MOVING WITH PRESENCE:
A VIRTUAL REALITY-BASED EXERGAMES INTERVENTION TO IMPROVE THE EXECUTIVE FUNCTIONS OF ADULTS AGED 50 AND OLDER

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ABSTRACT

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Prior literature in exergame research suggests that exergaming could improve cognitive function in older adults, yet what types of exergames would contribute to cognitive improvement have not been fully identified. This dissertation seeks to investigate whether level of immersion and type of cognitive load would yield differential outcomes in executive functions in the context of exergaming. The process model of the spatial presence experiences and perceptual load theory serve as the theoretical framework and guide the research design.

In a 2 (level of immersion: high vs. low) × 2 (type of task load: task-relevant vs. task-irrelevant) between-subjects experimental design, participants were randomly assigned into one of four conditions and asked to play an exergame (Fruit Ninja) for eight sessions within four weeks. Forty-one participants aged over 50 (mean age = 63) finished a single bout of exergaming training and 33 participated in the long-term training. Cognitive improvements were assessed after a single bout, after two weeks, and after four weeks.

The results of repeated-measures analysis of covariance (ANCOVAs) revealed a significant interaction effect of immersion × time for cognitive flexibility and inhibitory control, with an improvement in the high-immersion condition over the course of the four-week training. Furthermore, the feeling of spatial presence mediated the relationship between immersion and cognitive improvement. However, type of task load had no effect on any aspect of task performance over the course of the exergaming training. The results of intent-to-treat analyses,

which were conducted to handle missing responses, were consistent with the initial analyses using raw data.

These findings suggested that spatial presence, elicited by the immersive virtual reality, was involved in a cognitive process, which later led to an improved performance in inhibitory control and cognitive flexibility. This study also demonstrated the feasibility and potential for older adults to use virtual reality-based exergames as a potential tool for cognitive health. For the theoretical implications, this research extends previous research by showing how exergaming in virtual reality, which leads to the feeling of presence, could contribute to older adults' cognitive improvement. This study also provided practical implications such that the design of exergames could emphasize the game features requiring spatial attention and orientation, which can serve as a novel strategy for preventing cognitive decline in older adults.

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CHAPTER 1: INTRODUCTION

The older population has grown dramatically since the beginning of the 21st century. There has been a 21% increase in the older population aged 65 or more, and one-seventh of the population currently belongs to the 65 or more age group (Centers for Disease Control and Prevention, 2013). Older adults are at a considerably higher risk for having problems related to the aging of the brain, and several executive abilities associated with reasoning decline starting around age 45 (Singh-Manoux et al., 2012). According to the World Health Organization (WHO), more than 20% of older adults suffer from a mental or neurological disorders, one of the most common being dementia (Yasamy, Dua, Harper, & Saxena, 2013), which refers to an impairment of cognitive functions.

The cognitive problems of older adults need to be addressed due to the high costs of medical care and the negative social ramifications associated with dementia and other cognitive impairments. The economic cost of dementia in the United States ranged from $159 billion to $215 billion in 2010 and will increase to $511 billion by 2040 (Hurd, Martorell, Delavande, Mullen, & Langa, 2013). Most of these costs go toward institutional and home-based care, which accounts for 75% to 84% of dementia costs. Moreover, the annual costs of health care among adults 50 years and older is about $860 billion (Watson et al., 2016). Thus, it is important to promote healthy cognitive aging and to refine the prevention research in midlife and older adulthood.

Both scientific literature (e.g., Diamond, 2015) and health-related organizations (e.g., World Health Organization, 2015) have emphasized the positive impacts of physical activity on dementia and cognitive decline prevention. The WHO (2015) has listed several new treatments for the prevention of cognitive decline and dementia; one of which is physical activity. Furthermore, recent longitudinal studies found a positive relationship between physical inactivity and a higher risk for cognitive decline in older adults, whereas regular physical activity can delay or even prevent chronic and cognitive diseases in adults age 50 and over (Diamond, 2015). The promotion of physical activity seems to provide protective factors against cognitive decline for adults 50 years or older.

However, in the United States, 28% of adults ages 50 and older are physically inactive, which has been highly associated with mental illness, cognitive impairment, and the risk of premature death (Watson et al., 2016). Moreover, the Centers for Disease Control and Prevention (CDC) suggests that adults ages 50 and older should stay physically active because 80% of costly chronic conditions can be prevented or improved with physical activity (Centers for Disease Control and Prevention, 2014). The CDC emphasizes that adults age 50 and older should have more physical activity, which can reduce the risk of cognitive impairment and support healthy aging.

Exergaming, which refers to using active video games as a form of exercise that requires players to use motion-based controllers or body movements to play, has the potential to combine the benefits of physical activity and the attractiveness of video games (Blondell, Hammersley-Mather, & Veerman, 2014). The genres of exergames range from requiring arm and hand movements (e.g., boxing and baseball) to full body movements (e.g., dancing and jumping). As exergames exploded onto the market, researchers quickly began to study the effects of exergaming on executive functions in both children and older adults (Staiano & Calvert, 2011). In general, exergaming has been considered as a good alternative to, if not better than, traditional exercise because of its attractive combination of physical activity and gamification (Anderson-

Hanley, Maloney, Barcelos, Striegnitz, & Kramer, 2017; Monteiro-Junior, Otero Vaghetti, Nascimento, Laks, & Deslandes, 2016).

Similar to traditional exercise, exergames have been regarded as a potential tool to produce cognitive benefits and contribute to maintaining or improving executive functions (e.g., working memory and inhibitory control) in older adults (Staiano & Calvert, 2011). Researchers have identified two mechanisms that account for the relationship between exergaming and cognitive benefits: (1) physical exercise, which accounts for the increase in physiological arousal and attentional resources, and (2) mental exercise, which refers to the cognitive demands and mental effort during exergaming (Anderson-Hanley et al., 2017; Best, 2013). In other words, *moving with thought* during exergaming is key to improving cognitive functions in older adults.

Regarding the impact of physical exercise during exergaming, systematic reviews on the effects of exergaming have found that physical activity has a consistent impact on cognitive improvement (Ogawa, You, & Leveille, 2016). However, the findings of previous research on the effects of traditional exercises on cognitive improvement are not always consistent (Diamond, 2015). A possible explanation might be that movement during exergaming is different from movement during traditional exercise, which does not always activate the cognitive process. The one key factor that separates traditional exercise, which has inconsistent results, and exergaming is the concept of moving with thought. Only when moving with thought will the cognitive process be activated (Diamond, 2015). Therefore, simple aerobic activities that require little thought (e.g., running, resistance training) will not lead to cognitive benefits.

However, exercising with thought may not fully explain the difference between exergaming and traditional exercise in player’s cognitive improvement. For example, pure running during exergaming, an activity that is supposed to require little thought, still had a positive impact on cognitive functions (e.g., Best, 2012). The different effects of physical activity between traditional forms of exercise and exergaming on cognitive improvement might result from a *sense of presence*. Compared to traditional forms of exercise, exergaming involves moving within a mediated environment, which requires use of players' spatial navigation skills and selective attention to mentally simulate their locations (Monteiro-Junior et al., 2016). Spatial presence refers to the sense of being situated in a mediated environment and the perception of action possibilities in the space. Research indicates that spatial presence is another contributing factor that may help explain the cognitive benefits associated with being in mediated environments or virtual reality (VR) (Kober, Kurzmann, & Neuper, 2012). Another study applied a VR-based serious game, which consisted of daily life activities to train stroke patients, found a significant improvement in participants' cognitive functions after a 4–6 week intervention compared to those of people who were on the waitlist for the study (Gamito et al., 2017). Therefore, playing an immersive VR game should involve the cognitive and psychological process of spatial presence, and the sense of spatial presence associated with VR and other mediated environments may play a major role during exergame-based interventions.

Furthermore, neuroscientific techniques support the argument that the feelings of spatial presence elicited by immersive technologies are strongly associated with cognitive improvement. The brain circuits linked to executive functions become more active when media users navigate themselves within virtual environments (Monteiro-Junior et al., 2016). Studies using functional neuroimaging, a measure of the relationship between activities in certain brain regions and specific mental or cognitive functions, have found that executive functions (i.e., selective attention and task management) activated the dorsolateral prefrontal cortex (DLPFC) (Diamond, 2015). The right-DLPFC is associated with visual-related cognitive functions, and the left-

DLPFC is associated with the verbal-DLPFC (Lo Priore, Castelnuovo, Liccione, & Liccione, 2003). In addition to the associated executive functions, the DLPFC also plays a major role during the experience of spatial presence (Gamito et al., 2015, 2017), so the activation of DLPFC is related to both the use of executive functions and the feeling of spatial presence.

Based on the theoretical reasoning and neuroscientific evidence, the current research investigates the role of *spatial presence* in the process of exergaming. The core argument is that spatial presence plays a vital role in cognitive improvement via increasing players' attention allocated to the mediated environment. The first goal of this study is to investigate the effects of immersion (i.e., virtual reality and 3D environments) as well as the role of spatial presence on executive functions in the process of exergaming. The model of the formation process of spatial presence experiences (Wirth et al., 2007) is used to explain the mechanism underlying the cognitive process of how exergaming influences executive functions.

Recent studies have investigated the effects of cognitive loads on older adult's cognitive improvement in the context of exergaming. However, the effects of the cognitive demands of exergaming were not fully explored. It is still unclear what types of exergames and what elements of exergames contribute to cognitive improvement. Some studies found that both the physical activity and the cognitive load had an effect on cognitive improvement (Best, 2013; Ogawa et al., 2016) but some studies only found that physical activity had an effect (Best, 2012, 2013). The inconclusive findings may result from the different definitions of cognitive load used across studies on exergaming and cognitive improvement.

Some studies defined cognitive demand or cognitive load as task-relevant load, which refers to solving a task that requires higher-order cognitive processes or more working memory and selective attention (e.g., Anderson-Hanley et al., 2017; Best, 2012). Some studies defined cognitive demand or cognitive load as task-irrelevant load, which refers to solving an additional cognitively involving task in addition to doing the primary task (e.g., Radovanović, Jovičić, Marić, & Kostić, 2014). Both types of cognitive tasks require players' mental effort, but in different ways. The second goal of this study is to investigate the impacts of the different types of cognitive load during exergaming and the possible mechanisms that may account for the improvement of older adults' executive functions during exergaming. Perceptual load theory (Lavie, 1995, 2005) provides the current study with a general framework for classifying different types of task load based on previous research.

This research addresses the following questions: Does playing an exergame in a more immersive mediated environment lead to more cognitive improvement than playing it in a less immersive environment? Does the level of spatial presence associated with exergaming have an impact on executive functions after exergaming? What roles do cognitive load and spatial presence perform during exergaming in relation to improving executive functions in older adults? Does the type of cognitive load influence executive functions differently during exergaming? In the literature review, the current study discusses these two theoretical frameworks (i.e., the model of spatial presence experience and perceptual load theory) to answer these questions.

CHAPTER 2: LITERATURE REVIEW

Prior research has shown that physical activity can contribute to cognitive benefits in midlife and older adults through both physical exercise and mental exercise, and exergames include both factors (Anderson-Hanley et al., 2017). Before discussing the relationships among exercise, exergaming, and cognitive functions, the literature review begins with a brief overview of the conceptualization of executive functions as well as the characteristics of exergames.

Current research argues that being in an immersive environment is a key contributor to mental exercise in the context of exergaming. To better understand the proposed relationship, this section reviews prior studies on the effects of (1) being in a mediated environment and (2) the effects of mental simulation of the mediated environment on cognitive improvement in the context of exergaming. Previous research suggests that mental simulation of a mediated environment has been regarded as a form of mental exercise during exergaming (Monteiro-Junior et al., 2016). Also, being in a virtual reality (VR) and three-dimensional (3D) environment requires people to construct a mental simulation, which serves as a prerequisite of spatial presence experiences (Hofer, Wirth, Kuehne, Schramm, & Sacau, 2012; Schubert, 2009; Wirth et al., 2007). Therefore, the proposed study employs the process model of the formation of spatial presence experiences as the theoretical framework.

Besides exploring the role of spatial presence in the relationship between exergaming and cognitive improvement, this study examines the role of cognitive load in exergames. Previous studies conceptualized and operationalized cognitive load differently, which may have led to inconclusive results regarding the impacts of exergaming (Ogawa et al., 2016). This chapter reviews the literature relating to the effects of two types of cognitive load (i.e., task-relevant vs.

task-irrelevant) on media users' spatial presence and executive functions within the framework of perceptual load theory (Lavie, 1995, 2005).

The aim of this literature review is to (1) gain a better understanding of the role of spatial presence in the relationship between being in mediated environments (immersion) and cognitive benefits and (2) examine how different types of cognitive loads in exergames may influence older adults' executive functions. The first section starts with exploring what executive functions are and why they are important.

2.1. The Core Concepts of Executive Functions

Executive functions are defined as a series of top-down cognitive processes, including inhibitory control, working memory, and cognitive flexibility (Diamond, 2013). These three core executive functions are the foundations for higher-order cognitive functions, such as problem-solving, planning, and reasoning.

The first core executive function, inhibitory control, refers to our ability to control attention and behaviors, and to overcome impulses in order to do what is more suitable or needed (Diamond, 2013). Inhibitory control helps us react or pay attention to what we should focus on (e.g., specific or important tasks) instead of being affected by automatic responses (e.g., habits) to environmental stimuli. In other words, inhibitory control, which requires cognitive effort, prevents us from succumbing to responses to internal impulses or external distractions.

Inhibitory control includes several aspects, including selective attention, cognitive inhibition, and self-control (Diamond, 2013, 2014). First, selective attention refers to the ability to selectively focus on a stimulus or thought over other stimuli based on our intention. In other words, selective attention enables us to focus on what we choose. Another aspect of inhibitory control is cognitive inhibition, which refers to the ability to suppress our thoughts, memories, and other mental representations. Finally, self-control relates to the capacity to control our behaviors or emotions despite temptations or distractions. To sum up, these three aspects of inhibitory control help people stay focused on their goals and intentions by reducing environmental interferences.

The second core executive function, working memory, refers to the ability to hold information in mind and use it. Working memory includes two content categories: nonverbal working memory and verbal working memory (Diamond, 2015). For example, calculating a math problem without writing it down on paper requires working memory. Also, processing new information to make plans for the future requires working memory. Different from short-term memory, working memory allows us not only to store new information but also to manipulate that information. In short, working memory makes it possible for us to integrate mental resources by organizing and rearranging new information in our mind.

The other core executive function, cognitive flexibility, refers to the ability to "think out of the box" (Diamond, 2015, p. 147). For example, cognitive flexibility allows people to see things from another perspective or imagine events from another viewpoint. Cognitive flexibility is the ability to shift perspectives interpersonally or spatially. During the process of changing perspectives, we require the other two executive functions (i.e., inhibitory control and working memory) to switch from one perspective to another. Therefore, cognitive flexibility is highly dependent on the other two core executive functions. In the end, these three executive functions are essential for mental health as well as physical health (Diamond, 2015).

2.2. Executive Functions, Aging, and Cognitive Reserve

Over the past 100 years, researchers have consistently reported that age is one of the predictors of cognitive decline (Salthouse, 2009). For example, visual construction skills, which refer to the ability to assemble individual items and objects into a whole, decline with aging (Singh-Manoux et al., 2012). Cognitive skills such as concept formation, abstract thinking, and information processing speed, also decline during aging (Singh-Manoux et al., 2012). Thus, cognitive decline is highly correlated with age.

Much of the research on cognitive aging focuses on older populations, such as those aged 60 (or 65) and higher. However, the focus on the cognitive aging of older populations has been widely challenged. Recent studies have started to find that cognitive decline may begin earlier than we expected (Finch, 2009; Salthouse, 2009). Multiple studies found that cognitive functions may start dropping in performance after midlife (i.e., age 45–49) (Singh-Manoux et al., 2012) or about 50 to 55 years old (Albert & Moss, 1988; Ronnlund et al., 2005). Some researchers have even explicitly pointed out that the implicit assumption of little cognitive decline occurring before age 60 limits researchers to examining the correlates instead of the causes of cognitive decline (Singh-Manoux et al., 2012). To be more specific, the impact of cognitive decline may start from middle age, and people who are less than 65 years old may still suffer from age-related cognitive decline. Therefore, simply focusing on older adults may ignore some early risk factors for adverse cognitive outcomes.

Regarding executive functions, the brain regions associated with executive functions have been found to shrink with age. Inhibitory control, working memory, and cognitive flexibility are all susceptible to decline when the aging brain experiences physical and functional changes (Diamond, 2014). Regarding inhibition, the aging brain affects a person’s ability to inhibit automatic responses to a stimulus and ignore irrelevant aspects (Chao & Knight, 1997). Similar to inhibition, working memory and cognitive flexibility also decline with age due to age-related changes in certain brain regions or a loss in brain tissue (i.e., prefrontal cortex; Gazzaley, Cooney, Rissman, & D'esposito, 2005). Thus, aging is associated with declines in executive functions.

Fortunately, it is possible to slow down age-related cognitive decline if people receive adequate cognitive training or intervention (Stern, 2012). The concept of cognitive reserve points the way toward slowing down the level of cognitive decline and maintaining cognitive functions as much as possible (Stern, 2012). According to the theoretical framework of cognitive reserve (Stern, 2012), two types of reserves account for age-related cognitive loss: brain reserve and cognitive reserve. Brain reserve refers to genetically determined characteristics (e.g., brain volume and the number of neurons in certain brain regions). Cognitive reserve focuses on the brain’s potential for plasticity and reorganization in neural processing. Specifically, brain reserve emphasizes the *hardware* characteristics such as brain volume and neuronal structural integrity, and cognitive reserve highlights the *software* aspects such as the cognitive functioning and plasticity of neural circuits (Cheng, 2016). In other words, the concept of cognitive reserve explains how to preserve cognitive functions from both a hardware and a software perspective.

