The Influence of Social Engagement on Exercise-Associated Cognitive & Affective Changes Among Older Adult Women

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Kinesiology

Waterloo, Ontario, Canada, 2019

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Single bouts of aerobic exercise appear to elicit improvements in cognition and affect among older adults, which are dependent on exercise dose (intensity, duration). Social engagement, not typically considered in exercise prescription but often included in exercise delivery, may also influence these outcomes. This study examined the effects of social exercise and solo exercise versus a control on affect and cognition among older adult women. Thirty healthy older adult women were recruited to this study. In a repeated-measures design, participants each completed three sessions: 1) social exercise: moderate intensity treadmill walking with concurrent conversation with another participant; 2) solo exercise: moderate intensity treadmill walking alone; and 3) active control seated and listening to an informative podcast. Order of conditions was counterbalanced. Executive function was assessed immediately before and 10 minutes after each intervention using a modified Eriksen Flanker task. Response time (RT), accuracy, and inverse efficiency score (IES) were calculated from Flanker data. Affect was assessed using the Physical Activity Affect Scale (PAAS) immediately before and after each intervention and at 3-hour intervals throughout the day of intervention and the following day. PAAS subfactors of positive affect, negative affect, tranquility, and fatigue were used in analysis. To better examine variability in RT response to exercise, individual participant response times across conditions and time were examined and used to group participants in an exploratory analysis. Four groupings emerged: 1) Consistent Responders; 2) Social Responders; 3) Solo Responders; 4) Non-Responders. Differences in personality, activity levels, conversation characteristics, sleep, and energy expenditure were examined between groups.

Results show higher accuracy in exercise conditions than control, but with no change in RT over time or conditions. There was significantly lower IES in the social condition compared to control, but no difference between exercise conditions. Responder groups varied by personality, exercise history, and social engagement characteristics such that consistent and social responders tended to be more extroverted, agreeable, and conscientious than other groups. Social conversation quality and quantity was also higher among these groups, while contribution to the conversation was lowest. Subjective physical activity levels were highest in the non-responder group. Acute improvements in affect (denoted by higher positive affect and reduced negative affect) occurred following social exercise, but not solo exercise or control. This reduction in negative affect remained until 6h-post social exercise, however positive affect decreased. Overall, results provide only weak support for enhanced executive functions following exercise or social exercise. However, social engagement during exercise may lead to affective improvements, which may be sustained up to 6h-post intervention.

Acknowledgements

I would like to thank Dr. Laura Middleton for her guidance and expertise throughout the development of this thesis. Likewise, I would like to thank my committee members, Professors Richard Hughson and Myra Fernandes, for their expert insight into my research.

I would like to acknowledge all the members of the Brain and Body Lab (BaB Lab), with a special thank you to Kayla and Max for your constructive criticism, problem solving, and endless support, without which this research would not have been possible. I would like to extend my thanks to my fellow graduate students within the neuroscience stream, particularly those within the CCCARE community, for the valuable feedback and support that has helped shape this thesis.

Lastly, I would like to thank my family for continuously being my biggest fans, as well as my partner, William, and Bomber the dog, who never fail to remind me that nothing is ever as impossible as it seems in the moment.

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Abbreviations

PFC . . . . . Prefrontal Cortex

MCI . . . . . Mild Cognitive Impairment

fMRI . . . . . Functional Magnetic Resonance Imaging

BOLD . . . . Blood-Oxygen-Level Dependent

CBF . . . . . Cerebral Blood Flow

MDD . . . . . Major Depressive Disorder

EEG . . . . . Electroencephalography

ERP . . . . . Event-Related Potential

BDNF . . . . Brain-Derived Neurotrophic Factor

VEGF . . . . Vascular Endothelial Growth Factor

IGF-1 . . . . Insulin-Like Growth Factor

HPA . . . . . Hypothalamic-Pituitary-Adrenal

MVPA . . . . Moderate-to-Vigorous Physical Activity

POMS . . . . Profile of Mood States

GHQ-28 . . . 28-Item General Health Questionnaire

WRAP . . . . Waterloo Research in Aging Participant Pool

MoCA . . . . Montreal Cognitive Assessment

GAQ . . . . . Get Active Questionnaire

CSEP . . . . Canadian Society for Exercise Physiology

CEP . . . . . Certified Exercise Physiologist

PASE . . . . . Physical Activity Scale for the Elderly

TIPI . . . . . Ten-Item Personality Inventory

ECG . . . . . Electrocardiography

HRR . . . . . Heart Rate Reserve

SMHSQ . . . St. Mary's Hospital Sleep Questionnaire

PAAS . . . . Physical Activity Affect Scale

RPE . . . . . Rating of Perceived Exertion

STAI . . . . . State-Trait Anxiety Inventory

PANAS . . . Positive Affect Negative Affect Schedule

RT . . . . . . Response Time

ANOVA . . . Analysis of Variance

IES . . . . . . Inverse Efficiency Score

CQR . . . . . Conversation Quality Reflection

LME . . . . . Linear Mixed Effects

SD . . . . . . Standard Deviation

SE . . . . Standard Error

HR . . . . . . Heart Rate

Chapter 1

Introduction

The growing older adult population has prompted a wide range of research focusing on reducing the impact of impairment and diseases common with aging. The baby-boomer generation began to transition into older adulthood in 2010 [Alzheimer Society of Canada, 2016]. In 2031, when the entire baby-boomer generation will have reached over 65 years of age, this age group will account for approximately 23% of the total Canadian population [Alzheimer Society of Canada, 2016]. Life expectancy is also increasing, with a surge in global life expectancy of 5.5 years between 2000 to 2016 [World Health Organization, 2018], further contributing to the aging of the population.

Cognitive decline within certain domains is common with aging [Harada et al., 2013, Stern, 2009, West, 1996]. A general slowing of processing speeds is associated with reduced performance on neurobehavioural tasks in older adulthood [Carlson et al., 1995, Harada et al., 2013, Salthouse et al., 1995]. Both selective and divided attention are also associated with age-related decline [Harada et al., 2013]. Selective attention refers to the ability to attend to a stimulus while ignoring irrelevant stimuli; divided attention is the ability to focus on multiple tasks simultaneously [Carlson et al., 1995, Harada et al., 2013, Salthouse et al., 1995]. Episodic memory (memory of personally experienced events) shows a gradual decline across the lifespan while semantic memory (general knowledge not related to personal experience) declines in late life [Harada et al., 2013, Ronnlund et al., 2005]. However, the ability to recall motor and cognitive skills, referred to as procedural memory, is resilient to age-related cognitive decline [Harada et al., 2013]. Memory impairments associated with aging are generally due to a reduction in the rate of acquisition and retrieval as retention does not seem to be affected by normal aging [Haaland et al., 2003, Harada et al., 2013]. The executive functions, including working memory, response inhibition, and cognitive flexibility, are particularly susceptible to aging and will be discussed in more detail in section 2.1.1 [Coxon et al., 2016, Harada et al., 2013, Mcnab et al., 2015, Wasylyshyn and Sliwinski, 2011].

In addition to age-related changes in processing speed, attention, memory, and executive functioning, approximately 10% of adults over 65 years have accelerated cognitive decline, resulting in a diagnosis of mild cognitive impairment (MCI) or of dementia [Alzheimer Society of Canada, 2016, Harada et al., 2013]. MCI is defined as a disruption in memory, executive functioning, or language that exceeds age-related changes in these cognitive domains but does not interfere with an individual's daily life [Alzheimer Society of Canada, 2014]. Dementia is a syndrome defined as impairment in at least two cognitive functions which interfere with an individual's ability to function in their everyday life [Mckhann et al., 2011]. Cognitive impairments experienced with dementia can be diverse, including changes to acquisition and recall of new information, reasoning and judgement, behaviour and personality, language and communication, and visuospatial abilities and visual perception [Mckhann et al., 2011]. Since the risk of developing dementia doubles every 5 years after 65 years of age, its prevalence is expected to increase with the growing and aging population [Alzheimer Society of Canada, 2016].

In contrast, affective states tend to be preserved across the lifespan [Charles et al., 2001, Kunzmann et al., 2000]. The aging theories of emotion suggest that nearing end-of-life prompts older adults to prioritize attainable, short-term social and emotional goals that maximize affective gains [Carstensen et al., 1999, Cheng, 2004]. Likewise, older adults tend to have greater emotional stability than their younger counterparts, and experience fewer negative emotions [Carstensen et al., 2000, Charles et al., 2001, Gross et al., 1997]. These affective improvements are evident in longitudinal studies that suggest positive affect remains relatively constant into older adulthood, whereas negative affect declines [Charles et al., 2001].

However, aging is associated with increased prevalence of risk factors for depressive symptoms, such as social isolation and the presence of chronic diseases [Hall et al., 2002, Mayo Clinic, 2015]. Likewise, geriatric depression often goes misdiagnosed or untreated, and is one of the greatest risk factors for cognitive impairment, and can even be an early symptom of dementia [Baumgart et al., 2015, Bennett and Thomas, 2014, Canadian Psychological Association, 2015]. Despite preserved psychological states in older adulthood, strategies to improve affective gains may concurrently increase cognitive functioning and reduce the risk of dementia.

Over the last 10 years, increasing research has focused on neuroprotective factors to delay and reduce the magnitude of cognitive decline [Alzheimer Society of Canada, 2016]. Exercise is one promising strategy [Kramer et al., 2006, Olanrewaju et al., 2016, van Uffelen et al., 2008]. Benefits are observed both with long-term exercise [Colcombe et al., 2004, Kramer et al., 1999, Voelcker-Rehage et al., 2010, Weuve et al., 2004] and after an acute bout of aerobic exercise [Basso and Suzuki, 2017, Chang et al., 2012]. Social engagement may also have positive impacts on cognition in the short- and long-term [Li and Dong, 2017, Mortazavi et al., 2013].

Combining exercise with social engagement may accentuate effects on cognition. To our knowledge, there is no research exploring cognitive and affective changes after social engagement during a single bout of exercise. This study will help inform exercise delivery strategies targeted to aging brain health. Exercise recommendations for brain health should likely consider not only exercise dose but also exercise delivery (for example, social or solo setting), which may play a critical role in enhancing cognitive and affective benefits and improving quality of life.

Chapter 2

Literature Review

2.1 Age-Related Changes in Executive Function and Affect

2.1.1 Age-Related Changes in Executive Function

Common cerebrovascular and neurological changes likely underlie disturbances to cognitive function with aging, including reductions in cerebral angiogenesis, demyelination of axons, and impaired synaptic plasticity [Sonntag et al., 2007]. These age-related changes reduce the ability to store new memories, decrease information processing speeds, and impair executive function. The frontal lobe hypothesis of aging suggests that the prefrontal cortex (PFC) is the first cerebral victim to normal aging [West, 1996]. The cognitive reserve theories of aging suggest that young and older adults utilize similar neural networks to perform a task, but that older adults may do so with less efficiency and may require additional network compensation due to age-related neural changes [Stern, 2009].

Decline in cognitive functions in older adulthood preferentially targets executive functions [Harada et al., 2013]. Executive functions are the set of cognitive processes required for behavioural control and responses to stimuli [Diamond, 2013]. These functions allow humans to solve complex problems, reason, create and execute plans, inhibit inappropriate responses, ignore distracting stimuli to focus on a goal, and focus on multiple tasks simultaneously [Diamond, 2013].

Adequate executive functioning begins with three core functions: working memory, cognitive flexibility, and inhibition and interference control [Diamond, 2013]. Working memory is the ability to manipulate previously stored information to attain a goal [Diamond, 2013]. This executive function is necessary for reasoning, decision-making, and executing plans. The ability to find commonalities or differences between two objects, to dissect a single element from a whole concept, to execute written or verbal instructions, or to form or update plans based on previous experiences are all tasks that require adequate working memory capacity [Diamond, 2013]. Working memory capacity relies on selective attention towards relevant stimuli while suppressing input from irrelevant stimuli. This concept describes another of the core three executive functions, inhibition and interference control. Inhibitory control refers to the ability to suppress an inappropriate reaction to a stimulus despite a predisposition to respond in such a way, while interference control refers to the ability to selectively attend to relevant stimuli despite the presence of irrelevant stimuli [Diamond, 2013]. The third core executive function, cognitive flexibility, refers to the ability to shift attention between different perspectives [Diamond, 2013]. From these core functions, higher-order functions are derived that allow individuals to plan, reason, and solve problems [Diamond, 2013].

Executive functions rely primarily on the frontal cortex, a region that is susceptible to age-related neurological changes as early as the 5th decade [Diamond, 2013, West, 1996]. Consequently, older adults exhibit worse performance, relative to young adults, on behavioural tasks challenging working memory [Macpherson et al., 2014, Mattay et al., 2006, Mcnab et al., 2015, Wingfield et al., 1988], inhibitory control [Christ et al., 2001, Coxon et al., 2016, West and Alain, 2000], and cognitive flexibility [Berry et al., 2016, Cepeda et al., 2001, Kray et al., 2002, Kray and Lindenberger, 2000, Meiran et al., 2001, Salthouse et al., 1998, Wasylyshyn and Sliwinski, 2011]. Working memory capacity decreases significantly among older adults compared to younger adults, resulting in reduced performance and PFC activation in tasks requiring higher working memory loads [Mattay et al., 2006, Macpherson et al., 2014]. Inhibitory control can be tested in choice reaction time tasks with an interference effect, such as a Stroop or Flanker task [Christ et al., 2001, Coxon et al., 2016, West and Alain, 2000]. The interference effect occurs when an individual attends to a distracting cue rather than the target, and is greater among older adults compared to young adults [Christ et al., 2001, Coxon et al., 2016, West and Alain, 2000]. Similar impairments in cognitive flexibility have been documented, in which older adults experience a significantly greater difficulty in switching attention between tasks compared to younger individuals, suggesting a greater cognitive load associated with retaining multiple tasks in working memory [Wasylyshyn and Sliwinski, 2011].

The challenges commonly seen on executive functioning tasks among older adults seem to be associated with changes in neural activation patterns and neural networks within the frontal cortex. Functional differences are observable with functional magnetic resonance imaging (fMRI) during cognitive tasks. On average, older adults had impaired performance and neural activation (as indicated by a reduced BOLD response) during working memory tasks than younger adults [Nagel et al., 2009]. However, there was overlap where high-performing older adults had similar performance and neural activation patterns to low-performing young adults [Nagel et al., 2009]. In a task-switching test, similar levels of brain activity were seen between the young and older adults; however, older adults experienced reduced functional connectivity in task-switching-related regions during the cue period of the task compared to younger adults [Madden et al., 2010].

A reduction in regional CBF in the PFC likely contributes to cognitive impairment, and especially impairments in executive functions [Bertsch et al., 2009, Girouard and Iadecola, 2006]. Increased local neuronal activity prompts the redistribution of global cerebral blood flow (CBF), which leads to an increase in regional CBF in the area of activity, termed neurovascular coupling [Girouard and Iadecola, 2006]. This relationship is required to maintain adequate oxygen delivery to active brain regions, and is impaired in older age and disease states, likely contributing to the behavioural changes observed on tasks of executive function. Studies focusing on CBF have observed greater relative CBF in posterior cortical regions compared to anterior regions in older adults, which is referred to as hypofrontality and is the opposite of what is seen in young and middle-aged adults [Gur et al., 1987]. Reductions in regional CBF are observed with advancing age, cerebrovascular disease, and dementia [Shaw, 1984]. Areas and magnitude of reduced CBF can vary but have been predicted to exceed 27% in the PFC [Shaw, 1984].

