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Exergaming in Older Adults: Exercise for Body and Brain

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by

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Abstract

Exergaming has been demonstrated to be an effective method for cognitive and physical training and is used in clinical settings for older adults. The variety of games and settings allows for a wide range of movements and thus provides many opportunities for engagement. In order to plan an effective exergaming intervention, it is necessary to adapt the training to individual goals and abilities. This thesis monitors the cognitive demand and physical activity levels during an exergaming intervention and examines the impact of game characteristics on gameplay. Twenty-eight healthy older adults participated in a four-week exergaming intervention, playing two different exergames. Brain activity, physical activity, and perceived exertion (RPE) during exergaming were repeatedly monitored. In a cross-sectional approach, Paper 1 showed that frontal theta activity increased during exergaming compared to just performing movements and thus may be suitable to describe cognitive involvement. In addition, physical activity decreased with increasing game difficulty. Paper 2 confirmed this relationship longitudinally. Furthermore, tailoring the speed of the game led to an increase in physical activity and physical RPE compared to a game with fixed demands. Paper 3 demonstrated increased cognitive involvement during exergaming at all time points for both games and difficulty levels, which was unaffected by habituation or learning. These findings illustrate that game characteristics affect how people play and need to be considered. This thesis provides a basis for the development of individually tailored exergaming interventions based on specific internal training load measures.

Deutsche Zusammenfassung

Exergaming ist wirksam für kognitives und körperliches Training und findet Anwendung in Prävention und Rehabilitation älterer Menschen. Die Vielfalt der Spiele ermöglicht unterschiedliche Bewegungen und zahlreiche Einsatzmöglichkeiten. Für eine effektive Exergaming-Intervention ist eine Anpassung des Trainings an individuelle Ziele und Fähigkeiten notwendig. Diese Arbeit untersucht die kognitiven Anforderungen und das körperliche Aktivitätsniveau während einer Exergaming-Intervention sowie die Auswirkungen der Spieleigenschaften auf das Spielverhalten. Achtundzwanzig gesunde ältere Erwachsene nahmen an einer vierwöchigen Exergaming-Intervention teil und spielten zwei Exergames. Gehirnaktivität, physische Aktivität und empfundene Anstrengung (RPE) während des Spielens wurden wiederholt gemessen. In einem Querschnittansatz zeigte Paper 1, dass frontale Theta-Aktivität beim Spielen im Vergleich zur reinen Bewegungsausführung erhöht war und somit die kognitive Beteiligung beschreiben kann. Auch die körperliche Aktivität nahm mit steigendem Schwierigkeitsgrad ab. Paper 2 bestätigte dies im Längsschnitt und zeigte, dass individualisierte Spielgeschwindigkeit zu einem Anstieg der körperlichen Aktivität und des physischen RPE führt im Vergleich zu einem Spiel mit festen Anforderungen. Paper 3 zeigte, dass die frontale Theta-Aktivität während des Spielens zu allen Zeitpunkten für beide Spiele und Schwierigkeitsgrade zunahm. Diese Ergebnisse zeigen, dass Spieleigenschaften das Spielen beeinflussen und daher berücksichtigt werden müssen. Somit liefern sie eine Grundlage für die Entwicklung von Exergaming-Interventionen basierend auf individuellen Trainingsanforderungen.