Previous cognitive interventions have supported the theoretical framework of cognitive reserve. For brain reserve, researchers have found that physical activities, such as exercise and dancing, improve older adults’ cognitive functions via activating certain brain regions associated with cognitive functions (Crescentini, Urgesi, Fabbro, & Eleopra, 2014; Valenzuela, Sachdev, Wen, Chen, & Brodaty, 2008). A systematic review summarizing the effects of physical activity on peripheral brain-derived neurotrophic factors in healthy adults found a clear link between habitual physical activity (i.e., acute and chronic aerobic exercise) and brain health (Huang, Larsen, Ried‐Larsen, Møller, & Andersen, 2014). This relationship between physical activity and brain health was much stronger in the studies using subjects aged 50 years old and above rather than in the studies whose subjects were around 20 to 30 years old. Also, regular physical activity by people in midlife was associated with larger total brain volume in late life when compared to those with a sedentary lifestyle in midlife (Rovio et al., 2010). These findings show that brain reserve can be maintained by exercising regularly.

Regarding cognitive reserve and plasticity, it is possible to use cognitive training interventions to minimize the cognitive decline associated with advancing aging (Harada, Love, & Triebel, 2013). A meta-analysis has found that speed process training had a consistent impact on older adults' cognitive ability to perform daily living activities (Ball, Edwards, & Ross, 2007). Research also suggests that cognitively engaging activities have the potential to slow down the degeneration of the brain cells in certain regions (e.g., hippocampus) among older adults (Valenzuela et al., 2008). Furthermore, cognitive training interventions have been found to have long-term effects. The gains after various cognitive training interventions have been found to last for at least three months and up to two years after training (Ball et al., 2002; Brehmer, Westerberg, & Bäckman, 2012). In other words, interventions requiring cognitively engaging activities may help older adults preserve cognitive functions and promote healthy aging.

Research suggests that playing complex games in conjunction with performing aerobic exercise may produce a combination effect that increases both brain reserve from the exercise and cognitive reserve from the cognitive training (Stern, 2012). Studies further indicate that physical activity requiring limited or little thought (e.g., strength training and treadmill running) do not contribute to executive functions, and therefore moving with thought should be used to improve executive functions (Diamond, 2015). Interventions and training programs that incorporate cognitive engagement into physical activities may better prevent or limit cognitive decline in older adults.

Exergaming, which combines physical exercise with interactive gaming and cognitively engaging features, has become regarded as an effective means to promote desired health outcomes. Empirical evidence has shown that exergaming is an effective tool for cognitive improvement in older adults (Anderson-Hanley et al., 2017). Qualitative research indicates that exergames provide older adults with the perception of cognitive benefits from playing the games, which subsequently fosters adherence to exercise and also increases the motivation for participation (Meneghini, Barbosa, de Mello, Bonetti, & Guimaraes, 2016). That is to say, the effects of exergaming on cognitive benefits not only manifest in the participants' cognitive task scores in the lab settings but also in the subjective perception of cognitive improvement in daily life. The next section introduces the mechanism underlying the relationships between exercises and executive functions.

2.3. Exergaming: A Combination of Physical and Mental Exercise

Previous research has shown that both inhibitory control and working memory affect cognitive flexibility which declines during aging (Jurado & Rosselli, 2007; Salthouse, Atkinson, & Berish, 2003). Fortunately, these executive functions are trainable and can be improved by repeated practice (Diamond, 2014). In particular, physical activity has been regarded as one of the most effective ways to enhance cognitive functions and decrease cognitive decline (Diamond, 2015). Empirical evidence also shows that doing aerobic exercises improves older adults' executive functions, including processing speed, attention, and cognitive flexibility, even after controlling for age, gender, and education (Masley, Roetzheim, & Gualtieri, 2009). Similar conclusions have also been drawn in other studies (e.g., Hillman, Erickson, & Kramer, 2008; Kramer et al., 1999).

However, recent research has shown that simply doing physical exercise is not always an effective way to prevent cognitive decline in older adults. Two meta-analyses on the effects of physical exercise on executive functions found that many studies did not identify a significant improvement in cognitive benefits in older adults from doing simple aerobic exercises (Angevaren, Aufdemkampe, Verhaar, Aleman, & Vanhees, 2008; Smith et al., 2010). Another systematic review found that simple physical exercise (e.g., treadmill, running, and resistance training) had little or no effect on older adult's executive functions (Diamond, 2015). The researchers concluded that cognitive improvement requires both physical activity and cognitive effort (Diamond, 2015). Therefore, simply doing traditional aerobic exercise may not be enough to improve the executive functions, and moving with thought is a key factor for cognitive improvement.

Different from the results of traditional exercise on cognitive improvement, research has shown that older adults benefit from exergaming interventions across various genres of games. Exergames (or active video games), which are defined as video games involving motor skills and movements, have been positively linked to the improvement of executive functions in older adults (Staiano & Calvert, 2011). For example, a study on older adults' executive functions using a non-commercial biking game found that several of the participants' cognitive outcomes improved after the intervention, including executive functions (color trails difference, Stroop test, and digits backward test), visuospatial skills and memory, and verbal memory (Anderson-Hanley et al., 2012). Another study found that playing a dancing exergame (*Dance Dance Revolution*) helped elderly females improve their inhibitory control (Chuang, Hung, Huang, Chang, & Hung, 2015). These findings show that exergaming can have a positive impact on older adult's executive functions across different exergame genres. Moreover, compared to traditional exercises, aerobic exergaming seems to have a stronger impact on older adults' cognitive functions (Anderson-Hanley et al., 2012).

Regarding the difference between exergaming and traditional forms of exercise, researchers argue that exergaming requires players to move with more mental effort. To be more specific, the reason why exergaming has a stronger potential to improve people's executive functions is that exergaming is not only physically engaging but also cognitive engaging (Anderson-Hanley et al., 2017; Best, 2013; Monteiro-Junior et al., 2016). In the context of exergaming, players not only have to move in ways similar to traditional exercise but they also have to interact with the virtual environment and interpret the stimuli and cues from the environment (Anderson-Hanley et al., 2012; Monteiro-Junior et al., 2016). Therefore, when playing exergames, players have to be active both mentally and physically.

Similar to the concept of cognitive reserve, two main mechanisms underlie the effects of exergaming on executive functions: (1) physical exercise—e.g., moving, jumping, or running—which enlarges people's attentional pool by increasing physiological arousal and motor control skills, and (2) mental exercise—e.g., memorizing the rules and movements of an exercise—which involves higher-order cognition and primes players to use their executive functions (Anderson-Hanley et al., 2017; Barcelos et al., 2015; Best, 2012) . However, when discussing the effects of mental exercise, prior studies have mainly focused on the cognitive tasks in addition to physical tasks instead of the cognitive and psychological process of interacting with virtual environments. The current study argues that the media characteristics of exergames should also be examined instead of merely focusing on the effects of their additional cognitive demands. The following section discusses how media activate players thought within the theoretical framework of spatial presence experiences.

2.4. Exergames as Mediated Environments in Conjunction with Spatial Presence and Executive Functions

Compared to traditional exercise, exergaming, requires players to not only move physically but also to simulate virtual environments cognitively (Anderson-Hanley et al., 2017). When moving through a mediated environment, such as a virtual reality or gaming environment, players also have to invest their cognitive resources to simulate and interact with the environment, which contribute to greater cognitive benefits (Anderson-Hanley et al., 2012; Monteiro-Junior et al., 2016). In other words, the demands of both the cognitive (i.e., interacting with the mediated environment) and the physical tasks (i.e., exercise movements) lead to the greatest improvements in executive functions.

Regarding the impacts of media factors, research has pointed out the importance of presence during the cognitive process. Theoretically, presence has been defined as a key feature that relates to the central nervous system and helps human beings extend the perception of the sensory organs to better experience an external space (Riva, Waterworth, & Waterworth, 2004). The cognitive process of presence is also related to an automatic application of reasoning modules, which help humans understand physical and social causation better when interacting with mediated environments and objects (Lee, 2004). In other words, feeling presence is an innate function and is highly relevant to the reasoning functions of human beings.

Clinical findings and neuroscientific evidence also indicate that more immersive environments, such as three-dimensional or VR-based settings, are associated with the use of cognitive functions, especially among older adults. Clinical findings found that, compared to traditional exercise, stationary cycling within a virtual environment led to greater improvement in executive functions (Anderson-Hanley et al., 2012). Another study examining the effectiveness of VR-based serious games for stroke patients found that VR-based cognitive training enhanced the results of neuropsychological rehabilitation (Gamito et al., 2017). Biological mechanisms related to interacting with virtual environments could also improve people's executive functions.

Several brain areas that are responsible for cognitive functions become more active when people are in virtual environments (Maguire et al., 1998; Monteiro-Junior et al., 2016). Furthermore, interacting with virtual environments allows players to interpret the stimuli from the media, and this process activates specific brain circuits (i.e., hippocampus and frontal cortex) associated with cognitive functions (Maguire et al., 1998; Monteiro-Junior et al., 2016). In other words, players are more likely to become mentally stimulated in mediated environments when the media transmits more stimuli and cues. Therefore, the amount of stimuli and cues provided by media environments, which can be conceptualized as immersion (Slater & Wilbur, 1997), may be a key predictor of cognitive improvement. Based on the above theoretical frameworks and empirical findings, the first hypothesis of the current research is proposed:

> **H1**: In the context of an exergaming intervention, individuals in the high immersion condition will have better cognitive improvement in terms of executive functions as indicated in (a) inhibitory control, (b) cognitive flexibility, and (c) working memory than those in the low immersion condition.

Prior research on exergame interventions indicates that being in a mediated environment requires people to simulate the environment mentally, which leads to cognitive improvement in older adults (Anderson-Hanley et al., 2012). However, few empirical studies have directly investigated media characteristics, such as the amount of stimuli from media technologies (i.e., immersion), on the mental simulation of mediated environments in the context of exergaming. A better understanding of the relationship between immersion and cognitive improvement requires investigation of the role of immersion in the processes of mentally simulating mediated environments. The current study uses the model of the formation process of spatial presence experiences as the theoretical framework to illustrate how the immersion levels of media facilitates people's mental simulation of the mediated environments, which leads to a sense of presence.

According to the process model of the formation of spatial presence experiences (Hofer et al., 2012; Schubert, 2009; Wirth et al., 2007), the construction of a media user's mental simulation of a mediated environment requires their mental and attentional resources to process the spatial cues from the mediated environment. The more spatial cues from the mediated environments, the more attentional resources media users will allocate to the media. For example, compared to non-VR settings, VR environments provide richer spatial cues that will attract users' attention and allow them to build a better mental representation of the mediated environment. However, if users have fewer spatial cues from the mediated environment, it is less likely they will actively engage in constructing a mental representation of the environment. Thus, when the users allocate their mental effort and attentional resource to the virtual reality, they will actively build a spatial situational model of the mediated environment.

Forming a mental representation and simulation of a mediated environment is one part of the mental exercise during exergaming. Exergame players not only create mental representations of the environments but they also have to actively engage in executive controls, such as inhibitory control and working memory, to relocate themselves into the virtual environment (Anderson-Hanley et al., 2017; Monteiro-Junior et al., 2016). In other words, the mental exercise of exergaming, which is very similar to the perceptual processing of spatial presence experiences (e.g., Wirth et al., 2007), involves two processes: the construction of mental representations of mediated environments, and feeling relocated into virtual environments.

Application of the concept of a spatial situational model to the context of exergames suggests people will focus more attentional resources on the mediated environment when the media provide more spatial cues. Therefore, attention on the mediated environment should enhance the likelihood of the construction of a mental model of the mediated environment. In other words, if people play exergames in an environment with richer spatial cues, they are more likely to engage in mental simulations and construct spatial mental models compared to those in the less immersive environments (Hofer et al., 2012; Schubert, 2009; Wirth et al., 2007). Also, when people are more engaged in mental exercise, which refers to creating a mental representation of the environment in a context of virtual reality, they are more likely to improve their executive functions after exergaming (Anderson-Hanley et al., 2012).

Media users experience the feeling of spatial presence after going through a two-step *process* (Hofer et al., 2012; Schubert, 2009; Wirth et al., 2007). The first step is to create a mental representation of a mediated environment. During this process, individuals use their mental resources and allocate their attention to process the spatial cues from the mediated environment. When media users allocate their mental and attentional resources to the virtual reality, they can construct a spatial situational model of the mediated environment. During the second step, media users try to confirm or reject the mental representation of the mediated environment based on their knowledge and experience. If users' mental representation of the mediated environment is mapped onto real-life experiences, media users suspend their disbelief (i.e., they reject distracting information) and accept the spatial situational model as their primary frame of reference. After this occurs, the feeling of spatial presence emerges

How does immersion influence the formation process of spatial presence? In the early 1990s, presence scholars posited two contributors of presence: vividness, such as sensory breadth and depth, and interactivity, such as speed, range, and mapping (Steuer, 1992). A recent meta-analysis of over 100 experiments on technological immersion and presence found that immersive features have a medium effect size on the spatial presence (Cummings & Bailenson, 2016) . According to the two-step model of spatial presence experiences (Hofer et al., 2012; Wirth et al., 2007), an immersive technology (e.g., VR) will allow media users to allocate more attentional resources and enable individuals to construct better mental representations of mediated environments and stronger presence experiences. Therefore, a more immersive mediated environment, which contains more stimuli, will draw more of the user's attention and cognitive resources to build a better mental representation of the mediated environment than will a less immersive mediated environment.

Experimental and biological evidence also supports the argument that immersion, which leads to a greater attentional allocation to the mediated environment, is a contributor to spatial presence experiences. For example, previous research found that the quality of visual immersion in video games had an impact on players' construction of spatial situational models (Hofer, Sele, & Wirth, 2013). Another lab experiment on the technological features of video games also found that of immersion had an impact on users' spatial presence experiences (McMahan, Bowman, Zielinski, & Brady, 2012). Research using electroencephalography further suggests that participants invest more attentional resources in response to a more visually immersive experience when playing video games or doing spatial navigation tasks (Havranek, Langer, Cheetham, & Jancke, 2012; Kober et al., 2012).

Based on the theoretical framework of the model of spatial presence experiences (Hofer et al., 2012; Schubert, 2009; Wirth et al., 2007) and empirical evidence on the effects of immersion on presence experiences, this study proposes the following hypothesis:

> **H2**: In the context of an exergaming intervention, individuals in the high immersion condition will have a stronger sense of spatial presence than those in the low immersion condition.

Previous research indirectly supports that spatial presence is positively associated with cognitive improvement and suggests that future research should directly measure the impact of cognitive simulation during exergame interventions (Monteiro-Junior et al., 2016). A randomized clinical trial involving an exergaming intervention found that participants' mental effort while engaging with virtual-reality stationary biking, which also included being in a mediated environment, significantly improved their cognitive functions after the intervention compared to those of people who used a traditional stationary bike (Anderson-Hanley et al., 2012). To be more specific, the mental exercise associated with the exergame was linked to spatial navigation, prediction of obstacles, and decision making. Therefore, when playing an exergame, players require additional attentional resources, which are highly relevant to executive functions.

Biological evidence also supports the argument that the spatial presence elicited by immersive technologies is associated with cognitive improvement. Prior studies found that, compared to simply doing similar traditional exercises, virtual reality exercises can help increase institutionalized older adults' functionality of the brain circuits linked to cognition, including the hippocampus, caudate nuclei, frontal and parietal cortex, and cerebellum (Monteiro-Junior et al., 2016). Those brain circuits are associated with working memories, spatial navigation, problem-solving, and decision making. Moreover, research using functional neuroimaging also found that executive functions (i.e., selective attention and task management) activate the dorsolateral prefrontal cortex (DLPFC) (Diamond, 2015). The DLPFC was found to play an important role in the control of the experience of spatial presence (Gamito et al., 2017), and the right-DLPFC is specifically associated with visual-related cognitive functions (Lo Priore et al., 2003). Therefore, the activation of the DLPFC is strongly related to both executive functions and spatial presence. Based on the biological and empirical findings, the current study proposes the following hypothesis:

H3: When immersion has a main effect on cognitive functions, spatial presence will mediate the impacts of immersion on older adults' cognitive improvement in (a) inhibitory control, (b) cognitive flexibility, and (c) working memory.

2.5. Cognitive Load, Spatial Presence, and Executive Functions

As previous sections mentioned, cognitively engaging tasks have been regarded as one of the major contributors to cognitive improvement in the context of exergaming (Barcelos et al., 2015; Best, 2013). However, the types and characteristics of tasks in exergames that contribute to older adults' cognitive improvement are still unknown (Ogawa et al., 2016). Furthermore, prior research on media information processing found that not all task loads are equal regarding their demand on users' cognitive resources (Wang & Duff, 2016). Therefore, to better understand the effects of different types of cognitive loads while exergaming, it is important to distinguish the effects of different task loads on executive functions.

Regarding the role of cognitively engaging tasks in the process of exergaming, scholars have been paying attention to the impacts of cognitive load and mental effort during exergaming. Nevertheless, the definitions and manipulations of cognitive load are not consistent across studies. For example, some studies focused on task-relevant (gaming relevant) mental effort (e.g., Anderson-Hanley et al., 2017; Best, 2012) while others focused on task-irrelevant (non-gaming relevant) tasks (e.g., Radovanović et al., 2014). The different conceptualization and operationalization of cognitive load in exergaming research may have contributed to the inconsistent findings regarding the effects of cognitive tasks on executive functions after exergaming (Ogawa et al., 2016). This study uses perceptual load theory (Lavie, 1995, 2005) as a framework to investigate the mechanisms underlying the effects of cognitive load on executive functions in the context of exergaming.

According to the perceptual load theory (Lavie, 1995, 2005), the ability to remain focused on a task and ignore irrelevant distractors is strongly associated with people's cognitive functions. Moreover, when dealing with task-relevant and task-irrelevant load, people will experience two types of selective attention mechanisms associated with the increase of perceptual load: early and late selection. In the early selection condition, if task-relevant stimuli require a high perceptual load, people will not be able to process information about task-irrelevant information (i.e., distractors or interferences). Furthermore, during the early perceptual selection process, people will invest their entire cognitive load into the main task, which requires high cognitive load (Lavie, 1995, 2005). People with a high task-relevant load will allocate most of their attention and cognitive resources to process task-relevant information. In the late selection condition, if task-relevant stimuli require a low perceptual load, people's cognitive resources will spill over to task-irrelevant information until the cognitive capacity is exhausted (Lavie, 1995, 2005). Therefore, when dealing with high task-irrelevant load in the low task-relevant load situation, people will have to invest more cognitive efforts, such as inhibitory control, to keep the task-unrelated distractors from interfering with the task-relevant task. They will process both the task-relevant and task-irrelevant information.