2.1.2 Age-Related Changes in Affect

Emotional state of an individual can be described using a number of terms, each related but fundamentally different. Beginning generally, subjective well-being describes how an individual perceives their quality of life, and is derived from life satisfaction and affect [Cheng, 2004]. Life satisfaction refers to the degree of positivity an individual associates with their overall life [Prasoon and Chaturvedi, 2016]. Affect refers to the acute experience of an emotion that occurs in reaction to an event or stimulus and can fluctuate greatly moment to moment [VandenBos, 2007]. Affect is distinct from mood. Affect is transient and provoked. In contrast, mood is an emotional state that is thought to be influenced by personality traits so that it is more constant over time [VandenBos, 2007].

Mental health is the state of internal equilibrium of psychological well-being, cognitive, and physical aspects of life, that allows an individual to be aware of themselves and others, and be able to function effectively in society regardless of adverse circumstances [Galderisi et al., 2015]. Persistent disruptions to mental health can lead to depressive symptoms or progress to major depressive disorder (MDD) [Galderisi et al., 2015]. While each of these aspects (well-being, life satisfaction, affect, mood, mental health) can be influenced by events and time, they vary in their susceptibility to change based their relative stability.

There is a common misconception among both younger and older adults that older adults have worse mood [Lacey et al., 2006]. When prompted to reflect on their younger years, older adults recall greater happiness in their youth, with a progressive decline since their 3rd decade [Lacey et al., 2006]. However, these retrospective estimates employed in cross-sectional studies do not reflect the reports of their younger counterparts. Likely due to the dynamic nature of mood, retrospective reflection is often inaccurate as individuals are more likely to recall positive rather than negative memories [Cheng, 2004,Lacey et al., 2006].

The prevalence of better mood within older adults can be explained by changes in affect over the lifespan. While positive affect is stable or increases until very old adulthood (8^{th} decade), negative affect declines across the adult lifespan [Charles et al., 2001]. After the 8^{th} decade, positive affect decreased with further aging and greater functional health limitations [Kunzmann et al., 2000]. However, after adjusting for functional health limitations, an increase in positive affect was again positively associated with age [Kunzmann et al., 2000].

Researchers have explored how older adults seem to maintain or improve emotional states during a time characterized by more losses than gains [Baird et al., 2010, Baltes, 1997, Carstensen and Turk-Charles, 1994, Charles et al., 2003, Isaacowitz et al., 2006]. The aging theories of emotion suggest that older adults focus on setting attainable, short-term goals, and immerse themselves in an environment that maximizes positive affect while minimizing negative affect [Cheng, 2004]. It is possible that the anticipation of the end of life motivates older adults to focus on emotionally gratifying experiences [Carstensen et al., 1999]. Older adults attend to and recall positive stimuli much more than negative stimuli [Carstensen and Turk-Charles, 1994, Charles et al., 2003, Isaacowitz et al., 2006]. Emotional regulation also improves greatly over the life course [Gross et al., 1997], with older adults experiencing fewer negative emotions than young adults [Carstensen et al., 2000, Charles et al., 2001, Gross et al., 1997].

Overall, 15% of community-dwelling older adults report depressive symptoms [Canadian Psychological Association, 2015]. While aging itself is not a risk factor for mental health disorders, the presence of chronic diseases or a lack of social support are considered risk factors [Hall et al., 2002, Mayo Clinic, 2015] that become more common with age [World Health Organization, 2011]. According to the Canadian Community Health Survey of 2008/2009, over 80% of adults aged 71 and over have at least one chronic condition, with 21% having 3 or more chronic conditions [Sanmartin, 2015]. Though older adults have a lower incidence of depression than young and mid-aged adults, over half of affected older adults experience their first depressive episode after the age of 60 [Fiske et al., 2009]. Older adults with depression have affective symptoms more rarely, which are common in young adults, but more often display disinterest and physical symptoms such as pain, nausea, and dizziness [Fiske et al., 2009]. Geriatric depression often goes mis-diagnosed because the associated symptoms are difficult to dissociate from normal aging, and because of the common misconception, even among older adults, that negative moods are normal in aging [Canadian Psychological Association, 2015].

The relationship between cognition and psychological states has been well documented [Dickerson, 1993, Harmon-Jones et al., 2013]. In healthy populations, high levels of positive affect have been associated with broadened cognitive process [Harmon-Jones et al., 2013]. Similarly, depression is considered one of the strongest risk factors for cognitive impairment [Baumgart et al., 2015, Bennett and Thomas, 2014]. Not only is depression in young adulthood a risk factor for dementia in later life, but depression in older adulthood can be an early symptom of dementia [Bennett and Thomas, 2014]. Despite relatively preserved psychological states in older adulthood, strategies to improve positive affect may concurrently increase cognitive function and reduce risk for dementia.

2.2 Influence of Exercise on Cognition and Affect

2.2.1 Influence of Chronic Aerobic Exercise on Cognition

Aerobic training and fitness seem to confer benefits to cognition with aging. Overall improvements in cognitive function following aerobic training have been reported in both cognitively healthy and cognitively impaired populations [Colcombe and Kramer, 2003, van Uffelen et al., 2008]. Memory, information processing speeds, and executive functions have all been observed to improve with exercise [Bherer et al., 2013, van Uffelen et al., 2008]. While improvements seem to occur across cognitive tasks, executive functions tend to show the largest benefit from aerobic training among older adults [Colcombe and Kramer, 2003, van Uffelen et al., 2008].

Older adults who are more fit or who aerobically train over a period of time have better executive functioning [Colcombe et al., 2004, Kramer et al., 1999]. In particular, high-fit older adults had greater inhibitory control on a Flanker task, with only an 18% interference effect (difference between incongruent and congruent reaction times) compared to the 26% interference effect in low-fit older adults [Colcombe et al., 2004, Kramer et al., 1999]. Higher-fit older adults also had reductions in task-switching cost [Kramer et al., 1999], and greater performance on working memory tasks [Voelcker-Rehage et al., 2010]. Periods of training also carry cognitive benefits. Aerobic training for 6 months was associated with an 11% reduction in Flanker interference effect [Colcombe et al., 2004]. Overall, these results suggest that aerobic training is associated with improved inhibitory control, cognitive flexibility, and working memory.

Aerobic training and fitness have also been associated with various structural and functional brain changes. Structurally, prolonged aerobic training (e.g. 6 months) and aerobic fitness have been reported to increase prefrontal and temporal grey matter volume [Colcombe et al., 2004, Erickson et al., 2011, Hillman et al., 2008]. Functionally, aerobic training leads to greater connectivity between left and right PFC, which is thought to enhance fronto-executive network functioning [Voss et al., 2010]. Similarly, high-fit older adults have greater cortical activation in attentional control areas with reduced activation in interference control areas, relative to low-fit older adults [Hillman et al., 2008]. This suggests that aerobically trained older adults have greater attentional control during tasks and, because of more efficient neural networks, are able to inhibit distracting stimuli at a smaller cognitive cost [Hillman et al., 2008]. This enhanced task-specific cortical activation and efficiency of neural networks following training is related to the behavioural performance improvements previously discussed.

The physiological mechanisms that are responsible for the cognitive improvements with chronic aerobic exercise are not entirely clear but likely include some combination of changes in CBF, growth factor release, and hormonal fluctuation [Gligoroska and Manchevska, 2012]. Individuals who aerobically train or are high-fit have greater CBF velocities compared to their sedentary or low-fit peers [Ainslie et al., 2008, Gligoroska and Manchevska, 2012, Guiney and Machado, 2013], which may increase nutrient levels and oxygenation to regions required for executive functioning via neurovascular coupling [Brown et al., 2010, Guiney and Machado, 2013]. Aerobic training is also associated with increased growth factor and hormone release, including brain-derived neurotrophic factor (BDNF), vascular endothelial growth factor (VEGF), insulin-like growth factor (IGF-1), estrogens, corticosteroids, and growth hormone [Gligoroska and Manchevska, 2012]. The latter four are the peripheral regulatory mechanisms that mediate the release of BDNF. BDNF is thought to be the central factor promoting synaptic plasticity, and is directly involved in learning and memory [Gligoroska and Manchevska, 2012].

2.2.2 Influence of Acute Aerobic Exercise on Cognition

There is also evidence to suggest that even a single bout of aerobic exercise can improve cognitive functioning for up to 2 hours post-exercise, regardless of initial fitness level [Basso et al., 2015]. Similarly to chronic exercise, the most beneficial effects of acute aerobic exercise on cognition seem to occur within the PFC, with improvements evident in tasks that assess working memory, inhibitory control, cognitive flexibility, verbal fluency, problem solving, and attention [Basso and Suzuki, 2017, Chang et al., 2012]. However, these cognitive improvements following acute exercise seem to vary based on the characteristics of the exercise session [Chang et al., 2012]. For instance, a recent study demonstrated that executive function (as measured by the Stroop interference task) improved immediately following both 10 and 30 minutes of moderate intensity aerobic exercise, but that the maintenance of cognitive benefits depended on the duration of exercise [Johnson et al., 2016]. While the 10-minute session showed a gradual reduction in performance over the 60 minutes post-exercise, the 30-minute session returned to baseline cognitive levels by 30 minutes post-exercise, and was worse than baseline at 60 minutes post-exercise. In contrast, results from another study suggest that PFC-dependent task performance remained enhanced up to 120 minutes following 50 minutes of vigorous intensity aerobic exercise [Basso et al., 2015]. Comparisons across studies are complex due to differences in exercise dose, cognitive tasks, and experimental designs.

Electroencephalography (EEG) studies have provided insight towards the cortical activation patterns that may be responsible for the cognitive improvements following acute aerobic exercise [Basso and Suzuki, 2017, Kamijo et al., 2009]. The P3 component of event-related potentials (ERPs) exhibits a shorter latency and larger amplitude during executive function tasks following an acute aerobic exercise session [Basso and Suzuki, 2017, Kamijo et al., 2009]. A study comparing these effects following a low (30%) and moderate (50%) intensity aerobic exercise bout found that both young and older adults experienced decreased P3 latencies regardless of intensity [Kamijo et al., 2009]. These changes in the P3 component have been suggested to represent increased allocation of attentional resources following exercise [Basso and Suzuki, 2017].

The mechanisms that underpin behavioural and neurophysiological change that occur following an acute bout of aerobic exercise are not well known. Acute exercise of at least 10 minutes at 60% has been reported to sufficiently activate the hypothalamic-pituitary-adrenal (HPA) axis response, resulting in increased peripheral cortisol levels for up to two hours post-exercise [Basso and Suzuki, 2017, Duclose et al., 2001, Luger et al., 1987]. As suggested by the inverted-U hypothesis of arousal, moderately elevated cortisol levels seem to improve working memory [Basso and Suzuki, 2017, Etnier et al., 1997]. Acute aerobic exercise also increases levels of peripheral neurotrophins such as BDNF, IGF-1, and VEGF, as well as neurotransmitter release [Basso and Suzuki, 2017]. Unlike chronic exercise or highly-fit individuals, the neurotrophin surges following acute exercise are transient, and their role in neurogenesis, synaptic plasticity, and angiogenesis are less understood. However, the immediate increases in serum BDNF following aerobic exercise were associated with greater performance on a working memory task among older adults [Hakansson et al., 2017].

2.2.3 Influence of Chronic Aerobic Exercise on Affect

Exercise training has been reported to provoke affective gains [Arent et al., 2000, Reed and Buck, 2009]. Periods of aerobic training have been associated with greater positive affect and reduced negative affect, independent of initial health status [Arent et al., 2000]. While affective changes occur regardless of duration of training period [Arent et al., 2000], the greatest improvements seem to occur following 10-12 weeks of training [Reed and Buck, 2009]. However, the timing of effects may be influenced by exercise characteristics (frequency, duration, intensity) and baseline affective states [Reed and Buck, 2009].

Aerobic training has been associated with improvements in other psychological domains [Awick et al., 2017, Rhyner and Watts, 2016]. Over 6 months of training, increases in moderate-to-vigorous physical activity (MVPA) were associated with reductions in psychological distress (anxiety, depression, daytime dysfunction, stress) among older adults [Awick et al., 2017]. The association between exercise training and depression has been well documented, and suggests that chronic exercise may be an effective treatment option for individuals of all ages who experience depressive symptoms [Rhyner and Watts, 2016].

2.2.4 Influence of Acute Aerobic Exercise on Affect

Studies evaluating the exercise-related change in mood and affect often use an acute bout of exercise rather than chronic sessions, possibly to eliminate the external influences of daily life on such a transient measure [Basso and Suzuki, 2017, Ekkekakis and Petruzzello, 1999, Yeung, 1996]. Overall, affect seems to improve following acute exercise despite a variety of modes, durations, intensities, and individual characteristics (age, sex) across studies [Basso and Suzuki, 2017, Yeung, 1996].

While psychological domains show improvement following acute exercise, the dose necessary to elicit these effects remains unclear. It has been suggested that 10 minutes of 60% aerobic exercise is sufficient to increase vigor while decreasing fatigue and negative mood states (as measured by the profile of mood states - POMS) in young adults. Twenty minutes shows additional reductions in confusion with no effects in other aspects of the POMS (tension, depression, anger) [Hansen et al., 2001]. In another study, however, 30 minutes of aerobic exercise was sufficient to show improvements in all measures of the POMS other than fatigue, with total POMS score remaining improved up to 24 hours post-exercise [Maroulakis and Zervas, 1993]. Although the measures were centered around one single bout of exercise, the study was conducted in young- to mid-aged women who regularly exercised for at least a month prior to collection. It is possible that some aspects of general mood improve immediately following exercise, while others require longer intervals.

2.3 Moderating Effect of Exercise Prescription on Cognition and Affect

Though even an acute session of exercise seems to have cognitive and affective benefits, the characteristics of the exercise session that elicit the greatest or most consistent benefits are still unclear. Researchers have manipulated exercise dose to understand the dose-response on cognition. In a recent meta-analysis, improvements in cognition were observed with all intensity levels of exercise [Chang et al., 2012]. However, studies of moderate intensity exercise elicited the greatest cognitive benefits, independent of the timing of the cognitive test following exercise [Chang et al., 2012]. For duration, cognitive effects were greatest for studies where participants completed 20 minutes of moderate intensity exercise [Chang et al., 2012]. The timing of cognitive task administration also seemed to influence exercise-associated effects, where studies with a delay of 10 minutes after exercise until the cognitive assessment observed the greatest effects [Chang et al., 2012]. It is likely, however, that these three characteristics interact to influence cognitive function.

There is less extensive literature regarding the influence of exercise dose on affect and mood. A meta-analysis comparing the influence of exercise dose on psychological well-being among older adults found that moderate intensity aerobic exercise seemed to elicit the most beneficial effects [Netz et al., 2005]. An older review further concluded that the optimal dose for mood benefits is at least 10 minutes, but no more than 50 minutes of low-moderate intensity exercise [Hansen et al., 2001].

Prior research related to exercise and affect has also investigated other moderators (beyond exercise dose). For example, one study explored the relationship between enjoyment of the exercise and affective responses to exercise [Raedeke, 2007]. It found that enjoyment was positively associated with gains in positive affect, vigor, and energetic arousal following exercise, but was unrelated to changes in negative affect [Raedeke, 2007]. Another study compared the effects of a group- versus home-based 8-week exercise program on mental health among older adults [Mortazavi et al., 2013]. The group-based exercise was held in groups of 10 participants with one instructor, while the home-based program was performed in dyads (the participant and a carepartner or family member). Both groups showed improved mood as measured by the 28-item general health questionnaire (GHQ-28). However, there were significantly greater improvements among participants in the group-based program compared to the home-based program [Mortazavi et al., 2013]. However, these results should be interpreted cautiously as the group-based program featured individuals with lower GHQ-28 scores at baseline, suggesting better initial mood status [Mortazavi et al., 2013]. The context (social, visual, auditory) of exercise delivery varies greatly, but limited research suggests these aspects may influence cognitive and affective effects.