Norsk sammendrag

Exergaming har vist seg å være en effektiv metode for kognitiv og fysisk trening, og brukes mer og mer i trening og rehabilitering for eldre. De mange ulike spillene og innstillingene gir muligheter for en rekke ulike bevegelser og dermed mange ulike bruksområder. For å kunne planlegge en effektiv exergaming-intervensjon er det nødvendig med individuell tilpassing av treningen. Denne avhandlingen kartlegger kognitive krav og fysisk aktivitetsnivå i løpet av en exergaming-intervensjon, og undersøker hvordan spillets egenskaper påvirker spillingen. Tjue-åtte friske eldre deltok i en fire ukers exergaming-intervensjon, der de spilte to ulike spill. Hjerneaktivitet, fysisk aktivitet og opplevd anstrengelse (RPE) under spillingen ble målt regelmessig. I en tverrsnitts studie viste artikkel 1 at frontal theta-aktivitet økte under exergaming sammenlignet med å bare utføre bevegelser og derfor kan være egnet til å beskrive kognitiv involvering. I tillegg avtok den fysiske aktiviteten med økende vanskelighetsgrad i spillet. Artikkel 2 bekreftet dette forholdet i en longitudinell studie. Denne studien viste også at tilpasning av spillets hastighet førte til en økning i fysisk aktivitet og fysisk RPE sammenlignet med et spill med faste krav. Artikkel 3 viste økt kognitiv involvering under exergaming på alle tidspunkter for både spill og vanskelighetsgrad, noe som var upåvirket avtilvenning eller læring. Disse funnene viser at spillets karakteristikker påvirker hvordan folk spiller og må tas i betraktning. Denne avhandlingen gir grunnlag for utvikling av individuelt tilpassede exergaming-intervensjoner basert på spesifikke mål for intern treningsbelastning.

Declaration of Authorship

I declare to have read and accepted the PhD regulations of the Faculty of Sciences, University of Paderborn (no. 10.21, 31-03-2021) and Faculty of Medicine and Health Science, Norwegian University of Science and Technology (no. 207, 05-12-2018). Furthermore, I declare that the work presented in the present thesis is original and the result of my own work, except as acknowledged, and has not been submitted, neither in parts nor as a whole, for any other degree or qualification at another University. Content and ideas taken from other sources are - to the best of my knowledge and belief - cited correspondingly. As such, I declare that the research presented in the studies included was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

H.Müller

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“In every job that must be done there is an element of fun.”

Mary Poppins

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List of Publications

This cumulative dissertation is based on the following manuscripts:

Paper 1

Müller, H., Baumeister, J., Bardal, E. M., Vereijken, B., & Skjæret-Maroni, N. (2023). Exergaming in older adults: the effects of game characteristics on brain activity and physical activity. *Frontiers in Aging Neuroscience*, *15*(May). https://doi.org/10.3389/fnagi.2023.1143859

Paper 2

Müller, H., Skjæret-Maroni, N., Bardal, E. M., Vereijken, B., & Baumeister, J. (2024). Exergaming interventions for older adults: The effect of game characteristics on gameplay. *Experimental Gerontology*, *197*(October), 112610. https://doi.org/10.1016/j.exger.2024.112610

Paper 3 (under Review)

Müller, H., Büchel, D., Skjæret-Maroni, N., Vereijken, B., Baumeister, J. (2025). Monitoring Cognitive Load while Playing Exergames in a Four-Week Intervention for Older Adults: An explorative EEG Study. *Submitted for publication in Scientific Reports*

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List of Abbreviations

ACC	anterior cingulate cortex
ASR	artifact subspace reconstruction
BCI	brain-computer-interface
CBMS	community balance and mobility scale
CRUNCH	compensation-related utilization of neural circuits hypothesis
EEG	electroencephalography
ERP	event-related potential
FES-I	falls efficacy scale–international
fNIRS	functional near-infrared spectroscopy
HR	heart rate
ICA	independent component analysis
IC	independent component
MoCA	Montreal cognitive assessment
NFT	neurofeedback training
PASE	physical activity scale for the elderly
RPE	rate of perceived exertion
VAS	visual analog scale

1 Introduction

1.1 Motivation and Significance

Fall down. Stand up. Straighten your crown. Carry on.

This proverb can help us through the ups and downs of life. However, as we age, there may come a time when we experience a fall and cannot stand up again. The process of aging is often associated with functional decline and an increased risk of disease. This can result in a range of adverse outcomes, including cognitive impairment, frailty, and increased risk of falls. Addressing these challenges will become increasingly important as the world's average age continues to rise. In a significant number of countries, more than one in five people is over the age of 60 years. For the first time in history, the majority of people will reach this advanced age (World Health Organization, 2015). This demographic shift highlights the urgent need for effective strategies to prevent functional decline associated with aging.