Perceptual load theory (Lavie, 1995, 2005) suggests that when people are in a high task-irrelevant load condition, their attentional and cognitive resources will be used to prevent distractors. When players are forced to manage distractions during the process of exergaming, they will have to split their attentional and cognitive resources between both types of tasks, which requires the use of their cognitive functions. In this sense, dealing with a high level of high task-unrelated distractors in the low task-relevant load condition will improve cognitive performance.

However, the process model of spatial presence experiences (Wirth et al., 2007) predicts that people who cannot devote their full attentional resources to the mediated environment will be less likely to experience spatial presence. In the context of exergaming, when people play exergames in a high task-relevant load condition, such as dealing with a hard task within the game, they will spend more attentional and cognitive resources on the assigned task in the mediated environment, which will lead to a stronger level of spatial presence and improved performance in executive functions compared to those who have a lower level of spatial presence due to low task-relevant load. This assumption is also consistent with previous empirical findings on task-relevant load and cognitive improvement (Anderson-Hanley et al., 2017). Moreover, empirical evidence also shows that task-related stimulus should boost neural pathways by recruiting mental resources to process the information, which will also activate executive functions (Mansouri, Tanaka, & Buckley, 2009). Players have to actively and intensely process information from the mediated world, which makes people devote themselves more to the media, foster a sense of presence, and then activate larger cognitive resources. Therefore, people who experience high task-irrelevant load will be less likely to experience spatial presence and its subsequent cognitive benefits.

Based on the theoretical framework of perceptual load theory and empricial evidence, the current study proposes one more hypothesis. Furthermore, one research question is proposed to investigate whether task-relevant and task-irrelevant load have different impacts on cognitive improvement. Figure 1 shows the proposed model and the research question and hypotheses of the current research.

H4: In the context of an exergaming intervention, individuals in the high task-relevant load condition will report a stronger sense of spatial presence compared to people in the high task-irrelevant condition.

RQ1: In the context of an exergaming intervention, is there a difference between individuals in the high task-relevant load condition and those in the high task-irrelevant condition in terms of participants' performance in (a) inhibitory control, (b) cognitive flexibility, and (c) working memory?

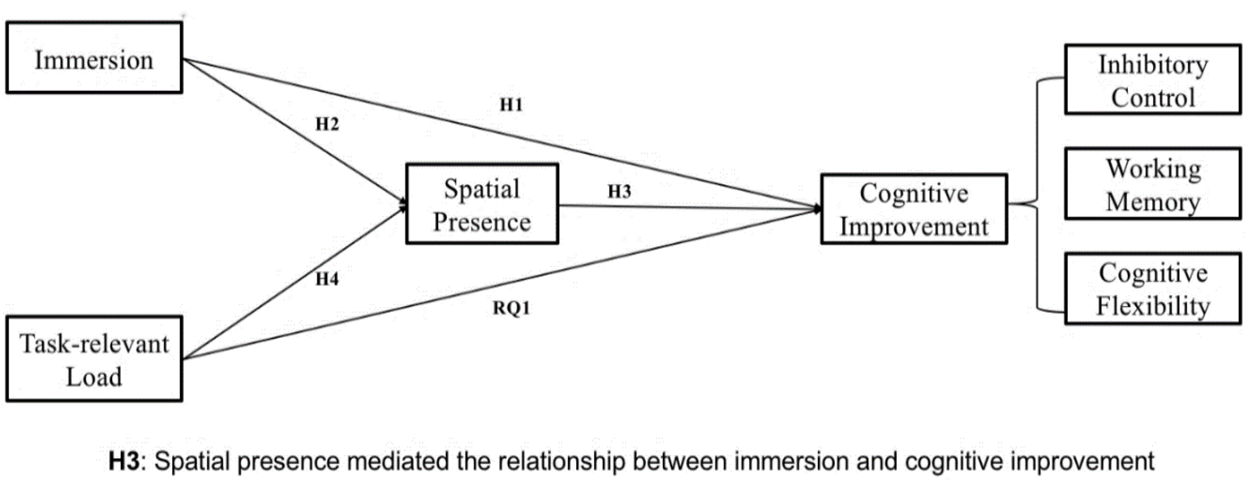

Figure 1: Research Question and Hypotheses of the Current Research

CHAPTER 3: METHODOLOGY

The goal of the current research is to examine the impacts of level of visual immersion, types of cognitive load, and feelings of spatial presence on older adults' executive functions during an exergame-based intervention. A four-week exergame-based intervention, which consisted of eight 20-minute exergame sessions (two sessions per week), was designed to test the hypotheses and research questions of the current research. Each individual session length was 20 minutes, which is similar to session length in previous research on physical activity and executive functions (e.g., Chu, Chen, Hung, Wang, & Chang, 2015; Kirk, MacMillan, Rice, & Carmichael, 2013). The intervention experiment was a 2 (task-relevant load vs. task-irrelevant load) × 2 (low immersion vs. high immersion) between-subject factorial design, and participants were randomly assigned to one of the four groups.

3.1. Participants

Exergaming had a medium effect size (d= 0.50) for executive functions across studies (Anderson-Hanley et al., 2012). Twenty-eight subjects were randomly assigned into the four conditions with repeated measures (four times), which reached a statistical power of 0.85 and passed the sufficient statistic power of 0.80 (Cunningham & McCrum-Gardner, 2007). Most of the studies examining the effect of exergaming on cognitive function had a small sample size (n= 8 to 10 per condition; e.g., Anderson-Hanley et al., 2017). The current research recruited a total of forty-one participants (eight in the pilot test and thirty-three in the 4-week training) who were at least 50 years old.

Recruitment was conducted mainly through the community SONA recruiting pool, a paid recruitment system managed by the College of Communication and Art Sciences at Michigan

State University. During the time of data collection, there were 405 total individuals in the recruiting pool: 230 individuals between 51 and 55 years old, 66 individuals between 56 and 60 years old, 87 individuals between 61 and 70 years old, and 22 individuals more than 70 years old. Besides recruiting thirty-two participants from the Community SONA recruiting pool, nine participants were recruited by snowball sampling in the Lansing and East Lansing areas.

Regarding the inclusion criteria, this study recruited subjects who were at least 50 years old. As previous chapters stated, there are two reasons for using the age of at least 50 as an inclusion criterion: First, peoples' cognitive ability may start declining at around 50 years old (Albert & Heaton, 1988). Second, adults aged 50–64 are one of the target populations for preventive care services, but 28% of this population are physically inactive (Watson et al., 2016). For the exclusion criteria, people who have cognitive disabilities, such as Alzheimer's disease or Parkinson's disease, were excluded. Also, people who have difficulty performing physical activities were excluded from recruitment.

All participants were encouraged to complete the 4-week exergaming intervention, including a total of eight sessions of exergaming (two sessions per week). Participants played an exergame for 20 minutes and were instructed to do cognitive measures in the first, fourth, and eighth sessions. For the incentives, participants received 30 US dollars for completing the first week of sessions (15 dollars for each session in the first week), 35 US dollars for the second week (after the second session of the week), 40 US dollars for the third week, and 45 US dollars for the last week (after the second session of the week). Each participant received up to 150 US dollars total as an incentive.

3.2. Stimuli and Intervention Design

The stimulus for the study was *Fruit Ninja*, which is an active video game in which players use arm and hand movements to swing virtual swords to slice fruit (see Figure 2). This game is designed to promote players' physical activity via slicing, juggling, and skewering fruit. Previous research also used a similar virtual reality exergame, which requires players' movements to match the programmed gestures or movements, to improve older adults' cognitive reaction (Pachoulakis, Papadopoulos, & Ieee, 2016). Therefore, *Fruit Ninja* was selected as the stimulus for the current study after a pilot test of manipulations (please see <u>Section 3.6: Pilot Test of Manipulations</u> for more details).

This game, which can be played in both VR (*Fruit Ninja VR*) and non-VR (*Fruit Ninja Kinect*) environments, shares the same rules in both conditions. Both versions have several types of difficulties and complexities and require varying levels of mental effort and cognitive load when playing the game. For example, in the **Zen mode**, players can just slice fruit without thinking about any rules, but players in the **Survival mode** have to avoid accidentally slicing bombs from flying cannons. The various *Fruit Ninja* game modes provide this study with an excellent manipulation of in-game task load.

Figure 2: Fruit Ninja in Virtual Reality

The intervention included two manipulations—visual immersion (high vs. low) and cognitive load (intrinsic: task-relevant vs. extrinsic: task-irrelevant). Regarding the levels of visual immersion, there were two conditions in the study—virtual reality (VR) and 2D screen conditions. In the **VR** (*Fruit Ninja VR*) condition, participants used a head-mounted display (Oculus Rift) to play the exergame. In the **non-VR** (*Fruit Ninja Kinect*) condition, participants used a 27-inch LCD monitor to play the exergame. When playing the 2D *Fruit Ninja Kinect* version, participants were instructed to stand in front of the television (1.5–2 m away) and use the motion-tracking Kinect controller to play the game. In the *Fruit Ninja VR* version, participants were asked to play the game with a VR head-mounted display and motion-tracking Oculus Touch controllers.

Regarding the manipulation of cognitive demand, there were two types of cognitive load in the intervention: high task-relevant load and high task-irrelevant load. For the **high task-relevant load** condition, participants were asked to play the game at an advanced level, which required them to invest more task-relevant load on slicing the fruit in more complicated ways. People in the high task-relevant load were asked to play the Survival mode, which required higher in-game load.

For the **high task-irrelevant load** condition, this study used one of the most cited manipulations of the task-irrelevant load: distractors or interference (Lavie, Hirst, de Fockert, & Viding, 2004). In the task-irrelevant load condition, participants were asked to remember a 7-digit (7±2) number as a distractor when they played the exergame at a basic level (i.e., Zen mode). Previous studies suggest that older adults showing no deficits in short-term memory can hold about 7 ± 2 digits if they rehearse the numbers in their mind (Glisky, 2007). The exact digits of the number were tested in the pilot study by using the forward digit span test.

The only difference between high task-relevant load and high task-irrelevant load conditions was whether the complexity of the rules was task-relevant or not. The frequencies of arm and hand movements between two modes were similar. Therefore, the level of energy expenditure should be similar across conditions. This study used heart rate sensors (Fitbit Charge 2 Activity wristbands) to control for the level of energy expenditure when analyzing the data. To make sure people in the high task-relevant and task-irrelevant conditions had similar levels of mental effort, the current study adjusted the length of the numbers based on participants' self-report of mental effort (see Section 3.6: Pilot Test of Manipulations for more details). Participants were randomly assigned to one of the four conditions based on the results of an online random number generator before they arrived at the lab for the first time. All participants were asked to play either Fruit Ninja VR or Fruit Kinect with motion-based controllers.

3.3. Manipulation Check and Test for Confounding

There were two manipulations in this study: (1) levels of visual immersion and (2) types of task load. To make sure the manipulations worked as expected, a manipulation check and a test for confounding were included in the study. For levels of visual immersion, participants were asked to rate five questions: (1) "how good was the quality of the visual immersion in the game?", (2) "how much did the visual display quality interfere or distract you from performing assigned tasks or required activities?", (3) the extent to which physical reality was shut out, (4) the breadth of range of sensory modalities accommodated, and (5) the degree of richness and information content of the displays. All responses were recorded using a 7-point Likert-like scale. All questions were adopted based on the definitions of technological immersion from previous research (Cummings & Bailenson, 2016; Schubert, Friedmann, & Regenbrecht, 2001; Witmer & Singer, 1998).

For types of task load, the current study used a three-item measure for mental effort adopted from previous studies on cognitive load and perceived mental effort (Leppink, Paas, Van der Vleuten, Van Gog, & Van Merriënboer, 2013) as the test for confounding. First of all, to check whether participants in two types of task-load conditions invested a similar amount of mental effort, participants were asked “How much mental effort did I invest during the gameplay that just finished?” Also, two questions were used to check the strength of task-relevant and task-irrelevant load. Participants in both conditions were asked “How difficult was the game I just finished?” and those in the task-relevant load condition were asked an additional question: “How difficult was the memory task that I just finished?” These items cover different types and dimensions of mental effort. Participants rated all responses to questions from 1 (very, very low mental effort) to 9 (very, very high mental effort).

People in the high task-relevant load condition were expected to score higher on “How difficult was the game that I just finished?” than people in the task-irrelevant load condition. Also, the scores of participants in the task-relevant load condition on “How difficult was the game that I just finished?” should also be similar to the scores of participants in the task-irrelevant load condition on “How difficult was the memory task I just finished?” People in both conditions should have similar scores on “How much mental effort did I invest in the gameplay that just finished?”

3.4. Outcome Variables

Spatial presence. The current study argues that spatial presence mediates the relationship between the improvement of executive functions and (1) visual immersion and (2) cognitive load. For the measures of spatial presence experiences, participants were asked to rate their subjective experience of spatial presence during the gameplay. The measures are adopted from the MEC Spatial Presence Questionnaires (MEC-SPQ; Vorderer et al., 2004). The MEC-SPQ scales have been empirically tested across diverse media settings (Hartmann et al., 2014) and theoretically tested via structural equation modeling (Hofer et al., 2012). The variables of the spatial presence experiences include attention allocation, spatial situational model, self-location, and possible action. Attention allocation is accessed using eight items (e.g., “I devoted my whole attention to the gaming environment”). The formation of a spatial situation model is assessed using eight items (e.g., “I was able to imagine the arrangement of the space very well”). The feeling of spatial presence includes two scales: self-location (e.g., “I had the feeling that I was in the middle of the action rather than merely observing”) and possible action (e.g., “I had the impression that I could act in the environment of the presentation”). All the items (see Survey Instrument) were rated on a 7-point Likert-like scale (1 = strongly disagree and 7 = strongly agree).

Executive functions. A systematic review found that studies examining the impacts of exergaming on older adults’ cognitive benefits mainly measured participants’ executive functions via subjects’ reaction times before and after the exergaming interventions (Ogawa et al., 2016). In previous studies, measures of executive functions can be divided into three categories: shifting (requiring cognitive flexibility), inhibition, and working memory (Eggenberger, Wolf, Schumann, & de Bruin, 2016). Consistent with previous studies, the measures for executive functions in this study include the Stroop test, trail-making task, and digit span. (Anderson-Hanley et al., 2017; Eggenberger et al., 2016).

The Stroop test (Color Word Stroop with Keyboard Responding) is an evaluation of inhibitory control, which requires participants to state a color under several conditions while suppressing habitual responses related to the conditions. The Stroop test is used to measure executive control by response inhibition. A 40-item version of the Stroop test was administered, which is consistent with previous studies (e.g., Barcelos et al., 2015). This test involves the use of a screen paired with a computer running the Inquisit 5.0 software and a keyboard with four highlighted colored buttons (G, R, B, & Y) which are matched with the test colors (green, red, blue, yellow; see Figure 3).

The Trail-making task is a well-established and empirically-tested measure (Kayama et al., 2014). The trail-making task is used to evaluate deficits in executive functions with a special focus on cognitive flexibility. The trail making task consists of two tasks, a visual scanning task and a cognitive flexibility task. Participants have to scan the locations of twenty-five circles and then connect them in numerical order. The scores are calculated as the difference between the pretest and posttest (see Figure 4).

Figure 3: Stroop Test

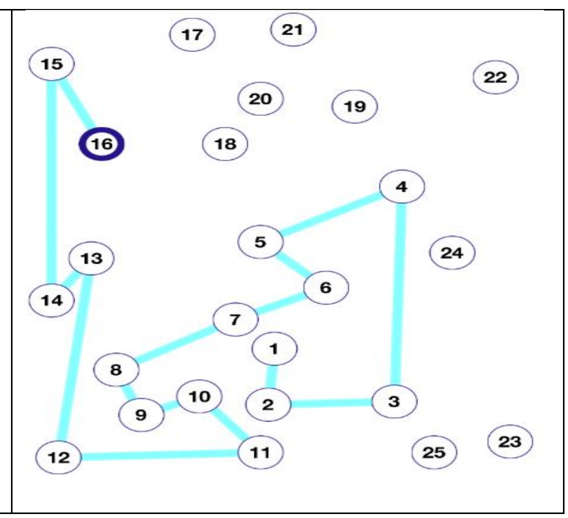

Figure 4: Trail-making Task

Digit Span is an evaluation of working memory. Participants first listen to a set of numbers; they then repeat the numbers in a forward order (digital span forward), listen to a set of numbers again, and then repeat the same set of numbers in a reverse order (digital span backward). The digit span score is computed by using the number of correct trails backward divided by the number of correct trails forward. A higher score indicates better cognitive function. Similar to the Stroop test, this test involves the use of a screen paired with a computer running the Inquisit 5.0 software and a keyboard with numbers from 0–9 (see Figure 5).

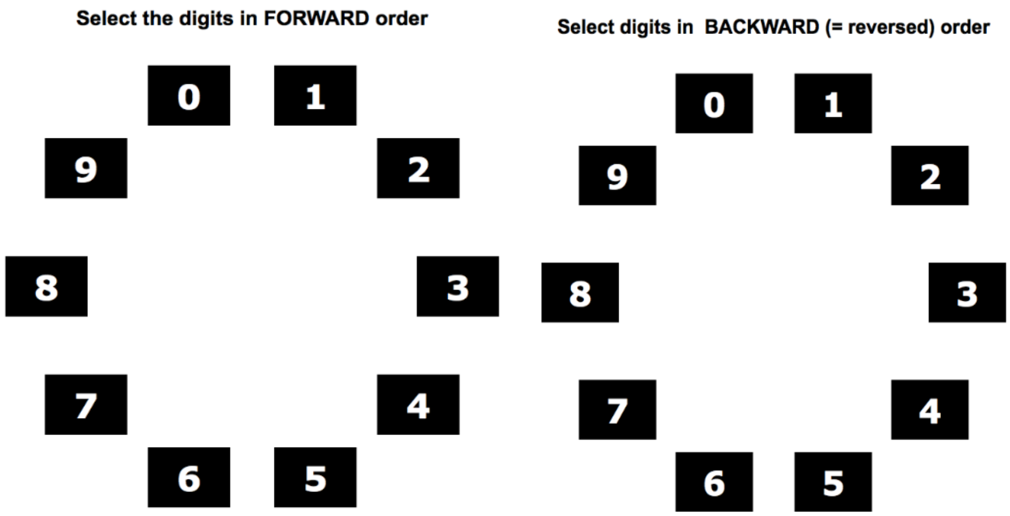

Figure 5: Digit Span Task

All the outcome measures were administered at baseline, after a single bout, after the second week, and after the 4-week intervention. Randomized reaction time measures were used to minimize practice effects. The results before and after a single bout were used to assess whether there was an immediate impact of exergaming. The outcome measures after the second week and the 4-week intervention helped the researcher track the effects over the course of the intervention.