2.4 Influence of Social Engagement on Cognition and Affect

Social engagement may also influence cognition and affect [Bourassa et al., 2017, Okura et al., 2017]. Social interaction seems to be a reliable predictor of cognitive performance across young to older adults [Ybarra et al., 2008]. Longitudinal studies have found a positive relationship between social network, social engagement, social integration, and cognitive functioning among community-dwelling older adults, reaching similar conclusions across various countries over many years [Bourassa et al., 2017, Fancourt and Steptoe, 2018, Li and Dong, 2017, Wang et al., 2002, Zunzunegui et al., 2003]. Older adults who lack social connections, are socially disengaged, socially isolated, and/or feel that they are socially isolated are at an increased risk of accelerated cognitive decline and dementia compared to socially active individuals [Bourassa et al., 2017, Cacioppo and Hawkley, 2009, Fancourt and Steptoe, 2018, Li and Dong, 2017, Wang et al., 2002, Zunzunegui et al., 2003].

The quantity, quality, and diversity of social engagement seem to moderate the relationship with cognition. Those with larger social networks and more frequent interactions have better executive functioning than those with smaller social networks [Bourassa et al., 2017, Fancourt and Steptoe, 2018, Li and Dong, 2017, Wang et al., 2002, Zunzunegui et al., 2003]. Greater social networks among healthy older adults are also associated with greater white matter integrity and reduced inflammation, which may underlie cognitive changes [Molesworth et al., 2015]. However, the feeling of emotional closeness to network members seems to be more beneficial to cognitive functioning than the number of connections [Li and Dong, 2017]. Moreover, having a social network that encompasses a variety of places/organizations/groups was associated with greater enhancement to white matter integrity [Molesworth et al., 2015]. It is possible that social interaction trains executive networks as a conversation requires attention, inhibition of irrelevant information, cognitive flexibility to change topics when needed, and working memory to temporarily store and recall information relevant to the conversation [Li and Dong, 2017]. It is possible that closer relationships may discuss more cognitively demanding topics, or require recall of long-term memories or of previous conversations. Diversity of a social network may challenge executive functions by broadening the topics of conversation.

Participation in social activities is also associated with greater positive affect. In a study examining the relationship between affect and social interaction, previously unacquainted young adults were deceptively video-taped during a 6-minute social interaction in groups of two [Berry and Hansen, 1996]. The social interactions were later scored on perceived enjoyment, engagement, intimacy, and depth of the conversation. The quality of the social interaction was positively associated with the degree of positive affect that it elicited [Berry and Hansen, 1996].

Chapter 3

Current Study

3.1 Rationale

Previous research has suggested that an acute bout of moderate intensity aerobic exercise has a positive effect on both cognition and affect, as does social engagement [Basso and Suzuki, 2017]. While exercise research often focuses on identifying the mode, duration, and intensity of exercise that elicit the most beneficial cognitive or affective effects, there has been no research to date exploring the influence that social interaction during exercise may have on cognition and affect. While there is some evidence to suggest that general mood state remains elevated at 24-hours post-exercise [Maroulakis and Zervas, 1993], there is no research that illustrates the trajectory of changes in mood over this time period, or that explores this effect with respect to exercise delivery variables, such as social context.

This study explored whether social exercise will elicit larger benefits to affect and cognition than solo exercise within older adult women. Further analysis compared the timeline of exercise-associated affective effects over the 34 hours post-exercise. Results from this study will help inform exercise delivery strategies targeted to aging brain health. To enhance cognitive benefits and improve affect, it is likely that exercise prescription should focus on the variables related to exercise delivery as well as exercise dose, which may play a critical role.

3.2 Objectives & Hypothesis

1. To compare the changes in executive function following social exercise, solo exercise, and control, as measured by a modified Flanker task.

   i) Relative to the control session, executive function will improve following both exercise sessions.

   ii) Relative to the solo exercise session, executive function will be enhanced more following the social exercise session.

2. To compare the changes in positive affect, negative affect, fatigue, and tranquillity following social exercise, solo exercise, and control, as measured by the Physical Activity Affect Scale.

   i) Relative to the control session, positive affect will increase and negative affect, fatigue, and tranquillity will decrease following both exercise sessions.

   ii) Relative to the solo exercise session, positive affect will increase and negative affect, fatigue, and tranquillity will decrease more following the social exercise session.

3. To compare the timeline of positive affect, negative affect, fatigue, and tranquillity over the 34 hours following each session.

   i) Relative to the control session, positive affect, negative affect, and fatigue will remain improved from pre-exercise levels for at least 24 hours following both exercise sessions.

   ii) Relative to the solo exercise session, positive affect, negative affect, and fatigue will have a slower rate of return-to-baseline following the social exercise session.

3.3 Methods

3.3.1 Sample Size

Sample size was powered to detect differences in behavioural measures between each exercise condition and the control condition (hypotheses 1i & 2i). In a meta-analysis outlining acute exercise effects on cognition, an effect size of 0.171 was associated with improved performance on tests of executive function [Chang et al., 2012]. In a meta-analysis outlining acute exercise effects on affect, an effect size of 0.35 was associated with improved positively activated affect following moderate intensity exercise [Reed and Ones, 2006]. The smaller of the two effect sizes (cognitive = 0.171) was used in this study. Using an alpha level of 0.05, power of 0.8, and a repeated measures ANOVA with a within-factor analysis design, accounting for a 10% drop-out rate, and counter-balancing of session sequences, a sample size of 30 participants was determined.

3.3.2 Participants

Healthy community-dwelling older adult women (60 years old and over) were recruited via the Waterloo Research in Aging Participant (WRAP) pool, posters in community centers in the Kitchener-Waterloo area, and word of mouth. To be eligible, participants were required to have no history of cardiovascular, neuromuscular, cognitive, or psychiatric issues within the last 2 years, as reported at baseline. Participants were required to have a Montreal Cognitive Assessment (MoCA) score of 26 or above, a cutoff that would screen out most people with MCI and dementia [Nasreddine et al., 2005]. Participants were also required to have a Geriatric Depression Scale score of 5 or below, a cutoff that would screen out most people with depressive symptoms [Yesavage and Sheikh, 1986]. Participants were also screened on their ability to perform physical activity using the Get Active Questionnaire (GAQ) (©CSEP-GAQ). A full description of inclusion and exclusion criteria can be found in figure 3.1.

Figure 3.1: **Eligibility criteria**

Criteria	Inclusion	Exclusion
Female ≥ 60 years of age	X	
Fluent in English language	X	
MoCA Score ≥ 26	X	
GDS Score < 5	X	
"No" to all GAQ questions*	X	
"No" to all medical screening form questions*	X	
History of heart disease		X
Uncontrolled diabetes and/or hypertension within last 2 years (not regulated by medicine, diet, or exercise)		X
History of neurological condition (stroke, epilepsy, dementia, recent concussion)		X
Uncontrolled mood disorder within last 2 years (depression, anxiety)		X

*or cleared by a CEP (or previously a doctor) based on reference document/detailed history

3.3.3 Study Design

This study used a repeated measures design. Participants completed three sessions, each including a different intervention (social exercise, solo exercise, or control). Sessions were randomized across participants with balanced permutations. The sessions were approximately one week apart to reduce learning and training effects between sessions. Testing and exercise times remained consistent within participants across sessions to eliminate the potential for circadian rhythm effects. All sessions occurred in the morning with start times of either 8:30am or 10:00am. Participants were asked to refrain from performing any moderate-vigorous physical activity within 24 hours prior to every session.

Experimental Sessions

During or prior to the first session, participants provided written informed consent and had eligibility confirmed. Then, participants completed the Physical Activity Scale for the Elderly (PASE), and the Ten-Item Personality Inventory (TIPI) to assess baseline physical activity status and personality, respectively [Gosling et al., 2003, Washburn et al., 1993]. Finally, resting heart rate and blood pressure were measured and 50% of age-predicted heart rate reserve (HRR) was calculated for each participant (50% $HRR = 0.5\ (HR_{age-predicted\ max} - HR_{rest}) + HR_{rest}$), to be used as a training intensity during the study paradigm [American College of Sports Medicine, 2014]. This intensity is considered moderate-intensity, which is associated with the most consistent cognitive and affective benefits [Basso and Suzuki, 2017, Chang et al., 2012]. We chose the mean of this moderate range to elicit effects while ensuring participants could still maintain a conversation. HRR was used rather than %HR as it takes into account individual differences in fitness by considering resting HR. This is particularly important since intensities were determined using a predictive value for HR max rather than obtaining a value from a graded exercise test.

The experimental measures were consistent across sessions. Only the intervention differed (social exercise, solo exercise, or control). Participants completed the St. Mary's Hospital Sleep Questionnaire (SMHSQ) at the beginning of each session and the following morning. Participants then completed mood and cognitive assessments before and after each intervention using the Physical Activity Affect Scale (PAAS) and a modified Eriksen Flanker task, respectively [Eriksen and Eriksen, 1974, Lox et al., 2009]. In addition, the PAAS was completed at 3-hour intervals throughout the day of intervention and the following day for a total of 10 time-points per session. Details regarding the PAAS and the Flanker task can be found in section 3.3.4. Participants were also asked to wear an ©ActiCal activity monitor and to log any physical activity over this time (34 hours post-exercise). Participants were asked to only remove the ActiCal only when sleeping or bathing for these two days. The activity log featured details on mode, intensity, duration, and social context.

Each intervention lasted for 26 minutes. In the solo exercise condition, participants completed a 3-minute warm-up, 20 minutes of moderate intensity walking (50% HRR), and a 3-minute cool-down on a treadmill. Warm-up was used to reduce rest-to-exercise effects by gradually increasing heart rate towards the target value for each participant.

In the social exercise condition, participants completed the same exercise protocol while also engaging in conversation with another participant. Previous literature suggests that the greatest cognitive benefit comes from high quality social interaction [Li and Dong, 2017]. While recruiting participants' family or friend to be their respective 'socializer' would most likely create high quality interaction, high quality conversation has also been elicited in dyads of strangers [Berry and Hansen, 1996]. Considering the feasibility of each option, we aimed to create high quality interaction by pairing strangers who share the commonality of participating in this study. Participants received identical instructions immediately prior to the social session, indicating that they are to get to know each other and keep the conversation going as best as possible for the duration of exercise. Treadmills were facing each other so participants could safely walk on the treadmill while still looking at their conversation partner. With participant consent, the social exercise session conversations were audio-recorded. Following the social exercise session, participants completed a brief questionnaire assessing the perceived quality of the social interaction [Berry and Hansen, 1996].

During the control session, participants remained seated for 26 minutes while listening to an informative podcast titled 'Exercise and Your Brain' narrated by Dr. Michael Trayford of the APEX Brain Centers.

Heart rate was monitored continuously throughout each session using an electrocardiogram (ECG) and recorded every minute. Rating of perceived exertion (RPE) was also recorded every 2 minutes using Borg's 20-point scale [Borg, 1998].

3.3.4 Measures

Modified Eriksen Flanker Task

A Flanker task has been used to monitor changes in PFC-dependent tasks following acute exercise [Basso and Suzuki, 2017, Botvinick et al., 1999, Eriksen and Eriksen, 1974]. The modified Flanker task used here featured 4 flanking arrowheads on a display screen that are either congruent (<<<<< or >>>>>) or incongruent (<<><< or >><>>) to the centrally-located target arrowhead [Kamijo et al., 2009]. Participants were instructed to respond to the direction of the target stimuli as quickly and accurately as possible, using the corresponding button on the response pad. All participants received identical instructions prior to every trial, had a viewing distance of 100 cm from the display screen, and were seated in a dark room.

Stimuli were presented for 500 ms each with a varying inter-stimulus interval of 1500 ms or 2000 ms, counter-balanced within blocks. A fixation cross appeared between stimuli to ensure participants remained centrally fixated. Incorrect responses, responses that occurred longer than 1000ms after stimulus onset, and double responses for a single stimulus (regardless of whether the first response was correct) were considered as errors and excluded from response time calculation. The pre-intervention Flanker task began with a practice block of 100 trials followed by a 10-minute break and a subsequent performance block of 200 trials. The post-intervention Flanker task occured approximately 10 minutes after the cessation of intervention and featured another performance block of 200 trials. All four stimuli sets (both options of congruent and incongruent trials) were equiprobable across the 200 trials and were randomized throughout the blocks. Response time (ms) and accuracy (%) were collected as indicators of executive function, response inhibition, attention, and information processing [Basso and Suzuki, 2017]. Further analysis was conducted on Flanker data using the Inverse Efficiency Score (IES) [Vandierendonck, 2017]. This scoring method provides a response time score that corrects for the amount of errors committed, thus allowing for greater interpretation of Flanker data.

Physical Activity Affect Scale (PAAS)

Mood was assessed using the Physical Activity Affect Scale (PAAS) [Lox et al., 2009]. This scale is composed of 12 affective terms. Participants were asked to indicate their current mood state for each item by circling the appropriate number on a 5 point scale (0=do not feel to 4=feel very strongly). Items were then totalled into their corresponding subscales: positive affect (enthusiastic, energetic, upbeat), negative affect (miserable, discouraged, crummy), tranquility (calm, relaxed, peaceful), and fatigue (fatigued, tired, worn-out) [Lox et al., 2009]. The PAAS was administered pre- and post-intervention of each session, and at 3-hour intervals for 34 hours following intervention (pre-intervention, post-intervention, 3h post, 6h post, 9h post on the day of intervention and at the same time-points the day following intervention). Participants received a package of 8 PAAS questionnaires at each session, and were asked to return them the following session, or mail them in the case of the last session. These repeated measures were collected to illustrate affective changes over the 34 hours after exercise.

The PAAS was chosen for its ease of administrations compared to other potential mood measures. The 12 item PAAS is quick to complete and requires little motivation from the participant compared to commonly-used measures such as the POMS, which features 65 items, or the GHQ-28 [Lox et al., 2009]. This was especially important in reducing any motivational biases when asking participants to record their affective status at such frequent intervals. The PAAS was derived from the Exercise-Induced Feeling Inventory and the Subjective Exercise Experiences Scale to have greater internal consistency and discriminant validity than its predecessors [Gauvin and Rejeski, 1993, Lox et al., 2009, McAuley and Courneya, 1994]. This more concise measurement tool assesses exercise-induced affective states, compared to more general affective states that are assessed by instruments such as the POMS, state-trait anxiety inventory (STAI), or positive affect negative affect schedule (PANAS) [Lox et al., 2009]. It has demonstrated measurement invariance across individuals with different activity levels, and sensitivity to acute exercise-induced mood effects [Carpenter et al., 2010, Lox et al., 2009].

Other Measures

Additional measures were collected to characterize participants or to control for confounding factors. Unless otherwise specified, these assessments were completed in the first session.

The MoCA is a brief cognitive screening tool that assesses attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, problem-solving, and orientation [Nasreddine et al., 2005]. This test has high sensitivity and specificity (90% and 87%, respectively) for detecting MCI.

The PASE is a brief survey assessing physical activity in older adults [Washburn et al., 1993]. This scale consists of information on leisure, household, and occupational activity over a one-week period.

The TIPI is a brief survey of personality [Gosling et al., 2003]. Participants were asked to rate the extent to which each personality trait reflects themselves on a 7-point scale (1=disagree strongly to 7=agree strongly). This survey quantifies personality based on the Five-Factor Model: extroversion, agreeableness, conscientiousness, emotional stability, and openness to experiences.