Physical activity has been demonstrated to counteract the age-related functional decline and enable healthier aging (Cunningham et al., 2020). However, the prevalence of physical inactivity and sedentary lifestyle across all age groups means that physical activity recommendations are often not met, thereby increasing the risk of functional decline, obesity and chronic disease (Cunningham et al., 2020; Izquierdo et al., 2021), as well as cognitive decline (Yamasaki, 2023).

One potential strategy for promoting physical and cognitive training is the use of exergames. These virtual games that are controlled by physical movements are increasingly being used in a variety of settings, including rehabilitation. There is growing evidence that exergames can improve both physical and cognitive functioning in older adults (Jiang et al., 2022; Suleiman-Martos et al., 2022). Nevertheless, it has been demonstrated that the implementation of individually tailored training protocols can lead to more pronounced training effects (Wollesen & Voelcker-Rehage, 2014). Therefore, it is essential to not only assess the impact of exergaming interventions, but also to monitor the effects of exergaming on the game play during the intervention itself.

Previous studies have employed a range of methods to assess the physical component of exergaming during gameplay. These include the use of heart rate (HR) measurement (Moholdt et al., 2017), motion capture-based methods for analyzing movements (Anders, Bengtson, et al., 2020; Skjæret-Maroni et al., 2016), or accelerometers (Skjæret-Maroni & Bardal, 2018). Regarding the cognitive component during exergaming, mobile electroencephalography (EEG) measurements may prove a viable option. It is notable that the number of studies investigating neurophysiological correlates of exergaming is limited (e.g. Anders et al., 2018; Baumeister et al., 2010; Ghani et al., 2021; Knols et al., 2017; Ko et al., 2020). However, they indicate that frontal theta and central and parietal alpha-2 activity could serve as potential parameters for describing cognitive involvement during exergaming (Anders et al., 2018; Baumeister et al., 2010).

This thesis aims to investigate the impact of exergaming on cognitive and physical activity in older adults across an exergaming intervention. Furthermore, the influence of game characteristics, such as difficulty level or game speed, will be investigated both in the short-term (single session) and in the long-term (four-week intervention). The findings of this research provide insights that could support the future use of exergames in an individualized manner to improve healthy aging.

1.2 Age-related functional decline

1.2.1 Challenges of aging

For many of us, the goal may be to grow old and to live happily ever after. But we are not part of a fairy tale, and age-related physical and cognitive decline, or illness may prevent us from achieving this goal. In the real world, living happily ever after means aging successfully. In this context, successful aging means developing and maintaining the functional capacity and competence that enable a high quality of aging. This multidimensional approach includes biomedical aspects such as disease prevention and good physical and cognitive function, as well as psychosocial factors such as psychological adjustment and active engagement in life (Urtamo et al., 2019). Research shows that it is important for older adults to maintain as much autonomy as possible (Fjordside & Morville, 2016). Living independently, shopping for groceries, preparing a meal, or meeting friends for coffee are all examples of activities that are taken for granted in younger years. However, the functional ability to perform these daily tasks is threatened by the normal level of functional decline that occurs with advanced age. Following the definition of de Vos et al. 2012, in this thesis age-related functional decline is defined as a change in either physical or cognitive function, and these changes affect the ability to care for oneself at home in order to maintain independence (de Vos et al., 2012). To live as long and as independently as possible, the most effective strategy would be to delay, reduce, or prevent the age-related functional decline (Seals et al., 2016). One approach to understanding functional decline in older adults is the Functional Spiral Model (Whitehead, 2019). It highlights how attitudes toward aging significantly influence physical activity, which in turn influences long-term functional ability. Positive attitudes toward aging encourage more physical and social engagement, which helps to maintain functional ability, while negative attitudes lead to reduced activity and faster decline. The spiral captures the compounding effect of these behaviors. Engaging in physical and mental activities early in life and continuing them consistently can prevent or delay decline later in life. This creates an upward spiral of better health, while inactivity can create a downward spiral of decline. The model emphasizes the link between physical and cognitive health. Staying active not only improves physical abilities but also supports mental well-being, creating a virtuous circle that benefits overall quality of life (Whitehead, 2019).