These three cognitive measures, which have been commonly used to measure executive functions, are sensitive for the detection of significant effects of experimental manipulations and have good validity across neuropsychological studies (Sánchez-Cubillo et al., 2009). Previous research has shown that these measures have good to excellent test-retest reliability between two or more data points (Calamia, Markon, & Tranel, 2013), which indicates a lower possibility of a practice effect. Furthermore, previous studies measured these three tests together when measuring older adults' cognitive functions, and those researchers did not report any task fatigue (Anderson-Hanley et al., 2017; Barcelos et al., 2015). Following previous studies, the total length of the outcome measures data collection was around 10 minutes (3–5 minutes for executive function tests and 5 minutes for surveys of spatial presence and subjective cognitive functions). The current study randomized these three tasks to avoid potential confounding factors.

3.5. Control Variables

Control variables include participants' demographic information (e.g., gender, age, race/ethnicity, and education level) and their experiences with virtual reality headsets (e.g., Oculus Rift, HTC Vive, and PlayStation VR). Concerning their VR experience, participants answered questions such as "Have you ever used VR technologies before (e.g., Oculus Rift, HTC Vive, PlayStation VR, and other smartphone VR headsets)?" Participants rated their experience from 1 (never) to 7 (very often). This study used heart rate sensors (Fitbit Charge 2 Activity wristbands) to measure participants' energy expenditure as a control variable for the strength of physical activity. Participants' gameplay scores were controlled in the data analysis.

3.6. Pilot Test of Manipulations

The purpose of the pilot test was to make sure both manipulations worked as expected. A total of eight participants (two participants per condition) were included in the pilot test. After playing the *Fruit Ninja* games in either the VR or the non-VR version, participants were asked to rate the quality of visual immersion. Ideally, people who played Fruit Ninja VR were expected to report higher scores on the quality of visual immersion than those who played Fruit Ninja Kinect (non-VR version). Both Fisher's exact test (Pett, 2015) and the Mann–Whitney U test (Nachar, 2008), which are designed for small sample sizes, were employed in the current study to determine whether there was a significant difference between two conditions. If participants who played *Fruit Ninja VR* did not report a higher level of immersion than people playing *Fruit Ninja Kinect*, this study would have used one of the other two virtual reality-based exergames, *VirZoom Arcade* or *Holodance*.

The *Virzoom Arcade* was one of the alternatives to the stimulus. The game requires players to use the pedals of the VirZoom bike to control their speed, complete missions, and compete with others on racetracks and battlegrounds. In the VR condition, people experience a 360-degree immersive view. For example, VR players are able to look back at opponents in a racing game or look around in a flying game. The other option, *Holodance*, is an exergame designed for players to dance in a virtual environment. *Holodance* is intended to promote players' physical activities via integrating dancing through a series of music videos. The themes of the *Holodance* game involve the player combating monsters such as dragons. Each song has several types of difficulties and complexities that require varying levels of mental effort and cognitive load when playing the game. In the VR *Holodance* game, participants are expected to hit virtual objects while synchronizing the movements to music. If *Fruit Ninja VR* had not provided participants with higher immersion than *Fruit Ninja Kinect* in the pilot study, there would have been another run of the pilot study using *VirZoom Arcade* or *Holodance* as the stimulus for the current research.

For the manipulations of types of cognitive load, this study also measured participants' perceived mental effort. Ideally, participants in the high task-relevant load condition were expected to report the same level of mental effort as those in the high task-irrelevant load condition. If participants had a significant difference in their ratings of mental effort across conditions, the difficulty of the task-irrelevant condition was adjusted by decreasing or increasing the number of digits (from 7 to 5 or 9) to be remembered.

The pilot data were collected during the first week of November 2017. A total of eight participants finished the pilot study. The results of Mann–Whitney U tests showed that participants in the VR condition reported a higher level of presence compared to those in the non-VR condition at the significance level ($Z = -2.274$, $p = .023$). People in both types of task-load conditions reported a similar level of total mental effort during the gameplay (task-relevant load: 6.57 vs. task-irrelevant load: 6.67), and also reported investing a similar amount of mental effort into the assigned tasks between task-relevant load (higher difficulty game:4.29 out of 9) and task-irrelevant load (memory task: 4.67 out of 9) conditions. Therefore, both manipulations were successful in the pilot test.

3.7. Process Evaluation

Building from previous research on health promotion programs (e.g., Moore et al., 2015; Saunders, Evans, & Joshi, 2005) and exercise interventions for older adults (e.g., Ellard, Taylor, Parsons, & Thorogood, 2011), I developed a process-evaluation plan for determining whether the proposed intervention and program activities were implemented as intended. I focused on the following five elements: fidelity, dose delivered and received, reach, recruitment, and context. The elements and tools of my process-evaluation plan are listed in Table 1.

Table 1: Process-Evaluation Plan

Component	Questions	Measures (Sources)	Timing of Collection	Data Analysis
Fidelity	To what extent is the intervention implemented as planned and consistently with the theoretical framework?	Manipulation checks (subjects' self-reported scores)	Each training session	Compare the mean difference between groups.
Dose	Do participants receive the intended units of the intervention? How often do the subjects come to the training sessions? How many subjects participate in at least half of possible sessions?	Time spent on exergaming (experimenter's logs) Physical activity level (heart rate monitors and accelerometers) Attendance rate & frequency of coming to the training sessions (experimenter's logs)	Each training session	Calculate the average scores based on percentage of intended units included
Reach	Does the demographic information of the subjects reflect the population characteristics in the Lansing and East Lansing areas?	Demographic information (subjects' self-reports)	In the beginning of the first training session	Compare the distribution of sample to the population in the target areas
Recruitment	What are the barriers to recruiting subjects?	Experimenter(s) will document all the recruitment activities (experimenter's logs)	During recruitment	Find the factors influencing recruitment from experimenter's notes.
Context	What are factors influencing the exergaming intervention?	1. Subjects' demographic Information & familiarity with VR (self-reported). 2. Enjoyment (self-reported) & scores of the gameplays (experimenter's logs)	1. In the beginning of the first training session 2. After each training session	List the contextual factors as covariates in the data analysis.

3.8. Procedure

All participants were encouraged to complete the 4-week intervention, which consisted of eight sessions of exergaming. All participants were randomly assigned to one of the four experimental conditions when they signed up the study. After they signed up for the study, they were asked to finish a pre-screen survey, which included questions about their demographic information and previous experience with VR headsets.

When they came to the lab, participants were asked to read the consent form first. After they agreed to participate in the study, they did a series of executive function tasks (Stroop test, Trail-making task, and Digit Span**)** before starting the first exergaming session. These results served as the baselines for participants' scores on executive functions.

Before participants started playing the exergame for a 20-minute session, they were asked to read the instructions for playing the game (please see Appendix) and then put on a fitness wristband, which measured their energy expenditure during the gameplay. If the participants were assigned to the high immersion (VR) conditions, they were asked to put on a head-mounted display and adjust the head-mounted display to the degree they feel comfortable before playing the game. They were told that they could ask to stop playing and then be dropped out of the study if they had motion sickness during the gameplay. Participants assigned to the low immersion conditions were asked to stand a proper distance (1-1.5 meters away from the screen) from the LCD monitor to play the game.

Participants in the high task-irrelevant load condition were instructed to (1) memorize a 7-digit number (the number of digits vary based on the results of the pilot study) through the 20-minute gameplay session and (2) report the number after the gameplay. Participants in the high task-relevant load condition were instructed to play in the high-complexity mode (i.e., Survival mode). Participants were asked to complete two 20-minute exergaming sessions a week for four consecutive weeks. For the measures and surveys, participants were asked to do three executive function tasks as well as answer questions about their spatial presence experiences and subjective perception of their cognitive functions before the first exergaming session. Participants then did the cognitive tasks and surveys after their first, fourth, and last sessions. After completing the first session participants could schedule a time for the next session if they decided to continue to participate. The total length of each session (including the gameplay and measures) was around 35 minutes.

In the other seven sessions, participants completed the same amount of exergaming (20 minutes) each time. Regarding incentives for participation, subjects received $15 after their first experimental session. After finishing the second session of the first week, participants received another $15. From the second to the fourth weeks, participants received incentives after completing every two sessions ($35 for week 2, $40 for week 3, and $45 for week 4). After four weeks, participants who completed the eight exergaming sessions also had cognitive measures conducted at four time frames: one pretest and three posttests.

3.9. Analytic Techniques

Three analytic techniques were implemented in the present study. First, descriptive statistics were used to estimate each variable of interest and gain a better contextual understanding of the data. Second, a series of repeated-measures, mixed-linear, two-way ANCOVA (analysis of covariance) were used to examine two manipulations by time interaction effects. Age and sex were included as covariates in statistical analyses, given their potential effects reported in previous empirical evidence (Huntley, Gould, Liu, Smith, & Howard, 2015; Lam et al., 2013). Last, to provide a more conservative way to interpret the data, a series of repeated ANCOVAs were conducted to address the issues of missing responses by using Intention-To-Treat (ITT) analysis. ITT analysis has been widely used to deal with noncompliance and missing outcomes in research using randomized controlled trials (Gupta, 2011). Previous studies (e.g., Peng, 2009) suggest three approaches to analyze missing values: (1) substituting the mean, (2) carrying the pretest value forward, and (3) carrying the posttest value forward. The current study provides results using these three approaches.

Regarding hypothesis testing, a series of repeated ANCOVA were the primary analytic tool used to examine the differences across the different conditions. In testing H1 and RQ1, the level of immersion and types of task load were the independent variables, and executive functions were the dependent variable, while age and gender were used as covariates. In testing H2 and H4, the level of immersion and types of task loads were independent variables, and spatial presence was the dependent variable, while age and gender were used as covariates.

After testing H1, H2, H4, and RQ1, the current study then tested H3, which showed a mediation effect of spatial presence on immersion and executive functions by using PROCESS mediation analysis (Hayes, 2013). PROCESS has been used to examine the potential mediating role of spatial presence between the independent and dependent variables instead of examining the entire proposed model simultaneously, as in previous studies. Descriptive statistics, ANCOVAs, paired t-tests, and PROCESS tests were conducted via SPSS 25.0.

CHAPTER 4: RESULTS

4.1. Demographics

There was a total of 41 participants, including those who only participated in a single-bout session (n=8) and those who finished all training sessions (n=33). Thirty-two participants were recruited from a paid-community research pool and nine were recruited through snowball sampling (e.g., other participants' invitations). No significant difference in demographics was found between the two recruiting pools. The average time of playing video games per day was less than 30 minutes, and 60% of participants did not play video games at all. None of the participants had played either version of Fruit Ninja before the exergaming training.

All the participants were invited to participate in the longer-term training after finishing the first single bout of exergame training. Eight participants were recruited for the single-bout session and served as the pilot test of the current study. Of the remaining 33 participants who intended to participate in longer-term training, one dropped out after the fourth session due to personal reasons. Overall, 32 participants finished all the training sessions and adhered to the minimum amount of training sessions (twice a week, 15–20 minutes per visit) over four weeks. The adherence rate (97%) of the current study was higher than those reported in similar studies, which normally ranged from 19 – 75% (Barcelos et al., 2015).

Before participants started their first training session, they were asked to complete three cognitive measures, which served as the baselines of their cognitive performance. The results of ANCOVAs showed that there was no significant difference among the four groups in all three cognitive measures in the pretest (see Table 2).

Table 2: Demographics and Baseline Executive Functions

	VRTR (N=10)		VRTI (N=10)		NVRTR (N=10)		NVRTI (N=11)		ANOVA
	M	SD	M	SD	M	SD	M	SD	p
Demographics									
Age	58.80	5.75	62.90	7.31	62.5	10.97	61.93	8.21	.59
Sex (Male)	40%		40%		20%		10%		.30
Education	17.40	3.31	16.80	2.78	16.50	2.27	16.01	2.59	.98
Active Level	4.40	1.43	4.90	1.45	3.70	1.42	4.28	1.42	.33
Adherent (%)	80%		90%		80%		73%		.82
Heart Rate	121.50	13.12	114.11	11.12	116.29	6.99	118.67	9.71	.14
Baseline Executive Function									
Trials Making	-.20	.55	.21	.86	-.04	.86	.00	.73	.67
Stroop AC	-.15	.73	.12	.96	-.14	1.31	.16	1.00	.85
Digit Span	6.30	1.34	5.20	1.69	5.10	1.45	5.54	1.97	.36

VRTR= VR + Task-Relevant Load
VRTI= VR + Task-Irrelevant Load
NVRTR= Non-VR + Task-Relevant Load
NVRTI= Non-VR + Task-Irrelevant Load
Active Level was measured on a 7-point scale (1: not active at all to 7: very active)
Both Trail Making and Stroop AC used standardized scores

4.2. Manipulation Check and Confounding Testing

There were two tests for manipulations in this study: a manipulation check (level of immersion) and a test for confounding (type of task load). Regarding level of immersion, participants in the VR condition reported a higher level of immersive quality compared to those in the non-VR condition across three posttests at a significance level. Therefore, the manipulation of immersion worked as expected (see Table 3).

Table 3: Manipulation Check of Level of Immersion

	VR		Non-VR			
	Mean (N)	SD	Mean (N)	SD	T-Test	P
First Manipulation Check	6.27 (20)	.62	5.17 (21)	1.12	3.90	.000***
Second Manipulation Check	6.25 (17)	.69	5.31 (16)	.95	3.26	.002**
Last Manipulation Check	6.21 (17)	.76	5.46 (15)	1.06	2.26	.027*

Regarding type of task load, the manipulation was to create two types of task load and induce a similar level of mental effort between two conditions. The confounding testing question asked participants about their mental effort during the gameplay and perceived difficulty of the game. Participants in both conditions (i.e., task-relevant and task-irrelevant load) reported a similar amount of mental effort across the three posttests, and those in the task-relevant load condition reported a higher level of perceived difficulty of the game than those in the task-irrelevant load condition. Therefore, the results of these two questions suggested that the difficult game mode resulted in a similar amount of mental effort as the combination of the easy game mode and the assigned game-irrelevant task. In both condition, participants invested more mental effort and performed the assigned tasks better at time 2 and time 3 than they did in the time 1.

To compare the perceived difficulty of assigned tasks (a more difficulty game mode vs. an additional memory task), participants in the task-irrelevant load condition were asked to answer another question about the perceived difficulty of the memory task. After comparing the scores for the perceived difficulty of the game in the task-relevant condition and the scores for the perceived difficulty of the assigned memory task in the task-irrelevant load condition, the results showed that participants in both conditions reported a similar amount of perceived difficulty of the tasks. Therefore, the amount of total mental effort during game play and perceived difficulty of the assigned tasks were similar between two conditions (see Table 4).

Table 4: Confounding Testing of Types of Task Loads

	Task-Relevant		Task-Irrelevant		T-Test	P
First Posttest	Mean(N)	SD	Mean(N)	SD		
How much mental effort you invested during the gameplay you just finished?	6.20 (20)	1.85	6.90 (21)	1.64	1.11	.27
How difficult the game that you just finished was?	4.90 (20)	2.10	3.05 (21)	2.60	2.50	.02*
[1]How difficult the memory task that you just finished was[1]?	4.90 (20)	2.10	5.86 (21)	1.32	1.76	.08

Table 4: Confounding Testing of Types of Task Loads (cont'd)

Second Posttest						
How much mental effort you invested during the gameplay you just finished?	7.25 (16)	1.57	7.59 (17)	1.26	.69	.49
How difficult the game that you just finished was?	5.88 (16)	2.21	3.94 (17)	2.63	2.55	.01*
[1]How difficult the memory task that you just finished was?	5.88 (16)	2.21	5.12 (17)	2.06	1.02	.31
Last posttest						
How much mental effort you invested during the gameplay you just finished?	7.75 (16)	1.29	7.53 (16)	2.03	.35	.71
How difficult the game that you just finished was?	6.75 (16)	1.77	3.73 (16)	2.34	4.64	.00***
[1]How difficult the memory task that you just finished was?	6.75 (16)	1.77	6.13 (16)	2.26	.85	.39

[1]Participants in the task-relevant load condition did not have this question, so the results of t-test is the comparison between difficulty of games vs. difficulty of memory tasks across two groups.

4.3. Overview: Effects of VR and Types of Task Load on Cognitive Improvement

The first hypothesis and research question investigated the impact of level of immersion and type of task load on cognitive improvement, including Stroop, trail-making, and backward digit span. A series of repeated ANCOVAs were conducted to examine whether there were differences in cognitive improvement among the four conditions across three posttests as an overview of the effects of the interventions.

4.3.1. Overview

The exergaming training included eight sessions, and each session was between 15–20 minutes. Before participants started playing the exergames in the first session, they were asked to complete a pretest survey and three cognitive measures (i.e., Stroop, trail-making and backward digit span). These cognitive measures served as their baseline cognitive performance. Over the course of the four-week training, they were asked to do posttests (a survey and three cognitive measures) in three different time frames: after the first single-bout session, after two weeks, and after four weeks. Forty-one participants completed the first session, 33 completed four sessions, and 32 completed all eight training sessions, resulting in a final sample of 32 for data analysis. Three sets of repeated measures ANCOVAs were conducted for the executive function measures while controlling for age, gender, and the baseline results of the executive function measures (see Table 5 & 6).