The SMHSQ is a 14-item scale assessing the duration, latency, and subjective quality of an individual's previous night's sleep [Ellis et al., 1981]. The scale consists of Likert-type and fill-in-the-blank responses and was designed for repeated use over an intervention period. Participants completed this questionnaire for the night prior to and the night following each experimental session. SMHSQ data was used to create a composite sleep score with previously published factor analysis for perception of sleep quality [Leigh et al., 1988].

The brief Conversation Quality Reflection (CQR) is an 11-item scale assessing the perceived quality of the conversation [Berry and Hansen, 1996]. Using a 5-point scale (0=not at all to 4=very much), participants were asked to indicate the extent to which each statement describes their previous conversation. This scale was completed immediately following the social exercise condition only.

Conversation quantity was scored for each social condition using total word counts between the participants, as captured by audio recordings. Individual contribution to the conversation was scored as a percentage of the words spoken by each participant.

ActiCal activity monitors were used to objectively quantify activity over the 34 hours following exercise. Monitors were worn at the hip placement. Participants removed the monitor only to bathe and sleep during this time, and removed it after completing the last PAAS of the condition. Data was processed using a single regression model with an outcome of energy expenditure (kcal/min/kg) within the Actical Software. Wake-times were set based on each session's day 2 SMHSQ data for each participant, and ActiCal data between the final day 1 PAAS and this wake-time was removed. The time that the participant completed their final PAAS questionnaire on day 2 was considered the end of ActiCal data for this session. Energy expenditure was averaged into epochs between PAAS questionnaires, or between wake-time of day 2 and the first PAAS questionnaire of that day. Due to very low adherence related to activity logs, ActiCal data was the sole determinant of activity during the 34 hours following intervention. Mean energy expenditure for each day was classified by epoch and matched to PAAS data.

3.3.5 Analysis

Statistical analysis was performed in RStudio. Participant characteristics are presented as mean ± standard deviation (SD) or percent as appropriate.

Flanker data (RT, accuracy) were examined using individual participant plots to understand the distribution of data, within and between subject variability, and to visualize trends. Data were assessed for normality through histograms and probability plots and were tested for homogeneity of variance using Mauchly's sphericity test. Since both RT and accuracy data violated sphericity, a linear mixed effects (LME) model without assumption of homogeneity of variance was used. All LMEs were done using the Welch-Satterthwaite approximation for degrees of freedom. LMEs for RT, accuracy, and IES had within subject variables of condition (social exercise, solo exercise, control), time (pre-/post-), and congruency (congruent, incongruent). Session (first, second, third) and participant were included as random effects within the models.

PAAS data violated sphericity; therefore, LME models were used for analysis. Acute changes from pre to post-intervention in PAAS subfactors were examined using an LME model with within-subject factors for condition (social exercise, solo, exercise, control), and time (pre-, post-), with session (first, second, third) and participant as random effects. To assess PAAS changes over the 34 hours following conditions, LME models were used, with within-subject factors for condition (social exercise, solo exercise, control), time (pre-/post-, 3h post, 6h post, 9h post) and day (1: day of intervention, 2: day after intervention), and random effects of session (first, second, third) and participant.

To understand the variability in response, plots of individual participant response times across conditions and time were examined and used to group participants. Four groupings emerged: 1) Consistent Responders; 2) Social Responders; 3) Solo Responders; and 4) Non-Responders (see appendix A.6). Consistent responders were identified as participants who showed improvements following both exercise conditions. Social responders were those who showed improvements following social exercise but not solo exercise. Solo responders were those who showed improvements following solo exercise but not social exercise, and non-responders were those who showed no consistent improvements within a particular exercise condition. Difference in actical, TIPI, PASE, SMHSQ, CQR, conversation quantity, and conversation contribution data between groups were examined as potential moderators (where formal effect moderation analyses were not sufficiently powered). Measures that were taken once were termed 'single-measure moderators' and consisted of TIPI, PASE, CQR, conversation quantity, and conversation contribution. Actical and SMHSQ were collected at each condition and were treated as repeated-measures moderators. Single-measure moderators were compared across groups using a one-way ANOVA. Repeated-measures moderators were compared across groups by condition and day/time using a one-way repeated-measures ANOVA.

Post-hoc analyses of main effects were performed using Tukey's test and values are shown as mean and standard error (SE) unless otherwise stated. Significant interactions were assessed using pairwise comparisons. A significance level of p=0.05 was used for all main outcome analyses. Residuals of all LME models were normally distributed.

3.4 Results

Participant Characteristics

Participant characteristics are outlined in table 3.1. All participants recruited were females over 60 years of age (mean = 69.9 years; SD =± 2.91 years).

Table 3.1: **Characteristics of participants and social conversation characteristics (mean ± SD). CQR = Conversation Quality Reflection.**

Participant Characteristic (n=30)	**Mean ± SD**
Age (years)	69.9 ± 6.38
BMI ($\frac{kg}{m^2}$)	25.4 ± 2.91
PASE Score	146 ± 66.5
Ten-Item Personality Inventory (out of 13)	
Extroversion	5.93 ± 1.51
Agreeableness	10.3 ± 1.93
Conscientiousness	11.4 ± 1.56
Emotional Stability	9.73 ± 2.33
Openness to Experience	9.63 ± 2.24
Social Condition Conversation	
Quality (CQR)	29.6 ± 4.91
Quantity (words)	1810 ± 320
Contribution (%)	50 ± 7.91

Exercise Characteristics

A summary of exercise characteristics can be found in table 3.2. Pre-intervention HR was not significantly different across conditions ($F_{(2,87)}$=0.130, p=.878), as expected. Intervention HR varied by condition ($F_{(2,87)}$=156, p<.001) such that HR during the solo and social exercise conditions was higher than the control condition (p<.001 for both). There was no significant difference between the solo and social exercise intervention HR (p=.141). Post-intervention HR was significantly different across conditions ($F_{(2,87)}$=20.9, p<.001), with significantly lower HR following the control condition compared to the solo and social exercise conditions (p<.001 for both). The post-intervention HR was higher following solo exercise compared to social exercise (p=.026). RPE was significantly different between solo and social conditions (p=.019, $t_{\bar{D}(28)}$=2.49), with solo exercise being associated with a higher RPE than social exercise. Mean RPE for each condition still fell within the target range of moderate (11-13) on the Borg 20-point scale.

Table 3.2: **Exercise characteristics by condition (mean ± SD).**

Exercise Characteristic	Control	Solo	Social
Pre-Intervention			
HR (bpm)	71.3 ± 8.5	72.5 ± 9.9	71.6 ± 11
SBP (mmHg)	124 ± 15	125 ± 17	125 ± 16
DBP (mmHg)	79 ± 8	77 ± 9	77 ± 9
Intervention			
HR (bpm)	68.4 ± 7.6	108.7 ± 11	107.1 ± 11.3
RPE (20-pt scale)	-	12.6 ± 1.4	11.9 ± 1.0
Post-Intervention			
HR (bpm)	66.9 ± 8.8	82.5 ± 11	79.2 ± 9.7
SBP (mmHg)	131 ± 22	122 ± 15	126 ± 21
DBP (mmHg)	79 ± 10	78 ± 8	79 ± 10

3.4.1 Flanker Task

Response Time (RT)

A summary of Flanker task RT data can be found in table 3.3. Analysis of RT did not show a significant condition x time interaction ($F_{(2,317)}$=0.881, p=.415). There was however a main effect of congruency on RT ($F_{(1,317)}$=139, p<.001), where incongruent trials had significantly longer response times than congruent trials. There was no significant difference in RT across conditions ($F_{(2,317)}$=1.41, p=0.247), or time ($F_{(1,317)}$=0.925, p=.337).

Table 3.3: **Flanker task response times (ms) for incongruent and congruent trials by condition and time (mean ± SD).**

Time	**Control**	**Solo**	**Social**
		Incongruent	
Pre	535.6 ± 54.7	530.7 ± 50.3	532.6 ± 67.2
Post	532.8 ± 56.8	532.2 ± 59.8	527.0 ± 69.4
		Congruent	
Pre	507.7 ± 44.8	504.8 ± 46.7	505.5 ± 59.9
Post	506.7 ± 50.0	506.0 ± 52.6	499.1 ± 58.4

Accuracy

A summary of Flanker task accuracy can be found in table 3.4. Analysis of accuracy showed a significant interaction of condition x time ($F_{(2,317)}$=3.15, p=.044). Post-hoc analysis indicated that participants had a decline in accuracy over the control condition (p=.007) and that post-intervention accuracy was lower in the control condition compared to the solo and social exercise conditions (p=.029 and p=.004, respectively). This interaction is illustrated in figure 3.2. There was also a main effect of condition ($F_{(2,317)}$=4.96, p=.008) on accuracy. Post-hoc analysis revealed that accuracy was higher during the solo and social exercise conditions compared to the control condition (p=.02 and p=.016, respectively), with no significant difference between solo and social exercise conditions (p=.997). There was also main effects of time ($F_{(1,317)}$=7.20, p=.008), and congruency ($F_{(1,317)}$=66.8, p<.001). Accuracy was greater pre-intervention than post-intervention (p=.008), and in congruent trials than incongruent trials (p=<.001).

Figure 3.2: **Flanker task accuracy over time pre- to post-intervention by condition. Condition x Time Interaction ($F_{(2,317)}$=3.15, p=.044).**

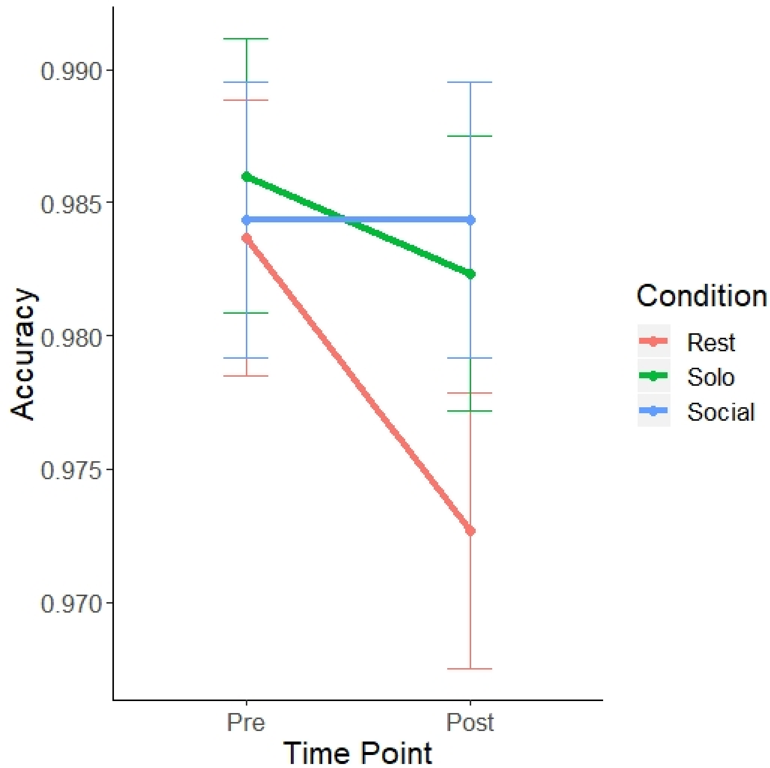


Table 3.4: **Flanker task accuracy (%) for incongruent and congruent trials by condition and time (mean ± SD).**

Time	Control	Solo	Social
		Incongruent	
Pre	98.0 ± 1.8	97.9 ± 2.3	97.6 ± 2.2
Post	96.4 ± 3.5	97.3 ± 2.3	97.7 ± 2.2
		Congruent	
Pre	98.8 ± 2.1	99.3 ± 1.1	99.3 ± 1.0
Post	98.1 ± 3.5	99.1 ± 1.1	99.2 ± 1.0

Inverse Efficiency Score (IES)

A summary of corrected Flanker scores using the IES method can be found in table 3.5. Analysis of IES did not show any significant condition x time interaction ($F_{(2,317)}$=1.49, p=.227). There was a main effect of congruency ($F_{(1,317)}$=150, p<.001), such that congruent trials had lower IES than incongruent trials. There was also a main effect of condition $F_{(2,317)}$=3.23, p=.041), such that the social exercise condition featured significantly lower IES compared to the control condition (p=.037), with no significant difference between exercise conditions (p=.774). There was no main effect of time ($F_{(1,317)}$=0.094, p=.76) on IES.

Table 3.5: **Flanker task inverse efficiency score (IES) for incongruent and congruent trials by condition and time (mean ± SD).**

Time	**Control**	**Solo**	**Social**
		Incongruent	
Pre	547.2 ± 59.8	543.0 ± 57.9	546.6 ± 76.2
Post	554.5 ± 76.4	547.4 ± 65.5	540.4 ± 77.9
		Congruent	
Pre	514.7 ± 51.5	508.2 ± 47.2	509.3 ± 61.3
Post	518.3 ± 68.8	510.6 ± 54.2	503.2 ± 59.7

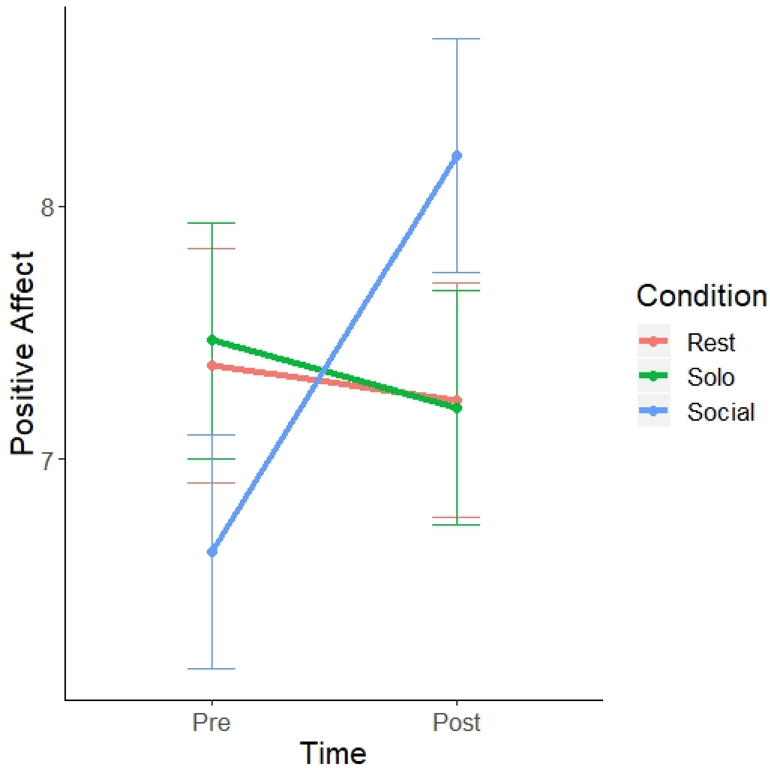
3.4.2 Physical Activity Affect Scale (PAAS)

All in-lab PAAS questionnaires were completed, and 97.9% of the remaining time-points were completed.

Positive Affect

Analysis of acute change in positive affect showed a significant interaction of condition x time ($F_{(2,143)}$=5.15, p=.007), such that the social exercise condition showed a significant improvement from pre- to post-intervention (p=.009), but not in the control (p=1.0) or solo exercise (p=.991) conditions. This is illustrated in figure 3.3. There was no main effect of condition ($F_{(2,143)}$=0.07, p=.931), or time ($F_{(1,143)}$=2.23, p=.137) in the acute model.

