk

28 September 2023

LETTER OF APPROVAL

APPROVAL HAS BEEN GRANTED FOR THIS STUDY TO BE CARRIED OUT BETWEEN 07/06/2023 AND 31/12/2023

Applicant (s): Ms Tamara Dkaidek

Project Title: The Influence of a 360-Immersive Ergometer Cycling Intervention on Cognition

Reference: 42008-A-Sep/2023- 47297-2

Dear Ms Tamara Dkaidek

The Research Ethics Committee has considered the above application recently submitted by you to add 25 Brunel student participants aged 18-35 to the study. Please ensure you correct (in both, the consent form and PIS) the typo in the statement relating to no detriment upon withdrawal for the Brunel students.

The Chair, acting under delegated authority has agreed that there is no objection on ethical grounds to the proposed study. Approval is given on the understanding that the conditions of approval set out below are followed:

- **The agreed protocol must be followed. Any changes to the protocol will require prior approval from the Committee by way of an application for an amendment.**
- **Please ensure that you monitor and adhere to all up-to-date local and national Government health advice for the duration of your project.**

Please note that:

- Research Participant Information Sheets and (where relevant) flyers, posters, and consent forms should include a clear statement that research ethics approval has been obtained from the relevant Research Ethics Committee.
- The Research Participant Information Sheets should include a clear statement that queries should be directed, in the first instance, to the Supervisor (where relevant), or the researcher. Complaints, on the other hand, should be directed, in the first instance, to the Chair of the relevant Research Ethics Committee.
- Approval to proceed with the study is granted subject to any conditions that may appear above.
- The Research Ethics Committee reserves the right to sample and review documentation, including raw data, relevant to the study.
- If your project has been approved to run for a duration longer than 12 months, you will be required to submit an annual progress report to the Research Ethics Committee. You will be contacted about submission of this report before it becomes due.
- You may not undertake any research activity if you are not a registered student of Brunel University or if you cease to become registered, including abeyance or temporary withdrawal. As a deregistered student you would not be insured to undertake research activity. Research activity includes the recruitment of participants, undertaking consent procedures and collection of data. Breach of this requirement constitutes research misconduct and is a disciplinary offence.

Professor Louise Mansfield

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