Table 5: Repeated ANCOVAs of Outcome Measures Across Three Posttests

Stroop AC (N=28)	df	F	P	Partial Eta^2
Time	2	2.38	.105	.102
Time × Baseline	2	1.22	.305	.055
Time × Age	2	2.00	.148	.087
Time × Gender	2	1.46	.243	.065
Time × Immersion	2	4.54	.016*	.178
Time × Types of Task Load	2	1.37	.263	.062
Time × Immersion × Types of Task Load	2	3.17	.052+	.131
Error (Time)	42			
Trail Making (N=28)	**df**	**F**	**P**	**Partial Eta^2**
Time	2	.84	.439	.038
Time × Baseline	2	.69	.506	.032
Time × Age	2	.70	.500	.032
Time × Gender	2	.09	.911	.004
Time × Immersion	2	3.39	.043*	.139
Time × Types of Task Load	2	1.68	.198	.074
Time × Immersion × Types of Task Load	2	4.42	.018*	.174
Error (Time)	42			
Backward Digit Span (N=30)	**df**	**F**	**P**	**Partial Eta^2**
Time	2	1.37	.263	.056
Time × Baseline	2	1.76	.184	.071
Time × Age	2	.898	.414	.038
Time × Gender	2	.552	.580	.023
Time × Immersion	2	1.24	.299	.051
Time × Types of Task Load	2	.484	.620	.021
Time × Immersion × Types of Task Load	2	3.92	.027*	.146

Table 6: Estimated Marginal Means of Outcome Measures Across Three Posttests

Stroop AC (n=28)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	-.164	.351	-.894	.565
VR + Task-relevant load (Time 2)	-.090	.342	-.801	.621
VR + Task-relevant load (Time 3)	.717	.333	.025	1.408
VR + Task-irrelevant load (Time 1)	.163	.289	-.439	.764
VR + Task-irrelevant load (Time 2)	-.426	.282	-1.012	.160
VR + Task-irrelevant load (Time 3)	.077	.274	-.494	.647
Non-VR + Task-relevant load (Time 1)	.142	.329	-.542	.826
Non-VR + Task-relevant load (Time 2)	-.520	.320	-1.186	.146
Non-VR + Task-relevant load (Time 3)	-.505	.312	-1.153	.143
Non-VR + Task-irrelevant load (Time 1)	.145	.396	-.677	.968
Non-VR + Task-irrelevant load (Time 2)	.795	.385	-.006	1.596
Non-VR + Task-irrelevant load (Time 3)	-.253	.375	-1.032	.527
*Covariates appearing in the model are: Age = 62.29, Gender = .32				
Trail Making (N=28)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	.151	.220	-.307	.608
VR + Task-relevant load (Time 2)	.358	.191	-.039	.754
VR + Task-relevant load (Time 3)	-.516	.203	-.939	-.094
VR + Task-irrelevant load (Time 1)	.011	.184	-.371	.393
VR + Task-irrelevant load (Time 2)	-.378	.159	-.709	-.047
VR + Task-irrelevant load (Time 3)	.046	.170	-.307	.399
Non-VR + Task-relevant load (Time 1)	.317	.228	-.156	.791
Non-VR + Task-relevant load (Time 2)	.029	.197	-.381	.440
Non-VR + Task-relevant load (Time 3)	.622	.210	.185	1.059
Non-VR + Task-irrelevant load (Time 1)	-.181	.236	-.672	.309
Non-VR + Task-irrelevant load (Time 2)	-.162	.204	-.587	.262
Non-VR + Task-irrelevant load (Time 3)	.114	.218	-.339	.567
*Covariates appearing in the model are: Age = 62.50, Gender = .28				
Backward Digit Span (N=30)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	5.645	.436	4.743	6.547
VR + Task-relevant load (Time 2)	6.369	.501	5.333	7.406
VR + Task-relevant load (Time 3)	6.205	.479	5.213	7.196
VR + Task-irrelevant load (Time 1)	6.305	.387	5.504	7.106
VR + Task-irrelevant load (Time 2)	5.817	.445	4.896	6.737
VR + Task-irrelevant load (Time 3)	6.369	.426	5.488	7.250
Non-VR + Task-relevant load (Time 1)	6.180	.440	5.269	7.091
Non-VR + Task-relevant load (Time 2)	5.941	.506	4.894	6.987
Non-VR + Task-relevant load (Time 3)	6.573	.484	5.572	7.574
Non-VR + Task-irrelevant load (Time 1)	5.472	.492	4.455	6.489
Non-VR + Task-irrelevant load (Time 2)	6.685	.565	5.516	7.854
Non-VR + Task-irrelevant load (Time 3)	7.338	.541	6.220	8.457
*Covariates appearing in the model are: Age = 61.93, Gender = .27.				

Regarding the Stroop results (n=28), four participants did not finish one of the posttests successfully and were excluded from data analysis. A significant interaction effect of level of immersion × time was found on Stroop at the significance level. [$F(2, 42) = 4.53$; $p = .016$; $\eta_p^2 = .178$]. The interaction effect suggested that people in the VR condition had a more improved performance in Stroop than those in the non-VR condition over the course of the training. Furthermore, a three-way interaction of level of immersion × type of task load × time was found on Stroop at a marginal significance level. The results suggested that the interaction effect of VR and task-relevant load on Stroop varied across three posttests, with those in the VR+ task-relevant load condition showing a more improved performance than those in the other three conditions across different time frames [$F(2, 42) = 3.16$; $p = .052$; $\eta_p^2 = .131$] (See Figure 6).

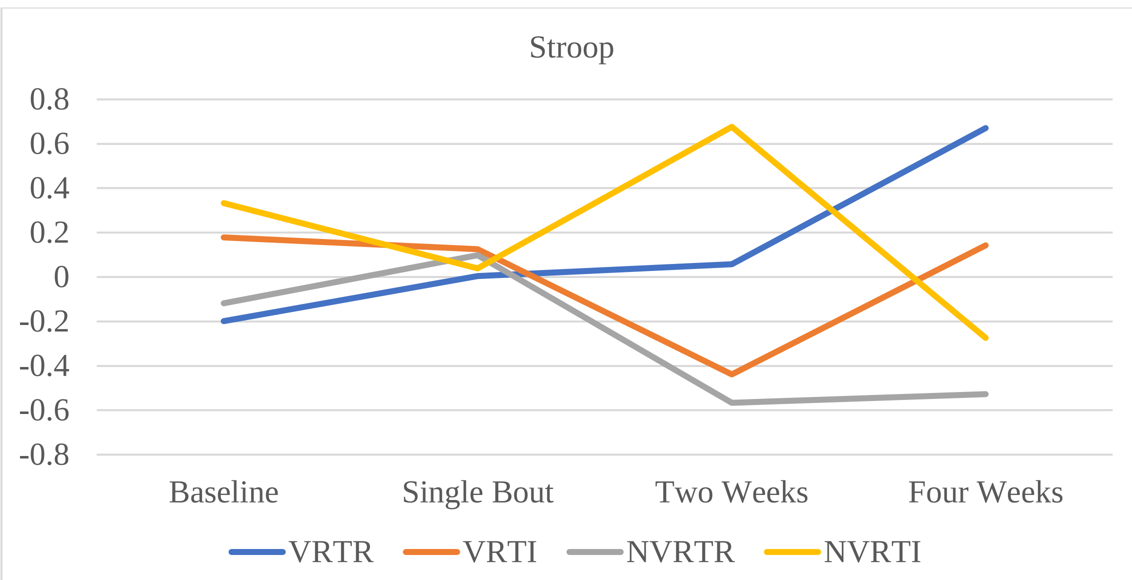

Figure 6: Stroop Results after A Single Bout, Two Weeks, and Four Weeks

Regarding the trail-making results (n=28), four participants did not finish one of the posttests successfully and were excluded from data analysis. Similarly, a significant interaction effect of level of immersion × time was found on the trail-making (n=28), which showed that participants in the VR condition had a more improved performance than those in the non-VR condition at the significance level [$F(2, 42) = 3.39$; $p = .043$; $\eta_p^2 = .139$]. A three-way interaction of immersion × task-relevant load × time was also found on the trail-making. The results revealed that the impact of the interaction VR + task-irrelevant load varied across three posttests, with those in the VR + task-relevant load condition showing a more improved performance among the four experiment conditions over the course of the training [$F(2, 42) = 4.42$; $p = .018$; $\eta_p^2 = .174$] (See Figure 7).

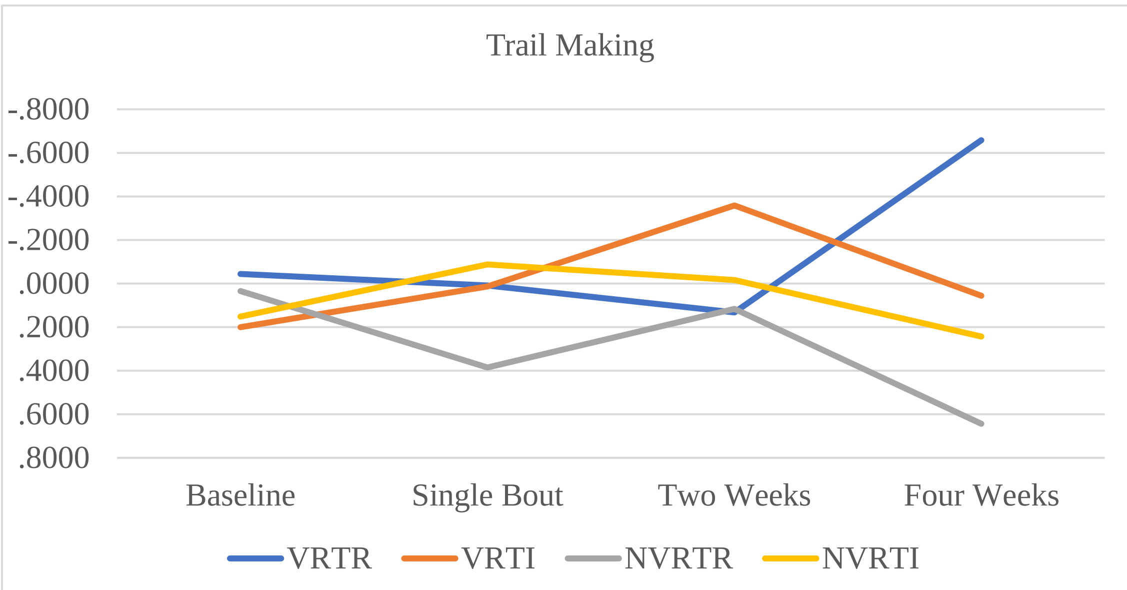

Figure 7: Trail-Making Results after A Single Bout, Two Weeks, and Four Weeks

Regarding the backward digit span (n=30), two participants did not complete one of the posttests and were excluded from data analysis. The results revealed a three-way interaction of level of immersion × type of task load × time at the significance level [$F(2, 42) = 3.92$; $p = .027$; $\eta_p^2 = .146$]. The findings indicated that the interaction effects of immersion and task-irrelevant load varied across three posttests, with those in the non-VR + task-irrelevant load condition showing a more improved performance in backward digit span compared with the other three groups (See Figure 8)

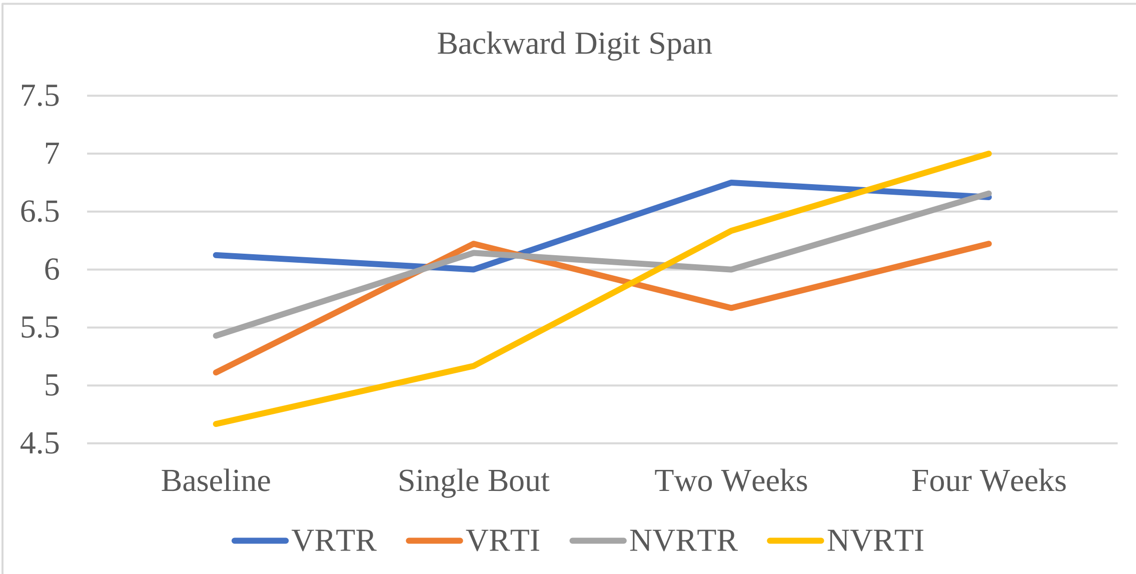

Figure 8: Backward Digit Results after A Single Bout, Two Weeks, and Four Weeks

In sum, level of immersion had an interaction effect with time in two of the three cognitive measures. Therefore, H1a and H1b were supported. Regarding the research question, there was no main effect of type of task load on participants' cognitive performance. Type of task load and level of immersion had interaction effects on all three outcome variables over the course of the exergaming training. Specifically, the three-way interactions revealed that participants in the VR + task-relevant load condition had a more improved performance across times on the Stroop and trail-making results compared to other groups, and those in the non-VR + task-irrelevant load condition had a more improved performance across times on backward digit span results compared to other groups.

4.3.2. Intention-To-Treat Analysis

To provide a more conservative way to interpret the data, a series of repeated ANCOVAs were conducted to address the issues of dropping-out cases and missing responses by using Intention-To-Treat (ITT) analysis. ITT analysis has been widely used to deal with noncompliance and missing outcomes in research using randomized controlled trails (Gupta, 2011). Previous studies (e.g., Peng, 2009) suggested three different approaches to analyze missing values: 1) mean substitution, 2) pretest value carried forward, and 3) posttest value carried forward. Therefore, the current study also provided results using these three approaches.

A total of 33 participants who decided to participate in the four-week exergaming training were included in the analyses. Among the 33 participants, four had missing values for one of their posttests and one dropped out after two weeks. After applying these three different approaches for analyzing missing values, most of the results were still consistent with the previous section's results using raw data (See Table 7). The main effect of level of immersion on Stroop and interaction effects on Stroop, trail-making, and backward digit span were either significant or marginally significant. However, the main effect of level of immersion on the trail-making test was no longer significant despite showing the same pattern as the previous analyses.

The results of ITT analyses showed that the impact of level of immersion and interaction effects of two manipulations were still significant or marginally significant even using stricter, conservative approaches to analyze the data. Therefore, it is safe to argue that immersion and its interaction with the task-relevant load had positive impacts on participants' performance in Stroop and trail-making at either a marginal significance or significance level.

To sum up, the ITT analyses showed that the patterns of main effect of level of immersion and interaction effects of level of immersion and type of task load were still the same despite the effect sizes being smaller. However, ITT has also been criticized for being more likely to have type II errors due to its conservativeness (Gupta, 2011). Therefore, ITT analyses served as references for the main analyses of the current study instead of as standards for answering research questions and supporting or rejecting the hypotheses.

Table 7: ITT Analyses of Outcome Measures Across Three Posttests

	Mean substitution		Pretest Carried		Posttest Carried	
Stroop AC (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	1.15	.042	1.60	.058	1.02	.038
Time × Baseline	1.52	.055	1.60	.058	1.45	.053
Time × Age	.97	.036	1.44	.052	.86	.032
Time × Gender	1.10	.041	.94	.035	1.25	.046
Time × Immersion	**3.86***	**.129**	**3.88***	**.130**	**3.85***	**.129**
Time × Types of Task Load	1.56	.057	1.59	.058	1.71	.062
Time × Immersion × Types of Task Load	**2.52+**	**.088**	**4.55***	**.149**	**3.42***	**.116**
Trail Making (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	1.30	.048	1.51	.055	1.02	.038
Time × Baseline	.69	.026	1.03	.038	.48	.018
Time × Age	1.08	.040	1.18	.043	.80	.030
Time × Gender	.12	.005	.55	.021	.02	.001
Time × Immersion	2.09	.074	1.06	.039	2.15	.076
Time × Types of Task Load	2.43	.085	1.08	.040	2.57	.090
Time × Immersion × Types of Task Load	**5.20****	**.167**	**5.20****	**.178**	**3.79***	**.127**
Backward Digit Span (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.70	.026	1.27	.047	1.00	.037
Time × Baseline	.54	.020	2.71+	.094	.92	.034
Time × Age	.44	.017	.68	.025	.77	.029
Time × Gender	.61	.023	.52	.020	.51	.019
Time × Immersion	1.36	.050	1.43	.055	.65	.024
Time × Types of Task Load	.38	.014	.94	.035	.41	.016
Time × Immersion × Types of Task Load	**2.59+**	**.090**	**5.00****	**.161**	**3.44***	**.040**

4.4. The Baseline-Posttest Comparisons at Different Time Frames

Besides conducting ITT analysis, this study also conducted repeated analyses to compare three posttests with the baseline separately to better understand whether there was a difference between the baseline measures and posttests at different times — right after a single bout of exergaming, after two weeks, and after four weeks. These post-hoc analyses included results using both raw data and ITT analyses.

4.4.1. First Posttest: After the first Single-Bout

A total of 41 individuals participated in the single-bout training. A series of repeated measures ANCOVAs were conducted for each of three cognitive measures while controlling for age, gender, and the baseline results of the executive function measures (see Tables 8 & 9).