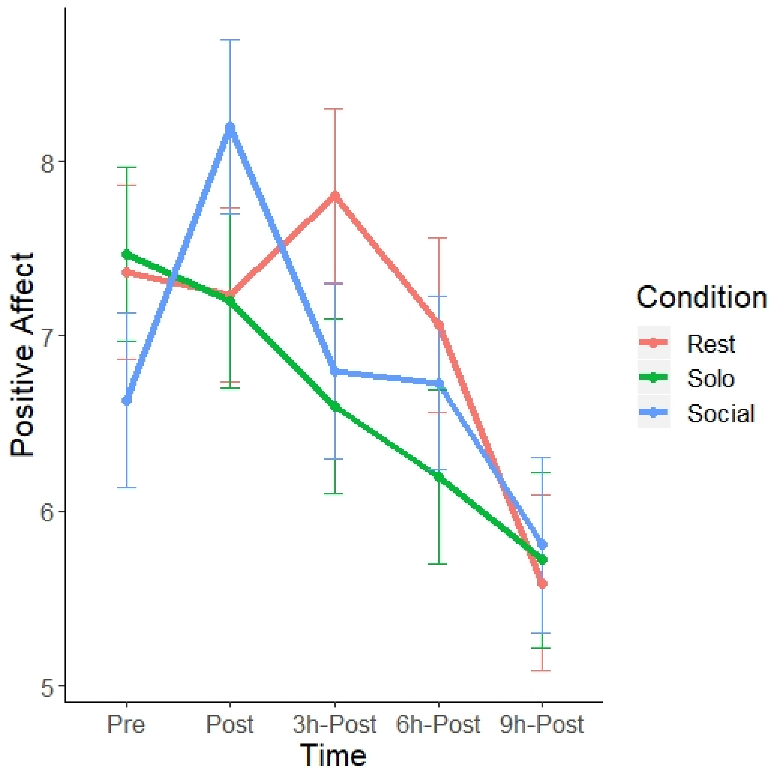
Figure 3.3: **Positive Affect over time pre- to post-intervention by condition. Condition x Time Interaction ($F_{(2,143)}$=5.15, p=.007).**



Positive affect analysis over 34h showed a significant condition x day interaction ($F_{(2,823)}$= 4.38, p=.013). While post-hoc comparison did not show any significance, there was a trend towards improvement over time in the solo condition (p=.139) with no significant change in the control condition (p=.536) or the social condition (p=1.0). There was also a main effect of time ($F_{(4,823)}$=18.6, p<.001). Positive affect was lower at 9h-post-intervention (either 18h30 or 20h00) than all other time points (p<.002). Additionally, positive affect was lower 6h-post-intervention compared to immediately post-intervention (p<.001). There was no main effect of condition ($F_{(2,823)}$=0.186, p=.83) or day over 34h ($F_{(1,823)}$=0.124, p=.725).

In exploratory analyses to further clarify the condition x time interaction, we broke the positive affect models into day 1 (day of intervention) and day 2. Both day 1 and 2 models illustrated the effect of time outlined above ($F_{(4,401)}$=12.4, p<.001 for day 1; $F_{(4,390)}$=6.99, p<.001 for day 2). For day 1, there was a condition x time interaction ($F_{(8,401)}$=2.1, p=.035), but not for day 2 ($F_{(8,390)}$=0.572, p=.801). Figure 3.4 illustrates this interaction, in which positive affect reduces over time (control: p=.022; solo: p=.27; social: p<.001).

Figure 3.4: **Positive Affect over time up to 9h-post intervention by condition. Condition x Time Interaction ($F_{(8,401)}$=2.1, p=.035).**

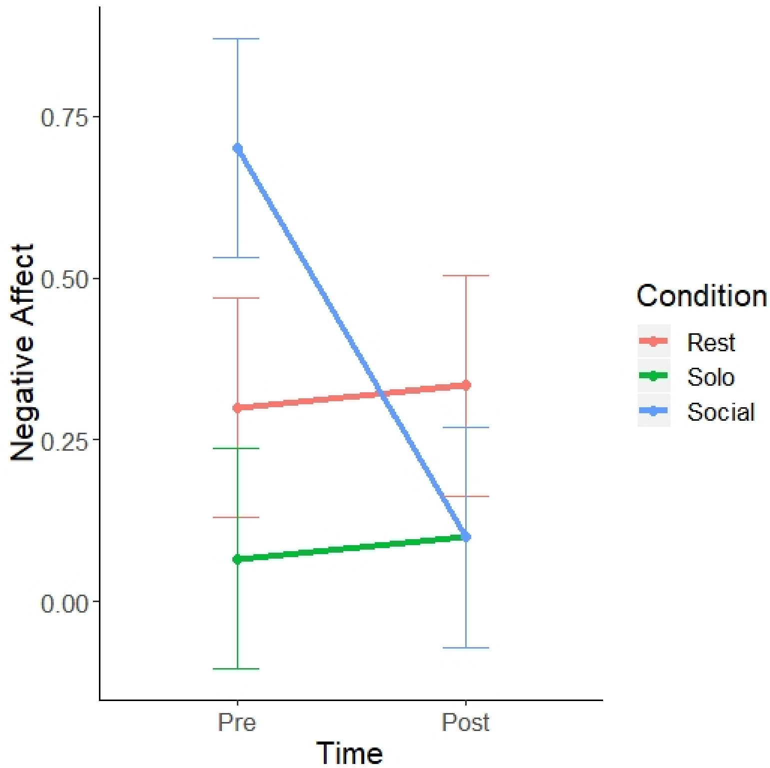


Negative Affect

There was a near-significant interaction of condition x time in analyses of acute changes in negative affect ($F_{(2,145)}$=2.94, p=.056), such that the social exercise condition was associated with a near-significant reduction in negative affect from pre- to post-intervention (p=.061). There was no significant effect of condition ($F_{(2,145)}$=2.37, p=.097) or time ($F_{(1,145)}$=2.08, p=.151).

There was a significant condition x time interaction ($F_{(8,823)}$=2.3, p=.019), with a gradual reduction in negative affect from pre-intervention over time in the social condition,

Figure 3.5: **Negative Affect over time pre- to post-intervention by condition. Condition x Time Interaction ($F_{(2,145)}$=2.94, p=.056).**



up until 6h-post (p=.003), but not in any other conditions (control: p=.628; solo: p=1.0). Pre-intervention negative affect was significantly higher in the social condition compared to the solo (p=.012). This is illustrated in figure 3.6. There was also a main effect of time ($F_{(4,823)}$=3.1, p=.015), in which negative affect was significantly lower 6h-post-intervention than pre-intervention (p=.006). There was no significant effect of condition ($F_{(2,823)}$=1.29, p=.275) or day ($F_{(1,823)}$=0.165, p=.685) on negative affect over 34h.

Tranquility

There was no significant condition x time interaction ($F_{(2,145)}$=1.85, p=.16), and no main effects for condition ($F_{(2,145)}$=0.003, p=.997) or time ($F_{(1,145)}$=0, p=1) in acute analyses of tranquility. A summary of acute scores can be found in table 3.6.

In analysis of tranquility over 34h, there was no significant condition x time ($F_{(8,823)}$=1.5,

Figure 3.6: **Negative Affect over time up to 34h-post intervention by condition. Condition x Time Interaction ($F_{(8,823)}$=2.3, p=.019).**

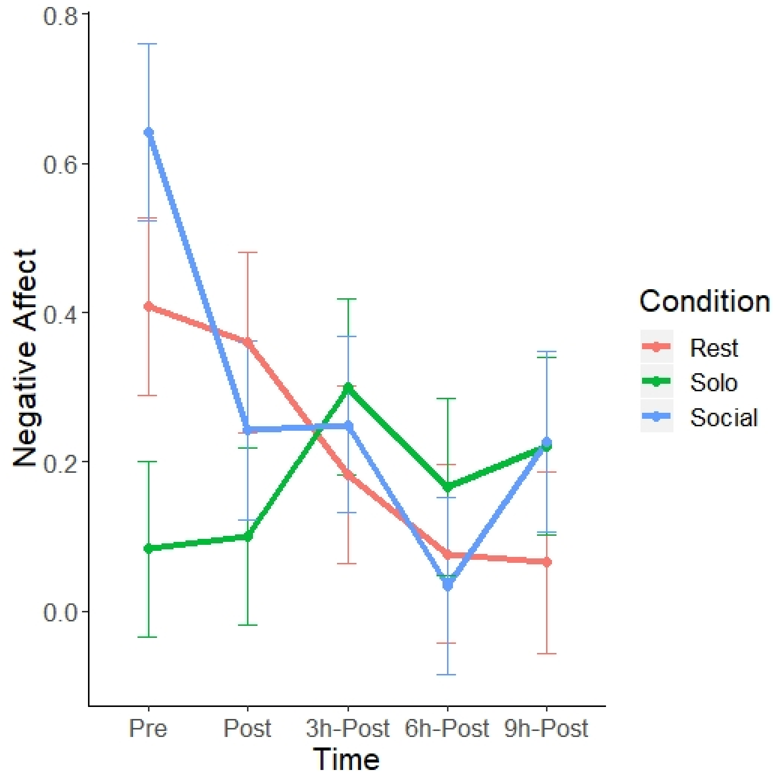


Table 3.6: **Tranquility & Fatigue scores from pre- to post-intervention by condition (mean ± SD). Note: scores out of 12; higher scores denote greater tranquility and higher fatigue.**

Time	Control	Solo	Social
		Tranquility	
Pre	1.07 ± 1.87	1.23 ± 1.45	1.57 ± 2.70
Post	1.50 ± 2.13	1.37 ± 1.65	1.00 ± 1.36
		Fatigue	
Pre	6.90 ± 2.50	6.53 ± 2.84	6.67 ± 2.44
Post	7.63 ± 2.83	7.03 ± 2.83	7.60 ± 2.11

p=.154), condition x day ($F_{(2,823)}$=1.31, p=.27), or time x day interactions ($F_{(4,823)}$=0.50, p=.734). There was, however, a main effect of time ($F_{(4,823)}$=7.83, p<.001). Tranquility was higher 9h-post-intervention than every other time-point (p<.002). There was also a main effect of day on tranquility ($F_{(1,823)}$=6.38, p=.012), in which day 1 (day of intervention) was associated with significantly greater tranquility compared to day 2. There was no effect of condition ($F_{(2,823)}$=0.59, p=.554) on tranquility over 34h.

Fatigue

There was no condition x time interaction ($F_{(2,143)}$=0.287, p=.751) in the analyses of acute change. However, there was a main effect of time ($F_{(1,143)}$=9.55, p=.002) in analyses of acute changes in fatigue, such that fatigue was higher post-intervention than pre-intervention. There was no significant effect of condition ($F_{(1,143)}$=1.52, p=.222). A summary of acute scores can be found in table 3.6.

In analyses of fatigue over 34h, there was no significant condition x time ($F_{(8,823)}$=0.944, p=.479), condition x day ($F_{(2,823)}$=1.7, p=.183), or time x day interactions ($F_{(4,823)}$=0.272, p=.896). However, there was a main effect of time ($F_{(4,823)}$=3.66, p=.006). Post-hoc analysis revealed that fatigue was higher post-intervention, 3h-post, and 9h-post compared to pre-intervention (p=.022, p=.017, p=.012, respectively). There was no main effects of condition ($F_{(2,823)}$=1.31, p=.27) or day ($F_{(1,823)}$=0.578, p=.447) on fatigue over 34h.

3.4.3 Variability in Response

Individual participant plots for Flanker task response time by condition, and congruency are found in Appendix B, and are sorted by group (non-responders, solo responders, social responders, consistent responders).

Differences in participant characteristics by group are displayed in table 3.7. There were significant differences in extroversion ($F_{(3,356)}$=3.13, p=.026), agreeableness ($F_{(3,356)}$=9.24, p<.001), conscientiousness ($F_{(3,356)}$=5.18, p=.002), and PASE score ($F_{(3,356)}$=5.68, p<.001) by groups. Consistent responders and social responders were more extroverted than non-responders (p=.044 and p=.047, respectively). Consistent responders and social responders were also more agreeable than solo responders (p<.001 for both). In addition, social responders had significantly higher conscientiousness than non-responders (p=.002). On the other hand, non-responders had significantly higher self-reported physical activity levels compared to solo responders (p=.004) and social responders (p=.01). Openness to experience ($F_{(3,356)}$=0.734, p=.532) and emotional stability ($F_{(3,356)}$=2.51, p=.059) did not differ by group.

All three conversation criteria showed a main effect of group. Conversation quality ($F_{(3,356)}$=23.5, p=<.001) was rated significantly higher by consistent responders compared to all other groups (p<.001 for all). Conversation quality was also rated higher among social responders (p=.008) and non-responders (p<.001) compared to solo responders. Similarly, conversation quantity ($F_{(3,332)}$=18.2, p<.001) was higher among consistent responders and social responders compared to non-responders (p<.001 for both) and solo responders (p<.001 and p=.001, respectively). In contrast, conversation contribution ($F_{(3,332)}$=10.2, p<.001) suggested that non-responders had significantly greater contribution to the conversation quantity than social responders (p<.001) and consistent responders (p=.019). Solo responders also contributed more to the conversation quantity compared to social responders (p=.007).

Composite sleep score ($F_{(1,164)}$=0.003, p=.955), day 1 energy expenditure ($F_{(1,252)}$=0.555, p=.457), and day 2 energy expenditure ($F_{(1,417)}$=1.08, p=.3) did not differ by group.

Table 3.7: **Single-measure moderators by Responder grouping (mean ± SD).**

Moderator	**Non-Responders** (n=10)	**Solo Responders** (n=2)	**Social Responders** (n=8)	**Consistent Responders** (n=10)
Ten-Item Personality Inventory				
Extroversion	5.6 ± 1.29	6.0 ± 1.02	6.13 ± 1.28	6.1 ± 1.82
Agreeableness	10.5 ± 2.12	8.5 ± 1.53	10.6 ± 1.74	10.2 ± 1.67
Conscientiousness	11.0 ± 1.56	11.0 ± 0	11.8 ± 1.65	11.5 ± 1.51
Openness to Experience	9.8 ± 1.95	9.5 ± 0.51	9.38 ± 2.19	9.7 ± 2.62
Emotional Stability	9.5 ± 2.47	9.5 ± 1.53	9.5 ± 2.07	10.2 ± 2.37
PASE Score	159 ± 63.9	113 ± 31.7	140 ± 76.9	142 ± 59.3
Social Conversation				
Quality	29.3 ± 3.65	25.0 ± 0	28.3 ± 6.81	32.0 ± 2.91
Quantity	1692 ± 299	1619 ± 330	1870 ± 274	1946 ± 294
Contribution (%)	52.4 ± 8.66	52.6 ± 3.21	47.0 ± 8.49	49.4 ± 5.16

3.5 Discussion

This study examined the influence of social engagement during exercise on exercise-associated affect and executive function. In this study, social engagement during exercise was associated with an immediate improvement in positive affect and reduced negative affect up to 6h-post intervention. In contrast, our results provide only weak support for enhanced executive functions following solo or social exercise. However, exploratory analyses across responder groups also suggested that individual characteristics, social engagement during exercise, and exercise habits may influence the cognitive response to exercise. Specifically, people who showed improvements in executive function after social exercise were more likely to be extroverted and to perceive high quality conversation during exercise. In addition, non-responders (no cognitive improvements after social or solo exercise) had higher habitual exercise. Our preliminary findings regarding the influence of social versus solo exercise suggest some benefits to executive function and affect after exercise, especially social exercise, but that the relative cognitive response may vary dependent on characteristics of the person, their habits, and the social interaction. This is a key area for future exploration.