To illustrate the downward spiral, consider Mr. Smith, who is a 68-year-old retiree who enjoys walking with his friends, but has not exercised in decades. When he begins to experience knee pain, he develops a negative attitude toward aging, believing that pain and frailty are inevitable. As a result, he reduces his physical activity, avoids walking, and becomes more isolated. This leads to muscle weakness, weight gain, and an increased dependence on assistive devices. His downward spiral accelerates, leading to a further decline in his physical and mental health, ultimately affecting his independence and overall well-being. As a result, Mr. Smith may need assistance with daily tasks such as shopping or preparing a meal.

Aging, functional decline and dependency are closely related (Whitehead, 2019). To better understand the reasons for Mr. Smith’s situation, the following chapter summarizes physiological changes that may also occur in Mr. Smith’s body.

1.2.2 Physiological causes

Biological aging is a multifactorial process involving interrelated molecular and cellular phenomena. It is characterized by a reduction in the reparative and regenerative potential of tissues and organs, resulting in a functional decline in multiple physiological systems (Khan et al., 2017). This decline is driven by homeostatic imbalances in various biological mechanisms and manifests at the molecular, cellular, organ, and organismal levels (Ferrucci et al., 2020). In particular, the aging process is heterogeneous among individuals and may not correspond directly to chronological age. Moreover, different organ systems show different degrees of vulnerability to age-related changes (Khan et al., 2017).

The cardiovascular system, for instance, becomes progressively more vulnerable to age-related pathologies such as hypertension, congestive heart failure, atrioventricular block, and aortic stenosis. Atherosclerosis, in particular, has been linked to premature biological aging (Khan et al., 2017). Furthermore, pulmonary function declines with age, as evidenced by a drop in peak aerobic capacity of more than 20% per decade after age 70, contributing to diminished physical endurance (Fleg et al., 2005). Additionally, older adults are more prone to respiratory infections, such as pneumonia, as a result of weakened immune defenses.

Regarding neurological function, cognitive decline is a hallmark of the aging process. According to Ridderinkhoff & Krugers (2022), the aging brain is subject to various metabolic and oxidative challenges, which render neurons vulnerable to decline. At the same time, the potential capacity of appropriate defense mechanisms is reduced. Over time, this can lead to cognitive and functional changes that may vary from individual to individual, depending, for example, on "environmental" challenges experienced and defense mechanisms that may be more genomic in nature (Ridderinkhof & Krugers, 2022). This decline is the result of two primary factors: structural changes in the brain and alterations in synaptic plasticity. From a structural perspective, the brain shrinks, accompanied by a decline in the integrity of both white and gray matter. This is particularly evident in regions such as the lateral prefrontal cortex, the cerebellar hemispheres, and the hippocampus. In contrast, the parietal, temporal, and occipital regions demonstrate relative stability in volume with age (Park & Reuter-Lorenz, 2009). These structural changes require older adults to recruit additional brain regions to perform tasks as accurately as young adults, as postulated by the Compensation-Related Utilization of Neural

Circuits Hypothesis (CRUNCH). While this compensatory mechanism enables older adults to maintain task performance, increased cognitive demands can eventually exceed their neural capacity, resulting in slower responses and an increased likelihood of errors (Reuter-Lorenz & Cappell, 2008). Functional MRI studies have demonstrated a decline in coordinated activation in brain regions involved in higher-order cognitive functions, indicating a global loss of integrative capability with age (Andrews-Hanna et al., 2007).

The musculoskeletal system also undergoes significant changes with aging. Muscle mass and contractile force decrease, limiting mobility (Distefano & Goodpaster, 2018). This loss of muscle mass, known as sarcopenia, is exacerbated by the infiltration of fat and connective tissue into the muscles (Reinders et al., 2015) . Muscle strength, particularly in the lower extremities, plays a critical role in maintaining balance and gait (Lord et al., 2018), and the muscles responsible for stabilizing the legs experience a greater decline than the primary movers (Daun & Kibele, 2019).