Table 8: Repeated ANCOVAs of Outcome Variables After the First Single-Bout

Stroop AC (n=39)	SS	df	F	P	Partial Eta^2
Time	.005	1	.006	.936	.000
Time × Age	.016	1	.020	.889	.001
Time × Gender	.509	1	.651	.426	.019
Time × Immersion	.018	1	.023	.881	.001
Time × Types of Task Load	.355	1	.454	.505	.014
Time × Immersion × Types of Task Load	.015	1	.020	.889	.001
Error (Time)	25.787	33			
Trail Making (n=37)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	.002	1	.004	.953	.000
Time × Age	.009	1	.021	.886	.001
Time × Gender	.018	1	.041	.840	.001
Time × Immersion	.246	1	.555	.462	.018
Time × Types of Task Load	2.297	1	5.178	.030*	.143
Time × Immersion × Types of Task Load	.012	1	.027	.869	.001
Error (Time)	13.753	31			
Backward Digit Span (n=41)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	2.527	1	2.089	.157	.056
Time × Age	.370	1	.306	.584	.009
Time × Gender	3.327	1	2.750	.106	.073
Time × Immersion	.178	1	.147	.704	.004
Time × Types of Task Load	.019	1	.015	.902	.000
Time × Immersion × Types of Task Load	5.492	1	4.540	.040*	.115
Error (Time)	42.342				

Table 9: Estimated Marginal Means of Outcome Variables After the First Single-Bout

Stroop AC (n=39)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	-.296	.357	-1.023	.430
VR + Task-relevant load (Time 2)	-.086	.365	-.828	.656
VR + Task-irrelevant load (Time 1)	-.115	.323	-.773	.543
VR + Task-irrelevant load (Time 2)	-.026	.330	-.698	.646
Non-VR + Task-relevant load (Time 1)	.165	.325	-.495	.826
Non-VR + Task-relevant load (Time 2)	.042	.331	-.632	.716
Non-VR + Task-irrelevant load (Time 1)	.217	.332	-.458	.892
Non-VR + Task-irrelevant load (Time 2)	.086	.339	-.604	.775
*Covariates appearing in the model are: Age = 61.6923, Gender = .2821.				
*The means were standardized. The higher scores mean the better reaction.				
Trail Making (N=37)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	-.150	.239	-.638	.339
VR + Task-relevant load (Time 2)	-.049	.196	-.449	.351
VR + Task-irrelevant load (Time 1)	.422	.273	-.135	.978
VR + Task-irrelevant load (Time 2)	-.162	.224	-.618	.293
Non-VR + Task-relevant load (Time 1)	-.052	.228	-.517	.412
Non-VR + Task-relevant load (Time 2)	.347	.186	-.033	.728
Non-VR + Task-irrelevant load (Time 1)	.115	.238	-.372	.601
Non-VR + Task-irrelevant load (Time 2)	-.275	.195	-.673	.124
*Covariates appearing in the model are: Age = 61.7027, Gender = .2162.				
*The means were standardized. The higher scores mean the slower reaction.				
Digit Span (n=41)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	6.005	.507	4.977	7.033
VR + Task-relevant load (Time 2)	5.878	.363	5.141	6.616
VR + Task-irrelevant load (Time 1)	5.171	.491	4.174	6.168
VR + Task-irrelevant load (Time 2)	5.889	.352	5.174	6.605
Non-VR + Task-relevant load (Time 1)	5.226	.495	4.220	6.231
Non-VR + Task-relevant load (Time 2)	6.203	.355	5.481	6.924
Non-VR + Task-irrelevant load (Time 1)	5.726	.481	4.749	6.702
Non-VR + Task-irrelevant load (Time 2)	5.463	.345	4.762	6.163
*Covariates appearing in the model are: Age = 61.9268, Gender = .2683.				
* The higher scores mean the better reaction.				

Regarding the Stroop results, two participants did not finish the first posttest successfully. Therefore, they were excluded from data analysis (n=39). The results of the repeated ANCOVAs did not reveal any significant main or interaction effects of level of immersion and type of task load on Stroop.

Regarding the results of the trail-making test, four participants who did not finish the test were excluded from the data analysis (n=37). A significant interaction effect of type of task load × time interaction was found on the trail-making, which showed that participants in the task-irrelevant load condition had a more improved performance than those in the task-relevant condition across two time points [$F(1,31) = 5.18$; $p = .030$; $\eta_p^2 = .143$].

Regarding participants' performance on backward digit span (n=41), there was a significant three-way interaction effect of level of immersion × type of task load × time on their first posttest. Specifically, the three-way interaction revealed that participants in the VR + task-irrelevant load condition improved their performance in the backward digit span the most among the four experimental conditions. The unexpected interaction relationship will be further illustrated in the discussion section [$F(1,35) = 4.54$; $p = .040$; $\eta_p^2 = .115$].

Table 10: ITT Analyses of Outcome Measures After the First Single-Bout

	Mean substitution		Pretest Carried		Posttest Carried	
Stroop AC (N=41)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.44	.012	.07	.002	.45	.013
Time × Age	.47	.013	.06	.002	.49	.014
Time × Gender	.33	.009	.49	.014	.30	.008
Time × Immersion	.00	.000	.01	.000	.01	.000
Time × Types of Task Load	.20	.006	.40	.011	.18	.005
Time × Immersion × Types of Task Loads	.53	.015	.25	.007	.61	.017
Trail Making (N=41)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.01	.000	.01	.000	.13	.004
Time × Age	.03	.001	.03	.001	.16	.005
Time × Gender	.00	.000	.02	.001	.01	.000
Time × Immersion	.50	.014	.49	.014	.16	.004
Time × Types of Task Load	4.56*	.115	4.61*	.116	3.42+	.089
Time × Immersion × Types of Task Loads	.14	.004	.17	.005	.52	.015

In general, level of immersion did not have any effect on outcome measures right after the first exergame training. Regarding the effects of type of task load, the task-irrelevant load had an impact on participants' performance in trail-making. Furthermore, the task-irrelevant load also positively affected the backward digit span results for those in the VR condition and the task-relevant load negatively affected backward digit span for those in the non-VR condition. The results of ITT analyses were consistent with the initial analyses (See Table 10).

4.4.2. Second Posttest: After the Two-Week Training (four sessions)

Of the 41 participants who finished the first exergame training, eight decided not to participate in the longer-term training. A series of repeated ANCOVAs were conducted to investigate the impacts of two manipulations (See Tables 11 & 12). For the Stroop task results after the two-week training, two outliers whose scores were below or exceeding three standard deviations (Khng & Lee, 2014) were excluded from the data analysis (N=31). There was a three-way interaction effect of level of immersion × type of task load × time [$F(1,25) = 5.07$; $p = .033$; $\eta_p^2 = .175$]. To be more specific, participants in the VR condition + task-relevant load and those in the non-VR condition + task-irrelevant load had the most improved performance in the second Stroop test among all experimental conditions. However, no effect of immersion and type of cognitive load was found on Stroop.

Regarding the trail-making test, three participants were excluded from the data analysis due to incomplete results (n=30). Similar to the findings of trail-making in the first posttest, the results of the second posttest also revealed an interaction effect of type of task load × time. To be more specific, participants in the task-irrelevant condition showed a more improved performance than those in the task-relevant condition [$F(1,24) = 8.55$; $p = .055$; $\eta_p^2 = .151$].

For the results of backward digit span, three participants did not complete the tests, and were thus excluded from the data analysis (n=30). The result showed a significant three-way interaction effect of level of immersion × type of task load × time on participants' backward digit span scores in the second posttest [$F(1,24) = 5.72$; $p = .026$, $\eta_p^2 = .214$]. Participants in the non-VR + task-irrelevant load conditions had improved their performance more between the baseline and posttest measures than in the other three conditions. No effect of level of immersion and type of task load was found on backward digit span.

Table 11: Repeated ANCOVAs of Outcome Variables After the Two-Week Training

Stroop AC (n=31)	SS	df	F	P	Partial Eta^2
Time	3.015	1	2.616	.119	.098
Time × Age	2.674	1	2.320	.141	.088
Time × Gender	.607	1	.527	.475	.021
Time × Immersion	.028	1	.025	.877	.001
Time × Types of Task Load	.102	1	.089	.768	.004
Time × Immersion × Types of Task Load	5.878	1	5.099	.033*	.175
Error (Time)	27.664	25			
Trail Making (n=30)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	.056	1	.126	.726	.005
Time × Age	.036	1	.081	.779	.003
Time × Gender	.023	1	.051	.824	.002
Time × Immersion	.165	1	.370	.549	.016
Time × Types of Task Load	1.824	1	4.086	.055+	.151
Time × Immersion × Types of Task Load	.028	1	.064	.803	.003
Error (Time)	10.267	24			
Backward Digit Span (n=30)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	6.704	1	7.066	.015*	.252
Time × Age	8.129	1	8.568	.008**	8.129
Time × Gender	.131	1	.139	.713	.007
Time × Immersion	.209	1	.221	.643	.010
Time × Types of Task Load	2.042	1	2.152	.157	.093
Time × Immersion × Types of Task Load	5.426	1	5.719	.026*	.214
Error (Time)	19.924	24			

Table 12: Estimated Marginal Means of Outcome Variables After the Two-Week Training

Stroop AC (n=31)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	-.459	.411	-1.308	.389
VR + Task-relevant load (Time 2)	.006	.376	-.769	.782
VR + Task-irrelevant load (Time 1)	.194	.341	-.510	.898
VR + Task-irrelevant load (Time 2)	-.459	.312	-1.103	.184
Non-VR + Task-relevant load (Time 1)	.157	.422	-.714	1.029
Non-VR + Task-relevant load (Time 2)	-.574	.386	-1.370	.223
Non-VR + Task-irrelevant load (Time 1)	.162	.373	-.609	.933
Non-VR + Task-irrelevant load (Time 2)	.893	.341	.189	1.598
Covariates appearing in the model are: Age = 62.9333, Gender = .3000.				
Trail Making (N=30)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	.010	.296	-.598	.619
VR + Task-relevant load (Time 2)	.211	.196	-.191	.613
VR + Task-irrelevant load (Time 1)	.201	.268	-.349	.751
VR + Task-irrelevant load (Time 2)	-.354	.177	-.717	.010
Non-VR + Task-relevant load (Time 1)	.282	-.635	.525	.282
Non-VR + Task-relevant load (Time 2)	.282	-.635	.525	.282
Non-VR + Task-irrelevant load (Time 1)	.135	.319	-.520	.791
Non-VR + Task-irrelevant load (Time 2)	-.210	.211	-.643	.223
Covariates appearing in the model are: Age = 62.1563, Gender = .2500.				
Digit Span (n=30)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	5.832	.603	4.579	7.085
VR + Task-relevant load (Time 2)	6.873	.483	5.869	7.876
VR + Task-irrelevant load (Time 1)	5.174	.541	4.049	6.299
VR + Task-irrelevant load (Time 2)	5.616	.433	4.715	6.517
Non-VR + Task-relevant load (Time 1)	5.598	.767	4.003	7.193
Non-VR + Task-relevant load (Time 2)	4.938	.614	3.661	6.216
Non-VR + Task-irrelevant load (Time 1)	5.558	.754	3.990	7.126
Non-VR + Task-irrelevant load (Time 2)	7.157	.604	5.901	8.413
Covariates appearing in the model are: Age = 62.2963, Gender = .2963.				

Overall, the results of cognitive training after two weeks (four sessions) did not show any effect of level of immersion on executive functions. However, level of immersion started to have an interaction effect with the task-relevant load on cognitive performance while the impact of task-irrelevant load persisted in certain conditions. Task-irrelevant load still had an impact on the trail-making, but only at the marginal significance level. The results of ITT analyses were consistent with the initial analyses (See Table 13).

Table 13: ITT Analyses of Outcome Measures After the Two-Week Training

	Mean substitution		Pretest Carried		Posttest Carried	
Stroop AC (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	1.47	.052	1.96	.069	2.14	.073
Time × Age	1.42	.050	1.78	.062	1.81	.063
Time × Gender	.26	.010	.46	.017	.70	.025
Time × Immersion	.38	.014	.30	.011	.44	.016
Time × Types of Task Load	.03	.001	.01	.000	.11	.004
Time × Immersion × Types of Task Load	3.84+	.124	4.56*	.144	4.14*	.140
Trail Making (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.11	.004	.22	.009	.11	.004
Time × Age	.06	.003	.15	.006	.07	.003
Time × Gender	.30	.004	.05	.002	.00	.000
Time × Immersion	.84	.024	.13	.005	.52	.019
Time × Types of Task Load	3.04+	.101	4.12+	.137	3.12+	.132
Time × Immersion × Types of Task Load	.59	.011	.86	.003	.11	.004
Backward Digit Span (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	5.59*	.202	5.43*	.198	5.84*	.210
Time × Age	6.78*	.235	6.58*	.230	7.32*	.250
Time × Gender	.17	.008	.17	.008	.07	.003
Time × Immersion	.05	.002	.05	.002	.03	.002
Time × Types of Task Load	1.30	.056	1.24	.053	1.50	.064
Time × Immersion × Types of Task Load	4.09+	.155	3.89+	.150	4.58*	.172

4.4.3. Third Posttest: After Four-week Training (eight sessions)

One participant dropped out of the exergame training after the forth session, and 32 remained for the rest of the training sessions. A series of repeated ANCOVAs were conducted to investigate the impact of two manipulations (See Tables 14 & 15). In the last posttest, level of immersion × time interaction had a significant impact on the Stroop, which revealed that participants in the VR condition had a more improved performance than those in the non-VR condition [$F(1,23) = 5.17$; $p = .034$; $\eta_p^2 = .197$]. Furthermore, a three-way interaction of level of immersion × type of task load × time was found. The results showed that VR and task-relevant load varied between two times, with those in the VR + task-relevant load condition having a more improved performance in Stroop compared to other conditions [$F(1,23) = 4.35$; $p = .049$; $\eta_p^2 = .172$].

Regarding the results of participants' trail-making performance, an interaction effect of level of immersion × time was found in the last posttest, which showed that participants in the VR condition had a more improved performance than those in the non-VR condition [$F(1,22) = 4.88$; $p = .038$; $\eta_p^2 = .181$]. Different from the first and second posttests, type of task load no longer had an impact on participants' trail-making performance.

Table 14: Repeated ANCOVAs of Outcome Variables After the Four-Week Training

Stroop AC (n=29)	SS	df	F	P	Partial Eta^2
Time	5.600	1	8.146	.009*	.279
Time × Age	5.072	1	7.378	.013*	.260
Time × Gender	2.360	1	3.433	.078+	.141
Time × Immersion	3.551	1	5.166	.034*	.197
Time × Types of Task Load	.220	1	.320	.578	.015
Time × Immersion × Types of Task Load	2.990	1	4.350	.049*	.172
Error (Time)	14.436	23			
Trail Making (N=28)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	.067	1	.192	.665	.009
Time × Age	.062	1	.178	.677	.008
Time × Gender	.166	1	.480	.496	.021
Time × Immersion	1.687	1	4.876	.038*	.181
Time × Types of Task Load	.158	1	.456	.507	.020
Time × Immersion × Types of Task Load	.312	1	.903	.352	.039
Error (Time)	7.612	22			
Digit Span (n=32)	**SS**	**df**	**F**	**P**	**Partial Eta^2**
Time	.778	1	.617	.439	.023
Time × Age	.560	1	.444	.511	.017
Time × Gender	.028	1	.022	.882	.001
Time × Immersion	2.856	1	2.266	.144	.080
Time × Types of Task Load	1.081	1	.858	.363	.032
Time × Immersion × Types of Task Load	.021	1	.017	.897	.001
Error (Time)	32.772	26			

Table 15: Estimated Marginal Means of Outcome Variables After the Four-Week Training

Stroop AC (n=29)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	-.565	.418	-1.436	.305
VR + Task-relevant load (Time 2)	.664	.339	-.041	1.369
VR + Task-irrelevant load (Time 1)	.174	.342	-.538	.886
VR + Task-irrelevant load (Time 2)	.143	.277	-.434	.720
Non-VR + Task-relevant load (Time 1)	.446	.476	-.544	1.437
Non-VR + Task-relevant load (Time 2)	-.466	.386	-1.269	.336
Non-VR + Task-irrelevant load (Time 1)	.094	.432	-.805	.993
Non-VR + Task-irrelevant load (Time 2)	-.093	.350	-.822	.635
Covariates appearing in the model are evaluated at the following values: Age = 63.4074, Gender = .3333.				
Trail Making (N=28)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	.007	.298	-.606	.620
VR + Task-relevant load (Time 2)	-.535	.185	-.915	-.155
VR + Task-irrelevant load (Time 1)	.199	.271	-.359	.756
VR + Task-irrelevant load (Time 2)	.054	.168	-.292	.399
Non-VR + Task-relevant load (Time 1)	-.070	.287	-.660	.521
Non-VR + Task-relevant load (Time 2)	.475	.178	.109	.841
Non-VR + Task-irrelevant load (Time 1)	-.123	.313	-.766	.519
Non-VR + Task-irrelevant load (Time 2)	-.001	.194	-.399	.397
Covariates appearing in the model are evaluated at the following values: Age = 62.0313, Gender = .2813.				
Digit Span (n=32)	Mean	S.D.	LLCI	ULCI
VR + Task-relevant load (Time 1)	5.879	.586	4.675	7.084
VR + Task-relevant load (Time 2)	6.396	.520	5.327	7.464
VR + Task-irrelevant load (Time 1)	5.264	.557	4.120	6.409
VR + Task-irrelevant load (Time 2)	6.752	.494	5.737	7.767
Non-VR + Task-relevant load (Time 1)	5.598	.767	4.003	7.193
Non-VR + Task-relevant load (Time 2)	4.938	.614	3.661	6.216
Non-VR + Task-irrelevant load (Time 1)	5.076	.623	3.797	6.356
Non-VR + Task-irrelevant load (Time 2)	7.038	.552	5.903	8.172
Covariates appearing in the model are evaluated at the following values: Age = 62.6250, Gender = .2813.				

Regarding backward digit span, neither level of immersion nor type of task load had an impact on participants' performance after four weeks of exergaming training. Furthermore, the interaction effects no longer persisted in the last posttest, which was different from the results of the first and second posttests.

To sum up, the level of immersion showed an impact on two out of three cognitive measures (i.e., Stroop and trail-making) in the posttest while the effect of task-irrelevant load was no longer significant. The results of ITT analyses were consistent with the initial analyses (See Table 16).