In this study, only Flanker task accuracy, and not RT, was better after exercise than after a control condition, providing only partial support for our primary hypothesis that executive function would be better after exercise than a control. Of note, accuracy was only stable during the exercise sessions but declined over the control condition, a positive outcome but not an improvement after exercise. This finding aligns with previous literature in which accuracy remained stable following a single session of moderate-intensity aerobic exercise [Davranche et al., 2009, Kamijo et al., 2009, Mcmorris et al., 2011]. It is possible that the reductions in accuracy following control are driven by reductions in arousal states, even though an active control (listening to podcast) as opposed to passive control was specifically selected to avoid boredom.

While the accuracy data provided some support that executive function is better following exercise, this notion was not supported by the RT results. In this study, there was no difference in Flanker task RT changes by condition. These findings are in contrast to a recent meta-analysis that has suggested that 20 minutes of moderate-intensity aerobic exercise elicits improvements on choice response time tasks [Chang et al., 2012]. However, there are several studies that have not found improvements in RT [Hillman et al., 2002, Hillman et al., 2003, Pontifex and Hillman, 2007, Themanson and Hillman, 2006], particularly among older adults [Hillman et al., 2002]. Inconsistent findings could be related to several differences across studies. First, it is possible that there were speed-accuracy tradeoffs in our data and that these account for the lack of difference in RT response across conditions. In this study, participants demonstrated very high accuracy, especially in exercise conditions, compared to prior studies using the Flanker task [Hillman et al., 2002, Kamijo et al., 2007, Kamijo et al., 2009, Themanson and Hillman, 2006, Hillman et al., 2003]. Participants were instructed to respond as quickly and accurately as possible, but this may have led to varying prioritization. Other studies have instructed participants to respond as quickly as possible [Hillman et al., 2003, Kamijo et al., 2007, Kamijo et al., 2009, Themanson and Hillman, 2006], which may lead to more consistent speed-accuracy tradeoff across timepoints. Alternatively, the differences seen in this study could be the result exercise intensity. In the current study, intensity was set using age-predicted maximal HR, whereas many studies use a graded exercise test to determine intensity [Johnson et al., 2016, Kamijo et al., 2007, Kamijo et al., 2009]. Age-related predictions in HR have not been well validated in older adults [American College of Sports Medicine, 2014, Tanaka et al., 2001], and consequently, the intensity set for the current study may not accurately represent the moderate-intensity range which tends to elicit the most consistent improvements in cognition [Chang et al., 2012].

Given that changes in accuracy can confound RT analyses, and potential inconsistent speed-accuracy tradeoffs in our data, we also created a combined score (IES) to examine overall Flanker performance [Vandierendonck, 2017]. The IES score corrects RT for error rate and is one recommended strategy to analyze data that includes both RT and accuracy scores [Vandierendonck, 2017]. In this study, the IES was better during the social condition compared to the control condition, but there was no significant difference in the change in IES (pre- to post-intervention) across conditions.

Our second hypothesis suggested that executive function would improve more after social compared to solo exercise, which was not strongly supported by our results. Despite no prior studies, a greater improvement in executive function was expected after social exercise because dual-task exercise similar to the social exercise condition (walking while doing a verbal cognitive task) has been previously associated with acute improvements in executive functions [Holtzer et al., 2011]. While a conversation may not be a traditional cognitive task, it does require attention, cognitive flexibility to change topics, working memory to temporarily store and recall information, and inhibition of irrelevant information [Li and Dong, 2017]. However, changes in accuracy and RT did not vary across solo and social exercise (or control) conditions. It should be noted, however, that mean RT was fastest, the post-intervention accuracy was greatest, and the IES best after the social exercise condition. It is likely that we were underpowered to detect a significant difference between changes after the social exercise condition and the solo exercise condition. Sample size was estimated using an effect size published in a meta-analysis (0.171) for differences in cognition between exercise and control [Chang et al., 2012]. Effect sizes between social exercise and solo exercise in this study ranged from 0.127 to 0.159. Consequently, a sample size of 33 to 48 would be required to detect differences in changes in executive function between social and solo exercise.

In exploratory analyses, responder groups were identified according to whether participants improved in Flanker RT during the social, solo, or both exercise conditions. Of 30 participants, a third improved RT after both exercise conditions, just more than a quarter improved only after the social exercise condition, and only 2 of 30 participants improved only after the solo exercise condition. The remaining third of participants did not improve RT following either exercise condition. Though very exploratory, the concept of variability in response to an intervention is not new. Prior literature suggests that there is a natural variability in how individuals respond on a particular task and to a particular training bout [Hecksteden et al., 2015, Mann et al., 2014, Montero and Lundby, 2017, Pickering and Kiely, 2019].

In this study, responder groups differed based on participant characteristics, conversation characteristics, and physical activity history. Participants who improved over the social exercise condition were more extroverted, conscientious, and agreeable than other groups. The reason behind this difference is unclear. However, individuals with higher extroversion have been previously documented to have faster reaction times compared to introverts [Brebner, 1980], likely due to faster motor processing speeds [Stahl and Rammsayer, 2008]. Extroversion has also been linked to greater P3 amplitudes compared to introverts [Cahill and Polich, 1992], possibly indicating greater allocation of attentional resources similar to what has been shown following exercise [Basso and Suzuki, 2017]. Additionally, conscientiousness has been linked to inhibition of distraction, and agreeableness to inhibition of interpersonal conflict [Hirsh et al., 2009]. It is possible that a combination of these factors may predispose this group to improvements in executive function and that social engagement during exercise may act as the stimulus to initiate these acute improvements.

In addition, the characteristics of the social engagement may also alter cognitive changes to exercise. Those who showed improved RT after exercise rated conversation quality during the social exercise condition as better than did other groups. While prior cross-sectional literature found that quality of social interaction is an important correlate of cognition [Li and Dong, 2017], it has not been examined as a predictor of cognitive change. The reason why conversation quality predicts cognitive changes is unclear. It may be partly confounded by participants characteristics, where people who are more agreeable may be more likely to report high quality conversations [Hirsh et al., 2009]. The groups that were responsive to social exercise reported high quality of conversation but tended to contribute less to the conversation than their partner. It is possible that increased active listening or listening to dialogue that was particularly interesting to them challenged cognitive functions more than talking. There is some evidence that increasing the cognitive challenge during exercise may further benefit executive function following exercise, as has been demonstrated in dual-task paradigms [Holtzer et al., 2011]. Alternatively, the difference of words contributed to the conversation may be related back to personality differences, in which agreeableness is characterized by low dominance [Hirsh et al., 2009], which could be the case where the participant let their partner control the conversation.

In this study, affect improved more after social exercise compared to either solo exercise or the control condition. Positive affect improved from immediately before to after the social exercise condition, which was not observed for the rest or solo exercise conditions. Additionally, negative affect was reduced up to 6 hours after the social exercise condition, but this trend was not seen in the control or solo conditions. This acute improvement in affect after social exercise aligns with previous studies suggesting that a meaningful conversation is associated with improved affect [Berry and Hansen, 1996]. Although affective changes have not previously been examined in relation to a single-session of social engagement with exercise, improvements in affect have been observed following a period of exercise training [Mortazavi et al., 2013]. Indeed, a recent cross-sectional study suggested that all types of exercise featured improvements in mood, but that team sports and group exercise, both social, had the greatest impact [Chekroud et al., 2018].

In this study, affect did not improve after solo exercise, which is in contrast to prior studies [Basso and Suzuki, 2017, Maroulakis and Zervas, 1993, Reed and Ones, 2006]. There are some possible reasons for this difference. First, we used an active control (rather than quiet rest) where participants listened to a podcast for 20 minutes. Subjectively, participants reported that they enjoyed the podcast as it was informative and interesting. In contrast, other studies have commonly used an independent control group, a rest condition, or an 'active' control using an exercise video [Barabasz, 1991, Basso and Suzuki, 2017, Maroulakis and Zervas, 1993, Reed and Ones, 2006], which may be less enjoyable. Alternatively, differences in pre-exercise mood may limit the influence of exercise-associated benefits, such that the greatest benefit in mood following exercise tends to occur in those who report lower pre-exercise mood [Reed and Ones, 2006]. It is possible that our sample had elevated pre-exercise mood compared to these previous studies, thus limiting increases following exercise compared to control. Though comparison across studies is limited due to differences in measurement scales, one study that reported affective improvements in the PAAS following exercise had lower mean positive affect and higher negative affect at pre-intervention compared to the current sample [Pittsinger et al., 2017].

Despite acute improvements in affect after social exercise, only improvements in negative affect were sustained, and even then, only up to 6 hours after social exercise. This was shorter than hypothesized (24h). This finding is in contrast to previous literature that found improvements in mood up to 24h after acute exercise [Maroulakis and Zervas, 1993]. It should be noted, however, that this previous study did not track changes over time and instead administered only pre-, post- and 24h-post questionnaires. It is possible that repeated completion of the PAAS negatively influenced affect and outweighed positive effects of exercise.

Our results partially support the hypothesis that overall affect would have sustained benefits following social exercise compared to solo exercise. In this study, the social exercise condition, but not the solo exercise condition, was associated with significant reductions in negative affect up to 6h-post intervention. Despite no prior research, we hypothesized that social exercise would have sustained improvements in affect, as exercise has previously elicited sustained improvements [Daley and Welch, 2007,Maroulakis and Zervas, 1993], and group exercise training has been associated with greater affective changes than individual exercise [Mortazavi et al., 2013]. However, it should be noted that pre-intervention negative affect was significantly higher in the social exercise condition compared to the solo exercise condition. It is unclear why negative affect was substantially higher at pre-intervention, however, since conditions were counter-balanced and participants were blinded to the condition when completing the PAAS.

In contrast to other studies, there was also no improvement in tranquility or fatigue (as measured by PAAS) after either exercise condition compared to the control condition. Tranquility did not vary within or between conditions, while fatigue worsened following all interventions. An acute worsening in fatigue is not surprising due to the physical effort required by exercise. Indeed, one study reported elevations in fatigue post-exercise, even though fatigue decreased by 30 minutes and 2 hours post-exercise in this study [Daley and Welch, 2007]. It is unclear why there were no delayed improvements in fatigue in the current study, but it could be due to the time periods captured (immediately post and then not until at least 3 hours post).

The findings of this study that there are no improvements in tranquility are also in contrast with previous literature, which suggests that moderate-intensity aerobic exercise elicits improvements in tranquility as measured by the PAAS or one of its precursor scales [Annesi, 2002, Pittsinger et al., 2017]. One of the prior studies used only new exercisers, and it is possible they are more responsive to an exercise intervention. Indeed, cognitive non-responders had higher average physical activity than other responder groups in this study [Annesi, 2002]. Another study of the acute affective changes following surfing found that tranquility and fatigue improved with exercise, but that this effect was smaller in magnitude in newer or infrequent surfers [Pittsinger et al., 2017]. In this case, the authors suggested that greater physical fatigue among inexperienced surfers may be the cause. It is possible that the greater fatigue observed post-intervention (all conditions) may have constrained positive changes in tranquility.

3.6 Limitations

This study was the first to examine the influence of social engagement during exercise on executive functions and affect. There are some important limitations that should be noted. Firstly, it is likely that the study was underpowered to detect differences between the social and solo exercise conditions, and possibly across all three conditions. Our sample size estimate, however, was based on a recent meta-analysis of the acute effects of exercise on cognitive function. In addition, the sample was limited to female participants. This sample was chosen to limit variability by removing sex-specific differences in personality and to increase the likelihood of stimulating meaningful conversations between strangers. However, this limits the interpretation of findings within this study to a broader population. Also, participants were instructed to respond as quickly and accurately as possible on every Flanker block. It is possible that this led to inconsistent speed-accuracy tradeoff, enhancing variability and decreasing power to detect effects across conditions. Lastly, participants were instructed to keep the conversation going for the duration of the social exercise, and some pairs required researcher help initiate the conversation. For this reason, the social conversation may not be considered entirely organic, and conclusions may be limited in their generalizability to more natural or unprovoked types of social engagement.

3.7 Conclusions & Future Directions

In this study, Flanker task accuracy improved after exercise and positive and negative affect improved after social exercise only. These results suggest that social exercise may carry additional benefits over solo exercise. A future study should compare the effect of social exercise to a social engagement only condition to determine whether there was an additive or multiplicative effect. Of note, the cognitive changes with exercise appeared to vary by personality, physical activity levels, and characteristics of the social engagement. Given that this study was underpowered to conduct formal moderator analyses, future studies should specifically probe how characteristics of the individual and social engagement alter cognitive and affective changes observed with exercise. Finally, this study included only females in the study sample. Future studies should expand investigations of social and solo exercise to a male sample, and compare the effects across sexes or gender.

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Appendix A

A.1 Ten-Item Personality Inventory

Ten-item measure of the Big Five 1

Ten-Item Personality Inventory-(TIPI)

Here are a number of personality traits that may or may not apply to you. Please write a number next to each statement to indicate the extent to which you agree or disagree with that statement. You should rate the extent to which the pair of traits applies to you, even if one characteristic applies more strongly than the other.

Disagree strongly	Disagree moderately	Disagree a little	Neither agree nor disagree	Agree a little	Agree moderately	Agree strongly
1	2	3	4	5	6	7

I see myself as:

1. _____ Extraverted, enthusiastic.
2. _____ Critical, quarrelsome.
3. _____ Dependable, self-disciplined.
4. _____ Anxious, easily upset.
5. _____ Open to new experiences, complex.
6. _____ Reserved, quiet.
7. _____ Sympathetic, warm.
8. _____ Disorganized, careless.
9. _____ Calm, emotionally stable.
10. _____ Conventional, uncreative.

TIPI scale scoring (“R” denotes reverse-scored items):

Extraversion: 1, 6R; Agreeableness: 2R, 7; Conscientiousness; 3, 8R; Emotional Stability: 4R, 9;

Openness to Experiences: 5, 10R.

A.2 St. Mary's Hospital Sleep Questionnaire

Session #: _________ Day: _________ Participant ID: ____________________

St. Mary's Hospital Sleep Questionnaire

Please answer the following questions based your sleep over the **last 24 hours**.

At what time did you:

1. Settle down for the night? _____Hrs. _____Mins.
2. Fall asleep last night? _____Hrs. _____Mins.
3. Finally wake this morning? _____Hrs. _____Mins.
4. Get up this morning? _____Hrs. _____Mins.
5. Was your sleep: (tick box)

   - ☐ Very light
   - ☐ Light
   - ☐ Fairly light
   - ☐ Light average
   - ☐ Fairly deep
   - ☐ Deep
   - ☐ Very deep

6. How many times did you wake up? (tick box)

   - ☐ Not at all
   - ☐ Once
   - ☐ Twice
   - ☐ Three times
   - ☐ Four times
   - ☐ Five times
   - ☐ Six times
   - ☐ More than six times

How much sleep did you have:

7. Last night? _____Hrs. _____Mins.
8. During the day, yesterday? _____Hrs. _____Mins.
9. How well did you sleep last night? (tick box)

   - ☐ Very badly
   - ☐ Badly
   - ☐ Fairly badly
   - ☐ Fairly well
   - ☐ Well
   - ☐ Very well

   If not well, what was the trouble? (e.g. restless, etc.)

   i. ____
   ii. ____
   iii. ____

10. How clear-headed did you feel after getting up this morning? (tick box)

☐ Still very drowsy
☐ Still moderately drowsy
☐ Still slightly drowsy
☐ Fairly clear-headed
☐ Alert
☐ Very alert

11. How satisfied were you with last night's sleep? (tick box)

☐ Very unsatisfied
☐ Moderately unsatisfied
☐ Slightly unsatisfied
☐ Fairly satisfied
☐ Completely satisfied

12. Were you troubled by waking early and being unable to get off to sleep again? (tick box)

☐ No
☐ Yes

13. How much difficulty did you have in getting off to sleep last night? (tick box)

☐ None or very little
☐ Some
☐ A lot
☐ Extreme difficulty

14. How long did it take you to fall asleep last night? _____Hrs. _____Mins.

A.3 Physical Activity Affect Scale

Participant ID: ___________ Session: ___________ Day: ___________ Time: ___________

Physical Activity Affect Scale (PAAS)

Instructions: Please use the following scale to indicate the extent to which each word below described **how you feel at this moment in time**. Record your responses by circling the appropriate number.