Another significant contributor to functional decline is age-related sensory impairment. Visual acuity, visual field, color perception, and depth perception all decline with age, which impairs the ability to safely navigate one’s environment (Salvi et al., 2006). Hearing loss, especially sensorineural hearing loss, results from the loss of sensory cells and the death of cochlear neurons. Proprioception, the body's ability to sense and control movement, also declines with age due to a decrease in muscle spindle density (Henry & Baudry, 2019) and mechanoreceptor sensitivity (García Piqueras et al., 2019) in the skin, especially in the feet. This makes it more difficult for older adults to accurately perceive the position of their feet, especially when wearing shoes, increasing the likelihood of balance problems (Osoba et al., 2019).

The vestibular system, which is responsible for detecting head position and movement, plays a crucial role in maintaining balance while standing and moving (Lord et al., 2018). However, this system also undergoes an age-related decline, which can result in difficulties maintaining one’s focus on objects while walking and an increased risk of dizziness. Furthermore, the transfer of sensory input from sensory organs to the central nervous system is hindered by reduced conduction velocity (Henry & Baudry, 2019), which slows down motor responses and increases the likelihood of errors in movement coordination.

In conclusion, the physiological decline associated with aging affects multiple organ systems, contributing to decreased cardiovascular, pulmonary, neurological, musculoskeletal, and sensory functions. This decline is driven by cellular, structural, and functional changes across the body. The progressive nature of age-related deterioration has a significant impact on all aspects of the lives of older individuals.

1.2.3 Risks and consequences

The physiological age-related decline affects various biological systems, resulting in far-reaching consequences on physical and cognitive functioning. As muscle mass and strength decrease with age (sarcopenia), older adults experience a reduction in mobility and balance (Distefano & Goodpaster, 2018). Moreover, the decline in cardiovascular and pulmonary function reduces endurance and exercise tolerance, rendering older adults more prone to fatigue and less capable of maintaining physical independence. This impairs the ability to perform everyday activities such as standing up, climbing stairs, or walking a longer distance. Furthermore, age-related cognitive decline manifests in a decline in cognitive abilities, including episodic and prospective memory, executive function, selective and divided attention, working memory, and processing speed (Oschwald et al., 2020). From the age of 65 years, older adults exhibit a decline in fluid cognitive abilities, including executive functions, processing speed, working memory, and episodic memory. Conversely, crystalline cognitive functions such as general intelligence or semantic memory remain relatively stable (Park & Reuter-Lorenz, 2009).

Let's return to Mr. Smith, who was in the downward spiral of the functional spiral model (Whitehead, 2019). After perceiving knee pain, he develops a negative attitude toward aging, avoids walking, and isolates himself by staying at home. In addition, he experiences feelings of insecurity and instability while walking, and one day he falls while trying to go down the stairs. Fortunately, he suffers only bruises and no fractures. How could this happen?

Both the cause and the effect of age-related decline may be falls. A fall is defined as "inadvertently coming to rest on the ground, floor, or other lower level, excluding intentional change in position to rest in furniture, wall or other objects" (World Health Organization, 2007). While a fall may be regarded as a relatively minor incident when experienced by a child or a healthy adult, it can have significant consequences for older adults. Annually, approximately

40% of individuals aged 65 and older experience a fall. Of these, one in forty will require hospitalization, and only approximately half of those hospitalized after a fall will survive for six months (Rubenstein, 2006). Even non-injury falls can lead to increased fear of falling, which can in turn result in reduced activity or depression, which can affect quality of life. This negative cycle increases in turn the risk of falling and should therefore be prevented through early intervention (Xu et al., 2022).

The maintenance of stable upright standing is dependent upon the central nervous system's processing and integration of information from the sensory system and properly scaled motor responses (Viseux et al., 2020). These postural movements are executed to control the spatial and temporal relationship between the body's center of mass and the base of support, primarily the feet, in order to maintain balance (Rogers & Mille, 2018). Should the position or motion of the center of mass exceed the spatial and temporal stability limits of the base of support, the result will be a loss of balance, which may result in a fall. Apart from sudden medical incidents (e.g. dizziness or seizures), imbalance is typically the result of perturbations, whether mechanical or sensory in nature(Rogers & Mille, 2018). Internal perturbations include internally generated actions, such as raising the arms, bending the trunk, or lifting a leg. Such movements change the relationship between the center of mass and the base of support and, if not compensated for, can lead to imbalance. Internal perturbations can be anticipated and thus the disturbances can be minimized in advance. In contrast, when tripping while walking or when the bus stops unexpectedly, it is necessary to respond quickly to these external perturbations by using postural actions to maintain balance. Examples of corrective strategies include maintaining the base of support and adjusting the center of mass by stabilizing in the ankles or counteracting by moving the hip forward or backward. Alternatively, the base of support can be altered by taking a step or reaching out to grasp for support (Rogers & Mille, 2018).