Table 16: ITT Analyses of Outcome Measures After the Four-Week Training

	Mean substitution		Pretest Carried		Posttest Carried	
Stroop AC (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	8.08**	.269	8.32**	.274	8.39**	.276
Time × Age	7.19*	.246	7.46*	.253	7.45*	.255
Time × Gender	4.17+	.159	4.03+	.155	3.96+	.153
Time × Immersion	4.70*	.176	5.07*	.187	5.21*	.192
Time × Types of Task Load	.17	.008	.23	.010	.26	.012
Time × Immersion × Types of Task Load	3.96+	.152	4.26+	.162	4.36*	.166
Trail Making (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.00	.000	.13	.000	.00	.000
Time × Age	.00	.000	.13	.000	.00	.000
Time × Gender	.00	.000	.14	.001	.00	.000
Time × Immersion	4.41*	.140	5.20*	.163	4.30*	.137
Time × Types of Task Load	.04	.002	.01	.000	.05	.002
Time × Immersion × Types of Task Load	2.75	.092	2.26	.076	2.79	.094
Backward Digit Span (N=33)	F	Partial Eta^2	F	Partial Eta^2	F	Partial Eta^2
Time	.05	.002	.03	.001	.26	.010
Time × Age	.19	.008	.57	.021	1.06	.038
Time × Gender	.54	.022	.33	.012	.27	.011
Time × Immersion	1.91	.074	.60	.022	.20	.008
Time × Types of Task Load	2.04	.078	1.04	.037	.45	.016
Time × Immersion × Types of Task Load	.29	.012	.32	.001	.00	.000

4.5. Effects of VR and cognitive load on Spatial Presence Experiences

To test the second and fourth hypotheses of the current study, a series of repeated ANCOVAs and ANCOVAs were conducted to examine the impact of level of immersion and type of task load on participants' spatial presence experiences across four weeks. Both independent variables are categorical, and the dependent variable is a scale of continuous data. Therefore, repeated ANCOVA and ANCOVA would be a suitable tool for interpreting the results. Age and gender were included as covariates in the analyses (see Table 17).

First of all, a repeated measure ANCOVA was conducted and there was no interaction effect of time and two manipulations for the within-subjects effects. For the between-subjects effects, the results showed that level of immersion had an impact on participants' spatial presence experiences [$F(1,26) = 186.17$; $p = .002$; $\eta_p^2 = .302$].. In other words, the impacts of immersion were consistent across three posttests, and participants in the VR condition reported a higher level of spatial presence than those in the non-VR condition.

Next, a series of ANCOVAs were conducted to investigate the impacts of level of immersion and type of task load on spatial presence after a single bout (the first posttest), after two weeks (the second posttest), and after four weeks (the last posttest). In the first posttest, there was a main effect of immersion on participants' spatial presence immediately after a single bout of exergame training [$F(1,35) = 21.24$; $p = .000$; $\eta_p^2 = .378$]. However, no effect of type of task load was found in the first posttest.

Similar to the first posttest, level of immersion had an effect on spatial presence in the second [$F(1,27) = 16.33$; $p = .000$; $\eta_p^2 = .377$] and last posttests [$F(1,26) = 6.38$; $p = .018$; $\eta_p^2 = .197$]. However, type of task load still had no impact on spatial presence.

Overall, the results suggested that participants in the VR condition reported a higher level of spatial presence experiences than those in the non-VR condition. Type of task load was not a predictor of participants' spatial presence experiences. Therefore, the second hypothesis was supported but the fourth hypothesis was not.

Table 17: ANCOVAs of Spatial Presence Experiences

Across Three Posttests (N=32)	SS	df	F	P	Partial Eta^2
Age	5.290	1	.320	.576	.012
Gender	1.415	1	.086	.772	.003
Immersion	186.171	1	11.269	.002**	.302
Types of Task Load	5.850	1	.354	.557	.013
Immersion × Types of Task Load	37.988	1	2.299	.141	.081
Error	429.540	26	16.521		
Adjusted R2=.250					
The First posttest (N=41)	SS	df	F	P	Partial Eta^2
Age	3.875	1	.712	.405	.020
Gender	.082	1	.015	.903	.000
Immersion	115.662	1	21.241	.000***	.378
Types of Task Load	2.982	1	.548	.464	.015
Immersion × Types of Task Load	14.853	1	2.728	.108	.072
Error	190.586	35			
Adjusted R^2=.350					
The Second posttest (N=33)	SS	df	F	P	Partial Eta^2
Age	5.413	1	.956	.337	.034
Gender	.006	1	.001	.974	.000
Immersion	92.504	1	16.331	.000***	.377
Types of Task Load	3.095	1	.546	.466	.020
Immersion × Types of Task Load	5.371	1	.948	.339	.034
Error	152.932	27			
Adjusted R^2=.289					
The Third posttest (N=32)	SS	df	F	P	Partial Eta^2
Age	2.807	1	.372	.547	.014
Gender	2.899	1	.384	.541	.015
Immersion	48.181	1	6.383	.018*	.197
Types of Task Load	6.393	1	.847	.366	.032
Immersion × Types of Task Load	14.396	1	1.907	.179	.068
Error	196.266	26			
Adjusted R^2=.109					

4.6. Mediation Effects of Spatial Presence on Executive Functions

To test the mediating role of spatial presence experiences in the relationship between two manipulations and cognitive improvement, a series of PROCESS mediation analyses (Hayes, 2017; Model 4) were employed in each of the posttests separately. Age, gender, and baseline cognitive measures were entered as covariates and bootstrapping methods were used (5000 samples). Regarding the first posttest, there was no main effect of immersion on cognitive outcomes. Therefore, no PROCESS mediation was conducted (see Table 18).

A mediation effect was found in the second posttest, which was conducted after the two-week training. The mediation model revealed a conditional mediation effect, which showed that playing the exergame in virtual reality with a task-relevant load influenced participants' spatial presence experiences ($b = 3.446$, $p = .001$), which then influenced the speed of doing the Stroop test ($b = .277$, $p = .049$). In the task-relevant load condition, the indirect effect from the VR condition to spatial presence experiences and then to the Stroop was significant in the second posttest ([95% CI .002, .55]).

Two more mediation relationships were found in the last posttest, which was conducted after all the training sessions had been completed. The first mediation model showed that level of immersion positively influenced participants' spatial presence experiences ($b = 2.463$, $p = .01$), which then led to better Stroop results ($b = .315$, $p = .007$). The indirect effect from immersion to spatial presence experiences and then to Stroop results was significant (95% CI [.08, .55]). The second mediation relationship in the last posttest revealed that level of immersion positively influenced participants' spatial presence experiences ($b = 3.30$, $p = .005$), which then led to a better performance in trail-making in the last posttest ($b = -.124$, $p = .04$). The indirect effect from VR to the trail-making test via spatial presence was significant (95% CI [-.24, -.01]).

To sum up, spatial presence experiences conditionally mediated the effect of level of immersion on Stroop in the second posttest and fully mediated the effect of level of immersion on Stroop and trail-making in the last posttest. In other words, when level of immersion had an impact on cognitive improvement, spatial presence experience was a mediator. There was no mediated effect of immersion on participants' working memory. Therefore, H3a and H3b were supported.

Table 18: PROCESS Mediation Analysis

Stroop at the second posttest (N=17)	β	se	t	P	LLCI	ULCI
Immersion → Stroop	3.45	.70	4.94	.000***	2.00	4.89
Immersion → Spatial Presence	-1.49	.61	-2.43	.025	-2.76	-.21
Direct Effect	-.61	.45	-1.34	.191	-.155	.33
Indirect Effect	.28	.13	2.11	.048*	.01	.55
Stroop at the third posttest (N=32)	β	se	t	P	LLCI	ULCI
Immersion → Stroop	2.46	.86	2.87	.008**	.71	4.22
Immersion → Spatial Presence	3.08	.85	3.64	.001**	1.35	4.82
Direct Effect	.72	.35	2.07	.055+	-.02	1.46
Indirect Effect	.32	.11	2.88	.011*	.08	.55
Trail Making at the third posttest (N=32)	β	se	t	P	LLCI	ULCI
Immersion → Trail Making	-.53	.23	-2.27	.034*	-2.55	.86
Immersion → Spatial Presence	3.30	1.06	3.12	.005**	1.09	.51
Direct Effect	-.17	.27	-1.04	.310	-.74	.40
Indirect Effect	-.12	.06	-2.20	.040*	-.24	-0.01

LLCI=lower limit confidence interval; LLCI= upper limit confidence interval

CHAPTER 5: DISCUSSION

The current study aimed to better understand the mechanisms of cognitive improvement in exergaming by investigating the impacts of immersion and type of task load on cognitive improvement. Prior studies have suggested that exergaming with cognitively challenging tasks had a strong potential to improve people's executive functions (Anderson-Hanley et al., 2017; Best, 2013; Monteiro-Junior et al., 2016). Furthermore, exergames require players to move physically and simulate virtual environments cognitively at the same time (Anderson-Hanley et al., 2017), which is consistent with the *moving with thought* argument for cognitive improvement (Diamond, 2015).

Based on prior research, the current study argues that the process of feeling located in an immersive virtual environment can be treated as a cognitive or mental exercise of exergaming. Thus, the study designed an exergaming intervention to investigate the impacts of level of immersion and two types of cognitive load on cognitive improvement.

There were three main questions that this study aimed to answer. First, does exergaming in a more immersive environment lead to more cognitive improvement than exergaming in a less immersive environment? Second, does being in a more immersive mediated environment influence participants' cognitive improvement of exergaming? If so, does the feeling of spatial presence, a brain process elicited by level of immersion, have an impact on the relationship between level of immersion and cognitive improvement? Third, this study further investigated whether type of task load had an impact on spatial presence and cognitive improvement in the context of exergaming.

This chapter will first provide an overview of the findings and results based on different time frames. Following this overview is an interpretation of these results based on previous research. Limitations and future research directions are included at the end.

5.1. Overview of the Findings

Table 19 includes the results of the current study's hypotheses. The first hypothesis posits that level of immersion will have an impact on participants' cognitive performance. The results, including those of all three posttests, suggested that level of immersion positively influenced participants' cognitive improvement in inhibitory control (Stroop) and cognitive flexibility (trail-making), despite having no impact on working memory (backward digit span). Therefore, H1a and H1b were supported.

The second hypothesis proposes a positive relationship between level of immersion and participants' spatial presence experience. The results revealed a between-subjects effect of level of immersion on spatial presence across all three posttests, which suggested that exergaming in VR positively influences participants' feelings of presence. Therefore, the second hypothesis was also supported.

The third hypothesis posits that spatial presence will mediate the effect of immersion on participants' cognitive improvement when level of immersion has an impact on their cognitive performance. In the first posttest, no main or mediation effect was found. In the second posttest, the results of mediation analyses revealed that spatial presence conditionally mediated the effects of immersion on participants' inhibitory control (Stroop). In the last posttest, the impact of level of immersion on inhibitory control (Stroop) and cognitive flexibility (trail making) were fully mediated by spatial presence. However, no mediated effect of immersion on participants' working memory (backward digit span) was found. Therefore, H3a and H3b were supported.

The fourth hypothesis posits that type of task load has an impact on participants' spatial presence experiences. However, the results suggested that there was no difference between task-relevant and task-irrelevant load in users' spatial presence experiences in all three posttests. Thus, the fourth hypothesis was not supported.

Table 19: Results of The Hypotheses of The Current Study

	Hypotheses	Results
H1	In the context of an exergaming intervention, individuals in the high immersion condition will have a better cognitive improvement as indicated in a) inhibitory control, b) cognitive flexibility, and c) working memory than those in the low immersion condition.	H1a: supported H1b: supported H1c: rejected
H2	In the context of an exergaming intervention, individuals in the high immersion condition will have a stronger sense of spatial presence than those in the low immersion condition.	supported
H3	H3: When immersion has a main effect on cognitive functions, spatial presence will mediate the impacts of immersion on older adults' cognitive improvement in a) inhibitory control, b) cognitive flexibility, and c) working memory.	H3a: supported H3b: supported H3c: rejected
H4	In the context of an exergaming intervention, individuals in the high task-relevant load condition will report a stronger sense of spatial presence compared to people in the high task-irrelevant condition.	H4: rejected

The study's research question investigated the impacts of task-relevant and task-irrelevant load on cognitive improvement. The findings suggest that type of task load did not have a main impact on participants' cognitive improvement over the course of the four-week cognitive training. However, type of task load and level of immersion did have an interaction effect on all three cognitive measures, either at a significance or approaching significance. To be more specific, participants in the VR + task-relevant load showed more improved performance in inhibitory control (Stroop) and cognitive flexibility (trail-making) compared to the other groups across three posttests. Interestingly, participants in the non-VR + task-irrelevant load condition improved the most in working memory (backward digit span) among the four groups across three posttests. Therefore, type of task load had an interaction effect with level of immersion on cognitive improvement despite having no main effect on all dependent measures.

5.2. Summary of Findings on Different Time Frames

Table 20 shows the effects of manipulations at different time frames. In the first posttest, the results suggest that participants in the task-irrelevant load condition had more improved performance in cognitive flexibility (trail-making) immediately after a single bout of exergaming training. For those in the VR condition, task-irrelevant load also contributed to participants' cognitive improvement in working memory (backward digit span).

In the second posttest, the task-relevant load started to have an interaction effect with immersion on inhibitory control (Stroop) while the impacts of task-irrelevant load on working memory (backward digit span) and cognitive flexibility (trail making) still persisted after two weeks of exergaming training.

Table 20: The Effects of Manipulation at Different Time Frames

	After the Single Bout	After the Two-Week Training	After the Four-Week Training	**Across Three Posttests**
Inhibitory Control (Stroop)	None	VR+TR	VR VR+TR	VR VR+TR
Cognitive Flexibility (Trail-Making)	TI	TI	VR	VR VR+TR
Working Memory (Backward Digit Span)	VR+TI	Non-VR+TI	None	Non-VR+TI
VR	VR+TR	VR+TI	Non-VR+TI	TI
Virtual Reality	Virtual Reality + Task-Relevant	Virtual Reality + Task-Irrelevant	Non-Virtual Reality + Task-Irrelevant	Task-Irrelevant

In the last posttest, no main and interaction effects of the task-irrelevant load were found while level of immersion positively influenced participants' inhibitory control (Stroop) and cognitive flexibility (trail-making). An interaction effect for Stroop also suggested that participants in the VR + task-relevant load condition improved the most in inhibitory control among the four groups.

5.3. The Role of Level of Immersion on Cognitive Improvement

The main purpose of this research was to investigate the impact of immersion on cognitive improvement. The results listed above reveal that immersion was a predictor of participants' cognitive improvement in inhibitory control and cognitive flexibility. Interestingly, results across different time frames indicate that the main effect of level of immersion did not show up immediately after a single bout of exergaming. To be more specific, the main impact of level of immersion on cognitive improvement did not emerge at the early stage of the exergaming training, despite having an overall significant effect across four weeks. A possible explanation is that the underlying mechanisms responsible for cognitive improvement of short-term versus long-term exergame training may be different (Barcelos et al., 2015) and the brain processes associated with long-term cognitive benefits may be triggered by immersion.

The results, based on different time frames, further confirm the speculation that different mechanisms are responsible for cognitive improvement of short-term versus long-term exergame training. The task-irrelevant load was the main contributor of cognitive improvement in cognitive flexibility right after a single bout of exergame training, which suggested that task-switching is the main mechanism responsible for cognitive improvement of short-term training. The impacts of the task-irrelevant load on cognitive flexibility was weaker, while immersion and the task-relevant load had an interaction effect on inhibitory control after four sessions of exergame training. After eight training sessions, immersion became the main contributor of cognitive improvement while the task-irrelevant load no longer had any impact on inhibitory control and cognitive flexibility.

Multiple studies found an immediate improvement on trail-making results after a single bout of exergame training and an improvement effect on both trail-making and Stroop results after three months (e.g., Anderson-Hanley et al., 2012; Maillot et al., 2012). Some studies (e.g., Barcelos et al., 2015) also revealed that inhibitory control and cognitive flexibility are associated with brain processes other than task-switching in a long-term intervention (i.e. three months). The results of the current study found that the brain processes elicited by level of immersion are key factors of cognitive improvement of long-term exergame training. Thus, people in the VR condition had a more improved performance in cognitive flexibility and inhibitory control in long-term training, but not in the short-term.

Regarding working memory, immersion was not a predictor of participants' cognitive improvement in backward digit span in all three posttests. Contrary to the first research hypothesis (H1c), participants in the non-VR + task-irrelevant load condition improved their working memory the most over the course of the intervention. The reason may be that the game-irrelevant task was memory-based training, which improved working memory as a result of "a transfer of training effects" (Barcelos et al., 2015, p. 774). Furthermore, in the non-VR condition, participants could entirely focus on the task-irrelevant memory training task. Therefore, they had the most improved performance in working memory (backward digit span).

5.4. Spatial Presence as a Mediator between Immersion and Cognitive Improvement

The other question this study aimed to answer was, does being in a more immersive mediated environment itself influence participants' cognitive improvement of exergaming? If so, does the feeling of spatial presence, a brain process elicited by level of immersion (Monteiro-Junior et al., 2016), have an impact on the relationship between level of immersion and cognitive improvement? Research on spatial presence experiences (e.g., Hofer et al., 2012; Schubert, 2009; Wirth et al., 2007) suggest that a higher level of immersion will elicit a feeling of presence, which is a psychological and cognitive process that requires media users to mentally engage in the environment. Consistent with previous literature, the findings revealed that participants in the VR condition reported a higher level of presence.

For the mediation relationship, the results revealed that the impacts of level of immersion on trail-making and Stroop were fully mediated by spatial presence. To be more specific, spatial presence may be the reason why participants in the VR condition improved their cognitive flexibility and inhibitory control after finishing the four-week exergame training. In other words, when players felt located within the immersive mediated environment (i.e., VR) and perceived the possibility of moving in that environment, they were more likely to have cognitive improvement after experiencing presence. The underlying mechanism for the cognitive improvement may be that the process of feeling presence served as a mental exercise of exergaming and activated the brain areas associated with executive functions (Monteiro-Junior et al., 2016).

These findings also reveal that the mediating effect of spatial presence did not happen immediately after a single bout of exergaming, which suggests that it takes time for spatial presence to make an impact on participants' cognitive improvement. An unexpected and non-significant finding was that spatial presence was not a mediator between immersion and backward digit span, which indicates that the feeling of presence as a mental exercise did not contribute to the improvement of working memory. It may be that spatial attention only contributed to spatial-related ability, such as spatial orientation and spatial working memory (Fabius, Mathôt, Schut, Nijboer, & Van der Stigchel, 2017), but not digit-related working memory.

5.5. Task-relevant vs. Task-irrelevant Load on Cognitive Improvement

Previous research has examined the impacts of cognitive demands and challenges in the context of exergames, with an emphasis on the comparison between high versus low cognitive demands (e.g., Anderson-Hanley et al., 2012; Maillot et al., 2012). However, the definitions and manipulations of cognitive demands were different across studies, and type of cognitive load were not discussed. This study further investigated the impacts of task-relevant versus task-irrelevant load on spatial presence and cognitive improvement in the context of exergaming.