	Do Not Feel	Feel Slightly	Feel Moderately	Feel Strongly	Feel Very Strongly
1. Upbeat	0	1	2	3	4
2. Calm	0	1	2	3	4
3. Energetic	0	1	2	3	4
4. Tired	0	1	2	3	4
5. Peaceful	0	1	2	3	4
6. Miserable	0	1	2	3	4
7. Worn-Out	0	1	2	3	4
8. Relaxed	0	1	2	3	4
9. Fatigued	0	1	2	3	4
10. Discouraged	0	1	2	3	4
11. Enthusiastic	0	1	2	3	4
12. Crummy	0	1	2	3	4

A.4 Social Exercise Session Conversation Instructions

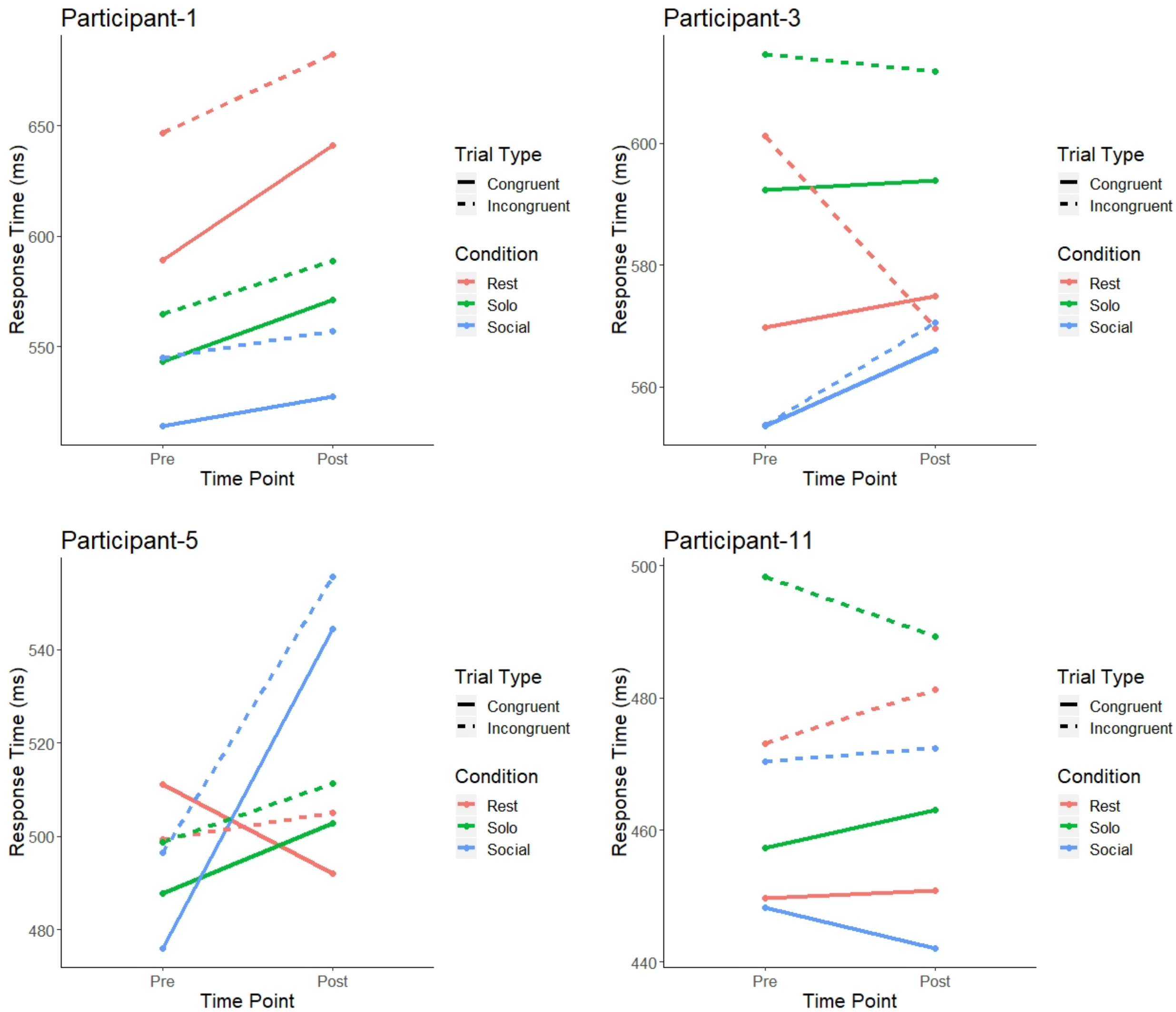
Today while you are walking on the treadmill, another participant will be walking on the treadmill across from you. We would like you to use the 26 minutes of exercise to get to know the other participant as best as you can. Ask questions, try to find a topic you both like to talk about, and keep the conversation going as best as you can.

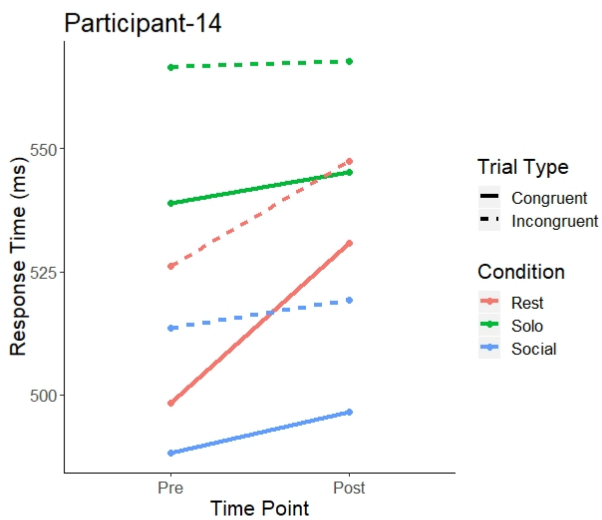
A.5 Modified Eriksen Flanker Task Script

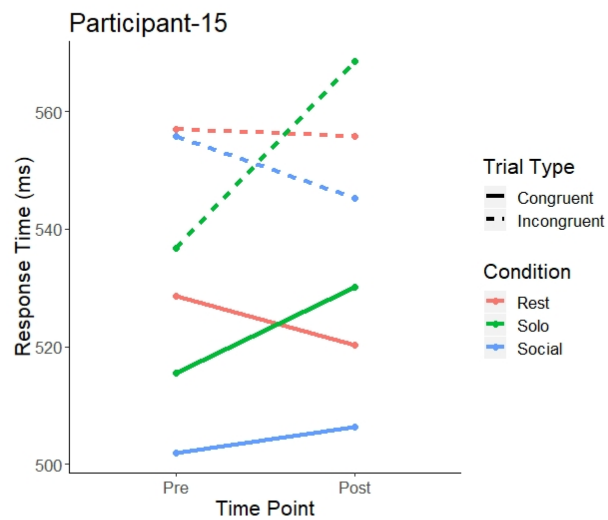
You are going to perform a Flanker task. 5 arrows will appear on the screen and I want you to focus on the direction of the center arrow while ignoring the direction of the surrounding arrows. If the center arrow points left press the button with your left thumb. If the center arrow points right press the button with your right thumb. Respond as quickly and accurately as possible. Remember to press the buttons firmly so that a response can be recorded.

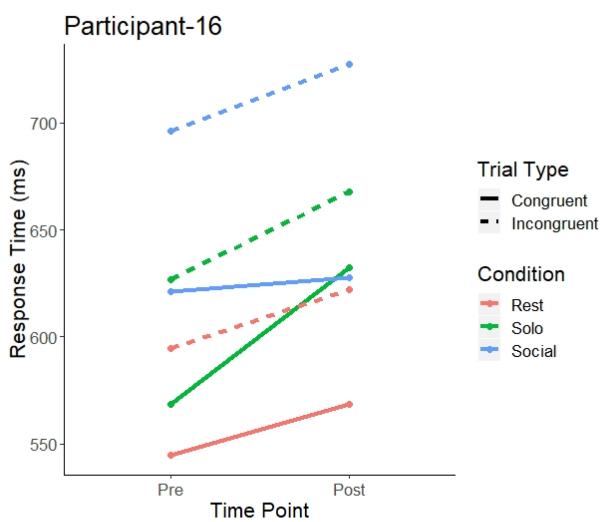
A.6 Supplementary Plots

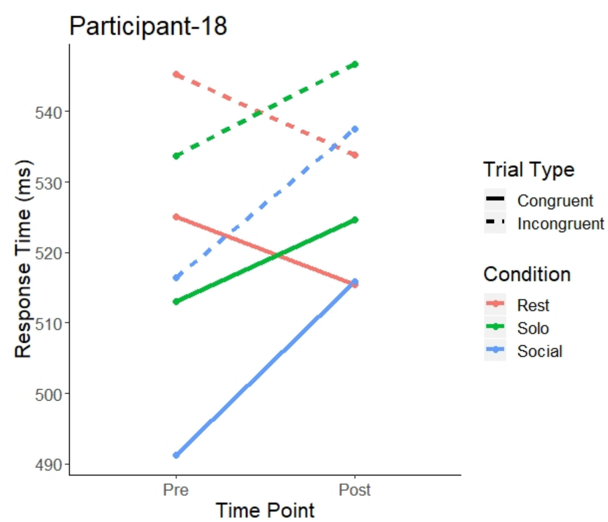
A.6.1 Non-Responders

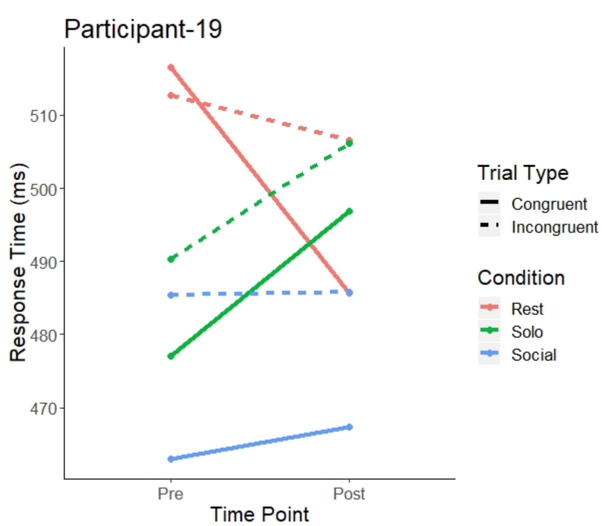


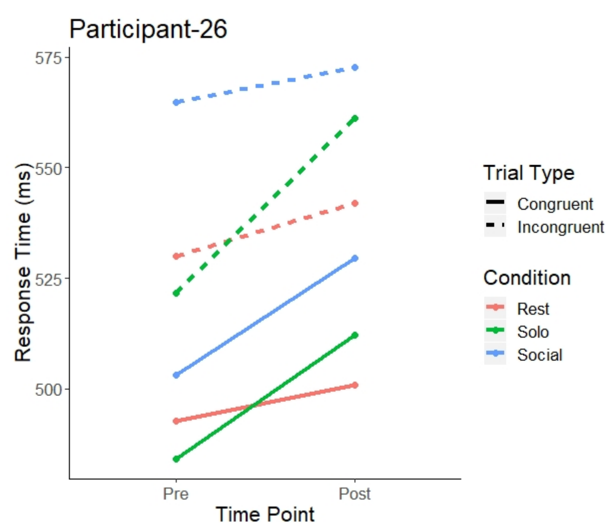

Participant-14
Response Time (ms)
550
525
500
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social


Participant-15
Response Time (ms)
560
540
520
500
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social

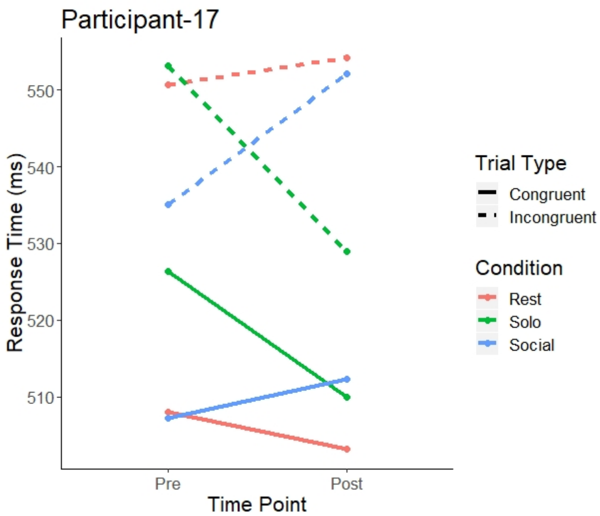

Participant-16
Response Time (ms)
700
650
600
550
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social

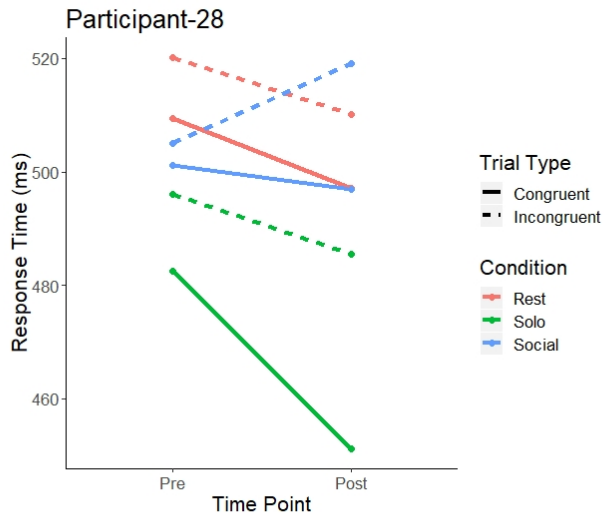

Participant-18
Response Time (ms)
540
530
520
510
500
490
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social


Participant-19
Response Time (ms)
510
500
490
480
470
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social

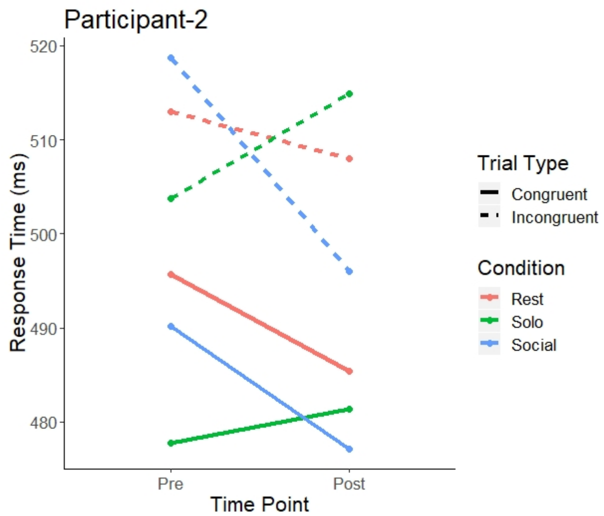

Participant-26
Response Time (ms)
575
550
525
500
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social