Such situations are encountered on a daily basis without conscious thought and without the individual losing their balance and falling to the ground. The coordination of the body is enabled by the interplay of sensory information, processing, and motor executive systems (Baumeister, 2013). The model of sensorimotor control (Figure 1) comprises two biological systems. The human musculoskeletal system provides mechanical stability and enables movement throughout the interaction of bones, joints, and muscles. Conversely, the nervous system, comprising the central and peripheral nervous systems, facilitates the transfer of information via afferent (sensory) and efferent (motor) neurons from and to the periphery to the central nervous system where the information is processed in the brain and spinal cord (Silverthorn, 2010).

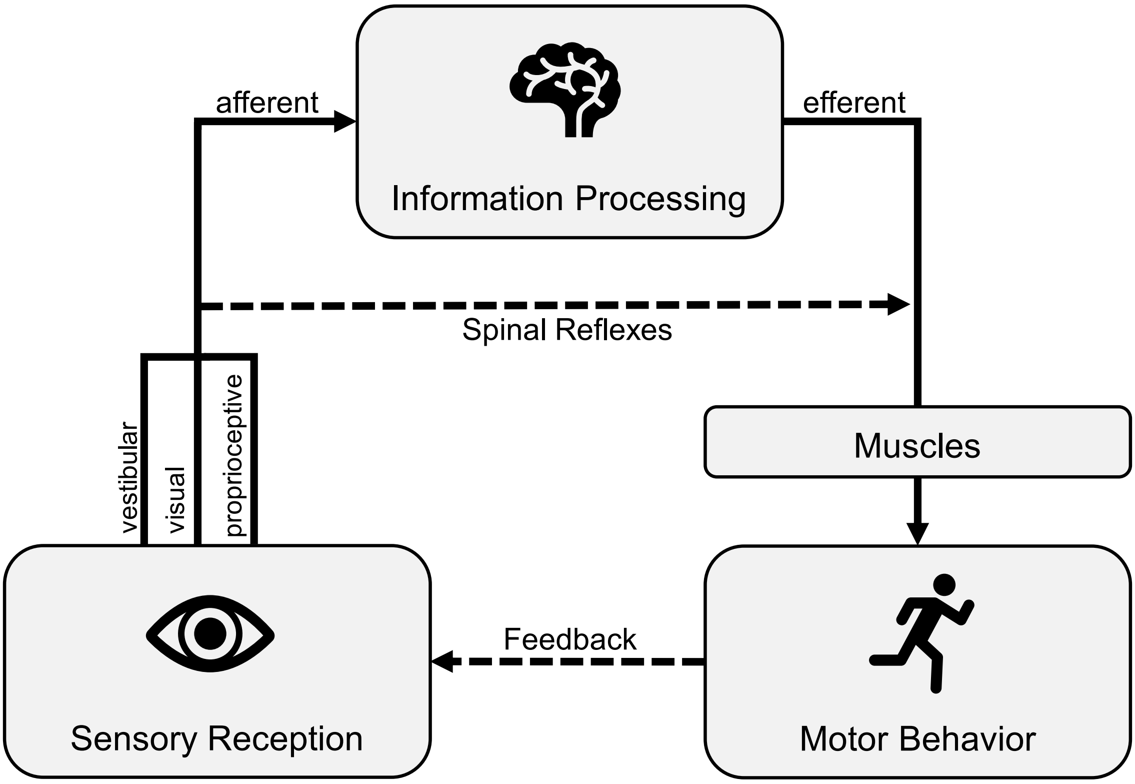

Figure 1: *Schematic model of sensorimotor control (adapted from Baumeister, 2013). External and internal sensory information are perceived by sense organs. The information is processed in the cortex and the motor response is transferred to the muscles that perform the motor behavior.*