This study's hypothesis that the task-relevant load would lead to a higher level of presence than the task-irrelevant load, however, was not supported by the data. It may be that participants did not increase, or decrease, their attention allocation to the mediated environment based on the type of task load. Another speculation is that merely being in the VR condition provided participants with enough information to build a spatial situational model. Even though type of task load affected the participants' attention allocation to and cognitive improvement in the mediated environment, they could still create a strong spatial situational model for the feeling of spatial presence.

Furthermore, cognitively engaging tasks have been found to contribute to cognitive improvement in the context of exergaming (Barcelos et al., 2015; Best, 2013), but the impacts were not consistent due to different definitions of cognitively engaging tasks; some studies focused on task-relevant (gaming-relevant) mental effort (e.g., Anderson-Hanley et al., 2017; Best, 2012) while others focused on task-irrelevant (non-gaming relevant) tasks (e.g., Radovanović et al., 2014). However, limited research compares the impacts of these two types of mental exercise on cognitive improvement within the context of exergaming.

This research explored whether the type of cognitive load influence executive functions differently during exergaming. Two competing theories were introduced to answer the research question of this study: perceptual load theory and the process model of spatial presence experiences. First, perceptual load theory (Lavie, 1995, 2005) predicts that people playing the exergame in a high task-irrelevant load condition will have to allocate their attentional and cognitive resources to both types of tasks, which requires the use of their cognitive functions. In this sense, dealing with task-unrelated distractors in the low task-relevant load condition will improve cognitive performance due to the practice of splitting attention. However, the process model of the formation of spatial presence experiences (Wirth et al., 2007) predicts that people cannot devote their full attentional resources to the mediated environment, so they are less likely to invest their cognitive resources and engage in the formation of spatial presence experiences. In other words, dealing with task-unrelated distractors in the low task-relevant load condition will not improve cognitive performance due to the lack of spatial presence.

This study's results suggest that both types of task load did not have a main effect over the course of four weeks. Instead, an interaction between level of immersion and type of task load was found across the four-week training. This is consistent with previous studies on the impacts of level of cognitive demands and load (e.g., Best, 2012), which found that cognitive demands and load moderated the effects of physical activity of exergaming on cognitive improvement in older adults despite having no main effect. In the current study, type of task load made the effect of level of immersion on inhibitory control and cognitive flexibility more salient during the intervention. One speculation is that playing a more difficult game (task-relevant load), which required more spatial attention and orientation, moderated the impact of immersion on cognitive improvement across the four-week training.

The findings, based on different time frames, reveals that the task-irrelevant load had an impact on cognitive flexibility right after a single bout of exergaming, but the effect started fading after the second week of training. No effect of task-relevance was found on cognitive flexibility and inhibitory control in the last posttest. One speculation is that participants in the task-irrelevant load condition might have developed a strategy to deal with the game-irrelevant task after two weeks, so they did not require the same amount of executive functions to process the two tasks separately as they needed in the first posttest, which was less likely to prime the use of their executive functions for the cognitive measures later.

The results, based on different time frames, also suggest that the task-relevant load had an interaction effect with immersion on inhibitory control across times in the second and last posttests. One possible explanation is that dealing with a game-relevant task in the immersive environment required participants' spatial attention and orientation to target certain fruits and avoid hitting bombs, which also amplified the impacts of immersion on participant's inhibitory control. No interaction effects between level of immersion and task-relevant load were found in the first posttest. A possible reason may be that the mechanisms for cognitive improvement of short-term versus long-term training were different, and VR + game-relevant load were more likely to contribute to the improvement of inhibitory control in the longer-term training (i.e., two weeks and four weeks). One speculation for the time effect of immersion is that it requires more time or training sessions for people to be familiar with the virtual environment and allocate their spatial attention to the environment, especially for people who did not have many gaming experiences. Future research could include neuroscientific evidence (e.g., functional magnetic resonance imaging and electroencephalography) to investigate whether there is a difference in brain functional connectivity or other brain activities associated with executive functions between different time frames.

The results, based on different time frames, also show complicated and unexpected interaction effects of task-irrelevant load and level of immersion. In the first posttest, an interaction effect was found: the task-irrelevant load had a stronger impact on participants' performance in the VR condition than on those in the non-VR condition. One speculation is that people dealt with the task-relevant and task-irrelevant loads differently. People in the VR condition had to process two incompatible loads at the same time, which is different from people in the VR+ task-relevant load condition. In addition, the manipulation of the task-irrelevant load was a memory-based task, which served as a practice of the working memory task, and VR served as a distraction for the participants to use their executive functions to keep those numbers in mind. Therefore, they had a better performance in working memory right after the first exergame training.

The interaction effects of the task-irrelevant load and level of immersion on participants' working memory showed a different pattern in the second posttest. Participants in the non-VR condition with the task-irrelevant load improved their working memory the most among the four conditions. An explanation for this interaction effect is that people in the VR condition have already developed a strategy to process these two loads with minimum mental effort and people in the non-VR condition can pay more attention to perform the assigned memory tasks. Therefore, people in the non-VR+ task-irrelevant load condition, instead of those in the VR+ task-irrelevant load condition, had a better performance in working memory among the four groups. Moreover, no effect was found on the last working memory posttest, which may have resulted from the participants' familiarity with the memory tasks, although they still reported a similar level of mental effort as in the previous two posttests.

5.6. Summary of Discussion

Overall, level of immersion had an impact on inhibitory control (Stroop) and cognitive flexibility (trail-making). Furthermore, an interaction effect between level of immersion and type of task load was found on inhibitory control, with the results showing that VR and task-relevant load led to a better performance in Stroop. When immersion had a positive impact on participants' cognitive performance, spatial presence mediated the relationship. These findings suggested that spatial presence, elicited by the immersive virtual reality, was involved in a cognitive process, which later led to an improved performance in visual processing speed and inhibitory control. Regarding working memory, using a game-unrelated memory task would directly contribute to participants' working memory.

The results, based on different time frames, further suggested that the underlying mechanisms responsible for cognitive improvement are different in short-term and long-term effects. The task-irrelevant load had a training effect. The immediate effect of the task-irrelevant load on working memory may suggest "a transfer of training effects" (Barcelos et al., 2015, p. 774) after dividing their attention between two tasks when playing the exergame in the low-difficulty mode and memorizing a seven to nine-digit number at the same time. After four training sessions, immersion and task-relevant load condition started to interact on participants' inhibitory control. In the last posttest, the impacts of task-irrelevant load no longer existed on cognitive flexibility, immersion had a main effect on cognitive flexibility, and had both main and interaction effects on inhibitory control. Therefore, immersion and task-relevant load were responsible for the long-term effect while task-irrelevant load was responsible for the short-term effect.

5.7. Limitations

Like previous studies of exergaming for cognitive improvement, this longitudinal study is not without limitations. First of all, the majority of the participants were white (90.2%) and most were females (73.2%). There was only one male participant in one condition (non-VR + task-irrelevant condition). Also, the results of this study may not be able to apply to all older adults since the average of the participants was 61 years old, which was considered as young older adults. Thus, the study's findings may not be able to be generalized to all populations. Future research could include more participants and make the sample more similar to the demographic or specifically targeting at people considered as older adults (i.e. aged 65 or older).

Second, small sample sizes and missing responses may decrease statistical power. However, this limitation was common in the previous studies due to limited resources. Furthermore, the adherent rate of the current study (96.9%) was higher than similar studies (Barcelos et al., 2015). Therefore, this limitation was not considered a threat to internal validity or statistical power. Future studies should consider implementing a large-scale longitudinal exergaming intervention given that the researchers have enough resources.

Third, similar to previous research on the impacts of exergaming on cognitive improvement, this research found an immediate effect after a single-bout of exergaming and also a long-term effect after the completion of four-week training. However, the current study could not predict how long the impacts would last. Previous studies on cognitive and physical interventions showed that the improvements after interventions (e.g., ten training sessions) continued for two years, and the effects of some training programs continued up to seven years.

The results can provide insight into the potential impact of the current study. Future studies should further investigate the long-term impact of interventions on executive functions.

Fourth, participants knew how well they performed when they did the backward digit span measure. In other words, they knew it was a memory task and could figure out how many digits they successfully memorized and how well they performed. If the participants did not perform very well at the beginning, they might have stopped trying to finish the task. Future studies should incorporate other working memory measures in which participants will be unaware of their performance. In addition, the relationship between exergaming and working memory might be different from exergaming and other executive functions (e.g., inhibitory control and selective attention). It is recommended that future research should further investigate what characteristics of exergaming would contribute to the improvement of working memory, including other types, such as spatial working memory.

In addition, previous studies showed that the impacts of exergaming on working memory, inhibitory control, and cognitive flexibility were different and suggested that the relationship between exergaming and working memory might be different from exergaming and inhibitory control or exergaming and selective attention (Barcelos et al., 2015). It is recommended that future research should further investigate what characteristics of exergaming would contribute to the improvement of working memory, including other types such as spatial working memory.

Fifth, it is hard to tell whether people allocated their attention to the memory tasks first and then to the game or the other way around. This study asked participants to try their best to perform both tasks well. Still, two participants did not focus on the game-irrelevant task and two participants failed to try their best to play the game in different time frames. As a result, these participants were excluded from data analysis. Future research could design better game-irrelevant tasks that participants would be more engaged in doing.

Sixth, the study used a self-reported screening survey to recruit cognitively and physically healthy participants. Future study could include neuroscientific measures to better assess participants' cognitive functions before the training.

Seventh, the results suggested that the impacts of immersion did not happen until participants finished their fourth training (two weeks). However, it is not clear whether long-term effect of immersion on cognitive improvement was a result of a time effect (i.e., requiring two weeks for the effect to show up) or dosage effect (i.e., requires four training sessions for the effect to show up). Future studies could separate these factors (e.g., four sessions in one day vs. four sessions in two weeks) to evaluate the cognitive improvement.

CHAPTER 6: CONCLUSION

This exploratory study of the cognitive benefits of exergame training for older adults particularly focused on the roles of level of immersion and type of task load. Overall, the findings suggest that the combination of virtual reality technology and exergames contributed to cognitive improvement in older adults in the four-week exergame training. Moreover, the feeling of presence mediated the impact of VR on cognitive improvement in the context of exergaming. The results, based on different time frames, further confirmed that the mechanisms responsible for older adults' cognitive improvement are different between short-term and long-term training.

This study has both theoretical and practical implications. Theoretically, this study adds to the literature that investigates the characteristics of exergames and improvement of executive functions. The results of this study support the concept of cognitive reserve (Stern, 2012), which argues that cognitive training interventions may be able to slow down the level of cognitive decline and maintain cognitive functions as much as possible. Specifically, brain reserve, which emphasizes *hardware* characteristics such as brain volume and neuronal structural integrity, can be strengthened by the physical exercise of exergaming, and cognitive reserve, which highlights the *software* aspects such as cognitive functioning and plasticity of neural circuits, can be boosted by the mental exercise (i.e., feeling of presence). The current research suggests that being in the VR condition required participants' cognitive resources to locate themselves in the virtual environment and perceive their actionable possibilities, which increases the amount of mental exercise during exergaming.

Previous studies suggested assessing potential mediators or moderators (Barcelos, et al., 2015) on the relationship between exergaming and neurobiological/neuropsychological benefits.

The current study applied the theoretical framework of spatial presence experiences to exergame scholarship and revealed that immersion had a positive impact on executive functions after the four-week training and spatial presence was a mediator between immersion and cognitive improvement.

Furthermore, the current research found that both perceptual load theory and the formation model of spatial presence experiences can be used to explain the results. Perceptual load theory can be used to explain the mechanism responsible for cognitive improvement in exergaming with a task-irrelevant load in short-term training, and the formation model of spatial presence can be used to explain the impacts of a task-relevant load and spatial presence on cognitive improvement in long-term training.

Regarding practical implications, the preliminary results of this four-week exergame training suggests that immersive technologies for health would be an effective tool to increase the intensity of physical and mental exercises (Blondell et al., 2014), which could be applied to both daily life and clinical settings. For older adults, playing virtual reality-based exergames two times per week for one month showed greater cognitive improvement compared to a similar dose of non-VR exergames.

This study shows the possibilities of applying the latest media technologies to exergaming, which amplifies the advantages of exergames — having the benefits of physical activity and attractiveness of video games. VR technologies have the potential to facilitate enjoyment and promote repeated use. Furthermore, the results suggested that the process of feeling presence served as a mental exercise within exergaming and activated brain areas associated with the use of executive functions. In this sense, VR-enhanced exergames, which combine physical and mental exercise, can serve as a good alternative for traditional exercise without the limitation of time and space. As VR technologies become more popular and affordable, individuals who want to ameliorate cognitive decline or avoid cognitive deficits may benefit from the use of exergaming in VR environments. This research also provided some suggestions for the design and development of exergames. The findings of the current research have shown that VR exergaming is beneficial for older adults' executive functions, and that the requirement of spatial attention and orientation may be the reason why older adults benefit from exergaming. In the future, the design of exergames could emphasize game features that require players' spatial attention and orientation, such as avoiding or locating certain objects, to provide novel strategies for preventing cognitive decline in older adults.

APPENDIX

RESEARCH PROTOCOL

Overview

- Recruit through community SONA (a screening survey asking if they can play games without glasses or with contact lenses)
- Room 511
- Set up equipment
- Pre-experiment online survey through SONA
- Pre-game Cognitive Tasks
- Play game for 20 minutes
- Post-game Questionnaire
- Schedule the appointment time for the next session (up to 8 sessions)
- Total time in lab: 30-35 mins

Equipment and software

- Computer
- Monitor/ TV screen
- Oculus Rift
- Xbox Kinect Motion Sensor
- Consent form (in the pre-test survey)
- Online questionnaires
- Experimenter sheet
- Dual-task response software (Inquisit 5.0)

Pre-Experiment

- Set up hardware
- Make sure the Oculus lenses are clean
    - Use the air bulb to remove dust/particles
    - Use the microfiber cloth to gently remove any grease/smudges from the lenses
- Open the software for pre-game cognitive tasks as well as a webpage with the post-game questionnaire
- Researcher answer the first question in the questionnaire (which condition the participant is in). Double check the schedule if you've chosen the right ones!

- Load the game and double check the schedule and the conditions again
    - Oculus/Zen Mode + memorizing a 10-digit number
    - Oculus/ Survival Mode
    - Screen/ Zen Mode+ memorizing a 10-digit number
    - Screen/ Survival Mode
- Enter participant's number and condition.
- Check settings of oculus rift. If participants are in the Oculus Condition, check if the light of Oculus Rift is on (blue). If participants are not in the Oculus Condition, make sure the Oculus Rift is off

Participant Arrives

- Explain Study:
  "This study is about the relationship between playing video games and health improvement. This is a 4-week study and consists of 8 sessions. This is the first session and we highly encourage you to finish 8 sessions. To thank you for your continued participation you will be paid each consecutive week you complete."
  ""Before the study starts, we will ask you to sign the consent form. If you consent to participate our study, you will be playing a video game in a virtual environment. You will be asked to do 3 tasks before and after you play a video game for 20 minutes. This video game will require your body movement to move to control the games. Please let me know if you have any questions or concerns."
- Sign the online Consent Form:
  "Please read this consent form thoroughly so that you understand it. Please let me know if you have any questions or concerns."

Details for conditions

Task-relevant load | 2 conditions: (High vs. Low immersion)

Double check they are in the survival mode

"Today you will be exploring the games using the [Oculus Rift/ TV] and the Oculus Controller. You will only need to use this equipment to play the video game.

Then adjust the sizing of the straps of the Oculus rift or the distance between the participant and the TV screen.

"Let me know if you have any issue on controlling or seeing objects in the games."

"You will have a minute to practice controlling the game. After that, you will be asked to play a game. If you feel uncomfortable or motion sickness, you can stop at any point during your game play."

After 20 minutes, Stop the experiments and assist in removing equipment and or help the participant to get back to the seat.

"Ok, that's it, we are going to stop here [and I'm going to take off the headphones and Oculus now]."

"Alright, let's do the cognitive tasks again and also fill out another survey."

Load the software for cognitive tasks and the Qualtrics questionnaire on computer monitor.

"Thank you for coming in today. This is the 15$ and we thank you for coming to this study. We also encourage you to keep participating this study and sign up for the next session now."

If they agree to stay in the intervention, then schedule the next session.

After the participant has left, open the window to let in some fresh air. Close it before the next participant arrives.

Task-irrelevant load | 2 conditions: (High vs. Low immersion)

Double check they are in the zen mode

"Today you will be exploring the games using the [Oculus Rift/ TV] and the Oculus Controller." You will only need to use this equipment to play the video game.

Then adjust the sizing of the straps of the Oculus rift or the distance between the participant and the TV screen.

"Let me know if you have any issue on controlling or seeing objects in the games."

“You will have a minute to practice controlling the game. After that, you will be asked to play a game. If you feel uncomfortable or motion sickness, you can stop at any point during your game play.”

Before starting the game, use an online randomizer to generate a 10-digit number and give the participant 1 minute to memorize.

“You should try your best to memorize this 10-digit number when you play the game. We will ask you to report this number after the 20-minute gameplay.”

After 20 minutes, Stop the experiments and assist in removing equipment and or help the participant to get back to the seat.

"Ok, that’s it, we are going to stop here [and I’m going to take off the headphones and Oculus now].”

“Alright, let’s do the cognitive tasks again and also fill out another survey.”

Load the software for cognitive tasks and the Qualtrics questionnaire on computer monitor.

“Thank you for coming in today. This is the 15$ and we thank you for coming to this study. We also encourage you to keep participating this study and sign up for the next session now”

If they agree to stay in the intervention, then schedule the next session.

After the participant has left, open the window to let in some fresh air. Close it before the next participant arrives.

Instruction of Game Play- Zen Mode

Fruit Ninja is very intuitive to play.

Kinect: Your arms are swords. VR: Your holding swords.

Use your swords to slice fruit as it flies across the screen

All fruit, no bombs. A great way to relax or hone your ninja skills.

Instruction of Game Play- Survival Mode

Fruit Ninja is very intuitive to play.

Kinect: Your arms are swords. VR: You are holding swords.

Use your body to slice fruit as it flies across the screen

All fruit, no bombs. A great way to relax or hone your ninja skills.

Face off against flying cannons! Slice fruit, avoid bombs

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