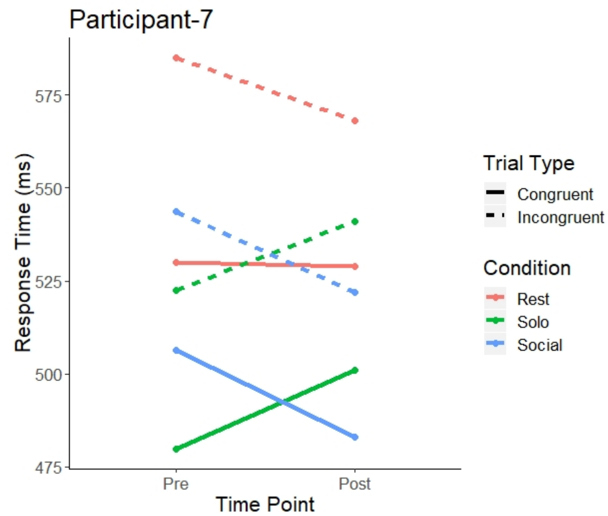
A.6.2 Solo Responders

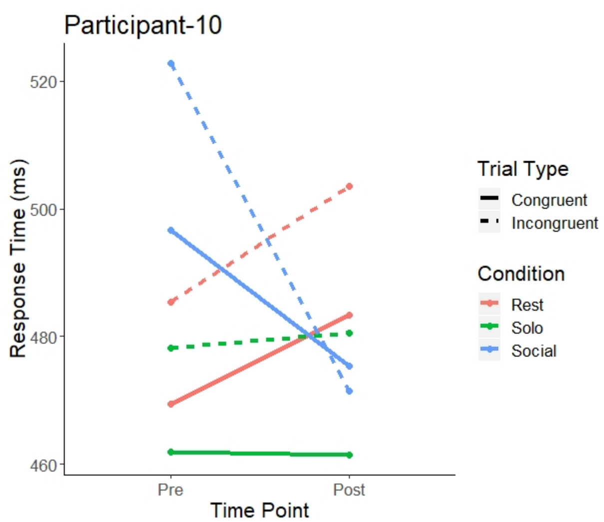


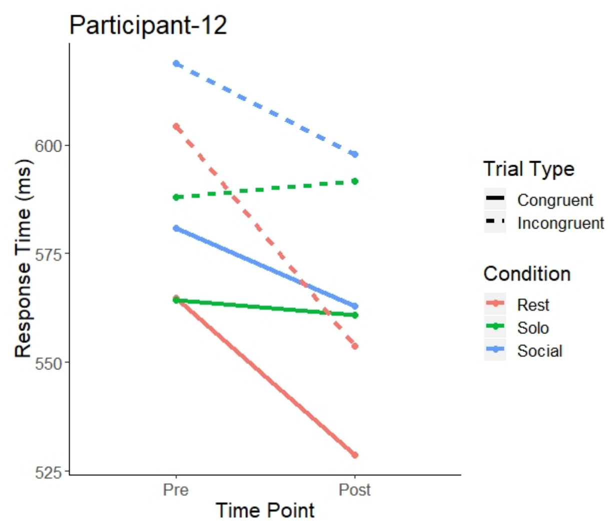


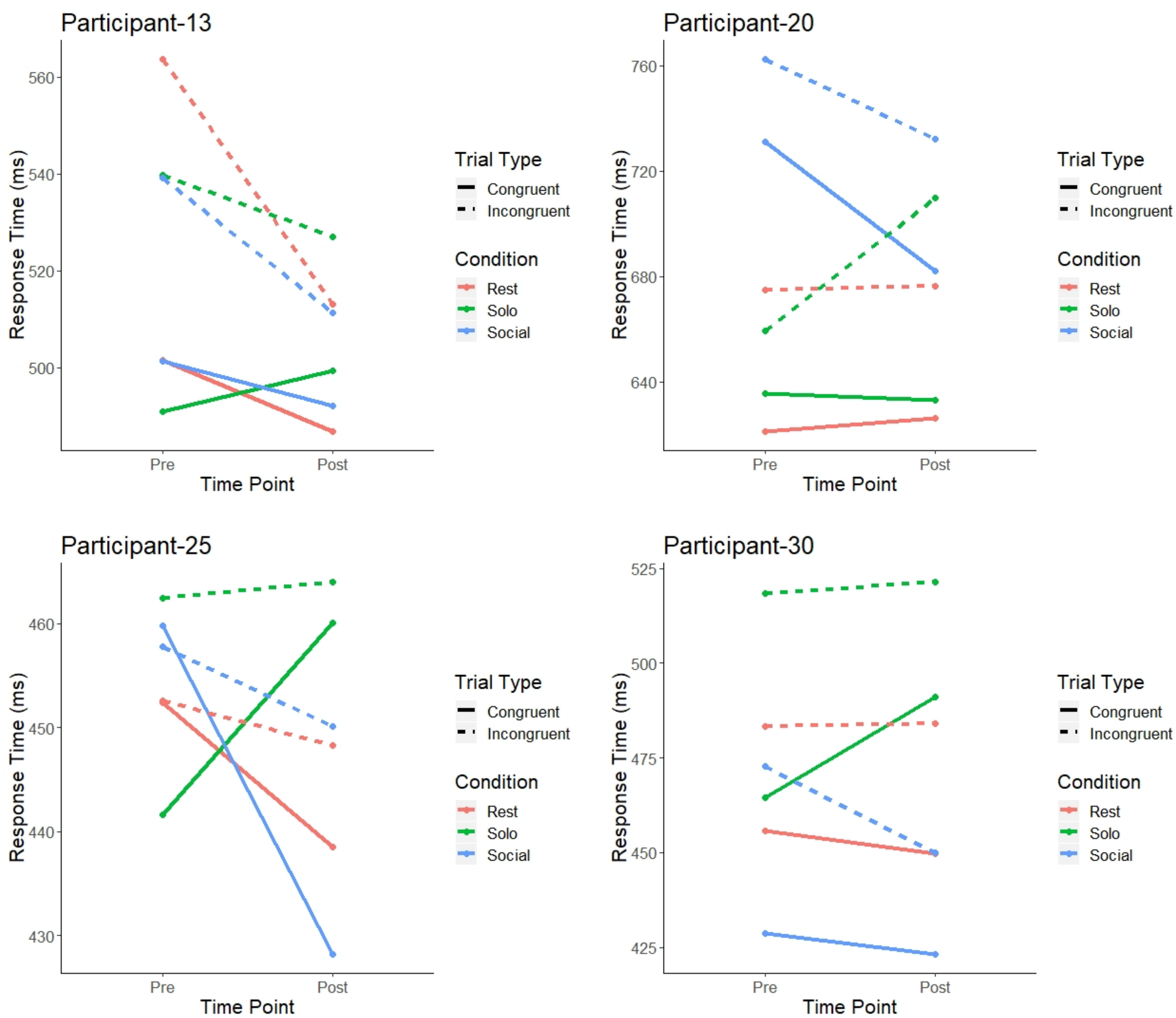
A.6.3 Social Responders



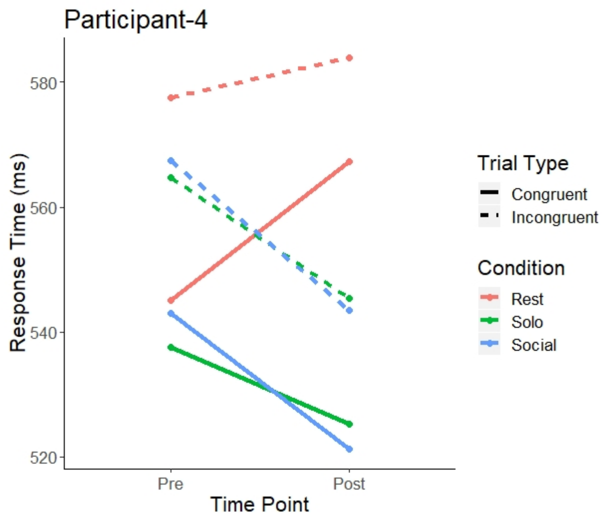


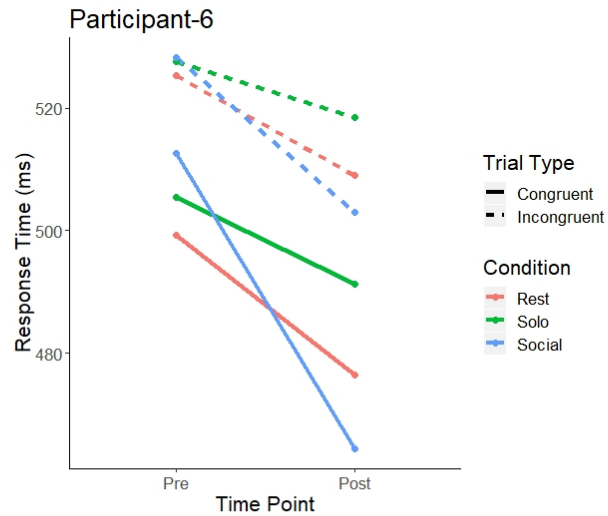


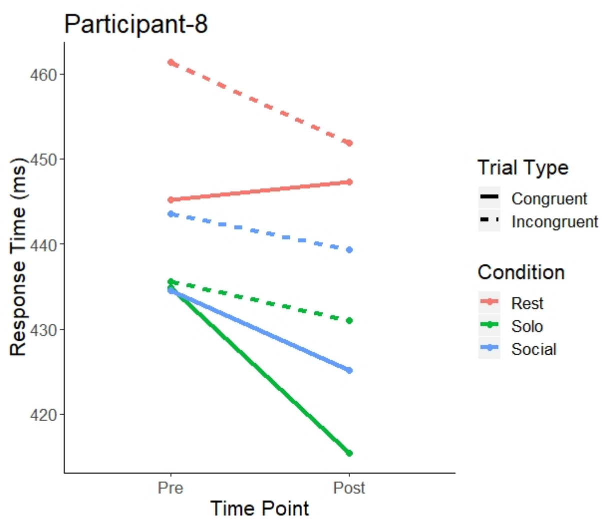


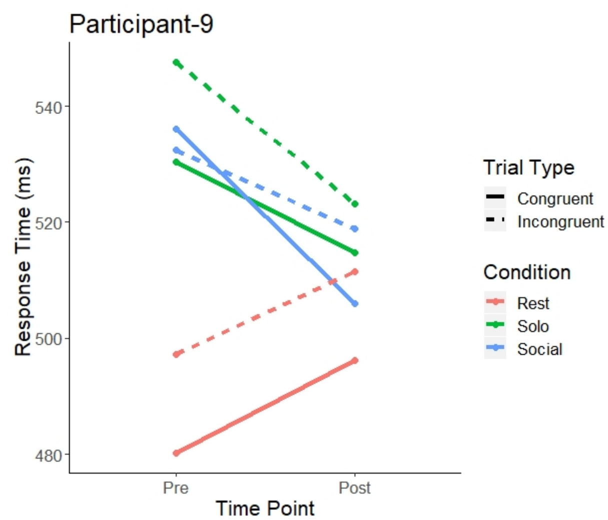

Participant-13
Participant-20
Participant-25
Participant-30
Response Time (ms)
Time Point
Pre
Post
560
540
520
500
760
720
680
640
460
450
440
430
525
500
475
450
425
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social

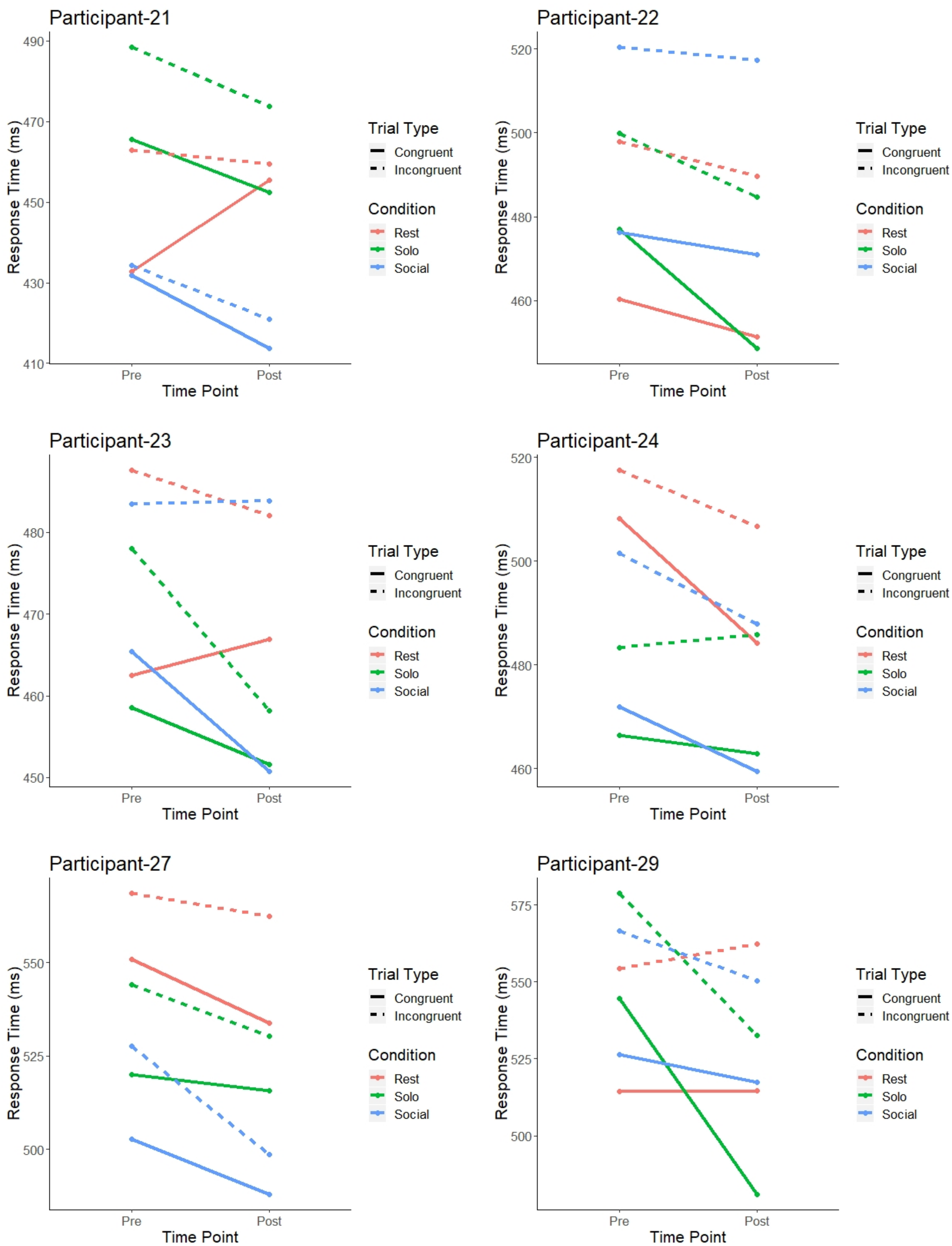
A.6.4 Consistent Responders










Participant-21
490
470
450
430
410
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social
Participant-22
520
500
480
460
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social
Participant-23
480
470
460
450
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social
Participant-24
520
500
480
460
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social
Participant-27
550
525
500
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social
Participant-29
575
550
525
500
Response Time (ms)
Pre
Post
Time Point
Trial Type
Congruent
Incongruent
Condition
Rest
Solo
Social