The sensory information perceived by the sense organs is of a multimodal nature during internal perturbations that disrupt equilibrium, such as stepping into a bathtub. These sensory inputs include visual (“I see the bathtub”), vestibular (“I lean towards the standing foot”), and proprioceptive information (“the knee and hip of the foot that steps into the bathtub are flexed, the muscles are tense”) that are transferred via afferent neurons to the central nervous system and undergo processing in the brain. The resulting motor response is sent via efferent neurons to the peripheral muscles that execute the motor behavior to prevent a fall. The change in posture resulting from motor behavior is perceived as feedback from the sensory organs. In the event of a sudden external perturbation, such as the foot becoming caught in the carpet, a spinal reflex initiates a motor response to the peripheral muscles without first processing the information in the brain. This minimizes the time required to respond (Baumeister, 2013).

Lord et al. (2016) postulate that falls are indicative of a fundamental motor impairment, specifically in the domains of reaching, standing, or stepping. If we consider that every successful motor output is the result of sensorimotor control and thus the interaction of sensory input, processing, and motor skills, we can also investigate the underlying cause of a fall (or unsuccessful motor output) within the sensorimotor system. Deficits at multiple levels within the sensorimotor system reduce the likelihood of successful performance of the movement. Furthermore, the functioning of all three levels declines with age, which is associated with an increased risk of falling (Lord et al., 2016).

1.2.4 Traditional training interventions

Mr. Smith is experiencing a downward spiral of age-related decline, both physically and cognitively. On the recommendation of a friend from his walking group, he enrolls in senior exercise classes at his local sports club to improve his physical condition and socialize. A distinctive aspect of the spiral model is that there is theoretically an opportunity to mitigate or reverse the trajectory of decline. Through education and intervention, Mr. Smith can learn to protect himself from negative attitudes toward inactivity, improve his functional health, and enhance his overall quality of life (Whitehead, 2019). The goal of interventions designed to counteract age-related decline is to maintain physical, cognitive, and social functioning.

Physical activity has been demonstrated to exert a beneficial influence on age-related functional decline, thereby inducing a healthier aging trajectory (Cunningham et al., 2020). Izquierdo and colleagues distinguish two phenotypes of aging, characterized by the presence or absence of healthy levels of physical activity and exercise. Depending on the onset of physical activity, it can serve as a form of preventive medicine for inactivity disorders or as a therapeutic intervention for these diseases (Izquierdo et al., 2021)

It has been demonstrated that exercise and physical activity can enhance physical function and quality of life, while also serving as a preventive measure against cardiovascular disease, diabetes, and obesity (Izquierdo et al., 2021). Moreover, a combination of balance and resistance training was shown to be the most effective approach for reducing falls. Resistance training has also been shown to be an effective treatment for sarcopenia, whereas pharmacological interventions have not demonstrated efficacy in addressing these conditions (Fragala et al., 2019).

The World Health Organization recommends that adults aged 65 and above engage in a minimum of 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity aerobic activity per week, in addition to two or more days of muscle-strengthening exercises (World Health Organization, 2020). However, these recommendations are frequently not met, thereby increasing the risk of sarcopenia, frailty, obesity and chronic diseases (Cunningham et al., 2020; Izquierdo et al., 2021). It is therefore crucial to identify strategies that integrate physical activity into the lives of individuals across all age groups. Exercise should be considered a form of medicine, with physical activity tailored to the desired outcome and individualized and controlled as any other medical treatment (Izquierdo et al., 2021).

Nevertheless, it is important to note that physical activity is not solely beneficial for counteracting the physical effects of aging. Furthermore, evidence indicates that physical exercise can enhance cognitive functions and mitigate the cognitive decline associated with aging. In particular, physical activity performed in dynamic and changing environments may prove more effective than in stable environments (Yamasaki, 2023). The combination of cognitive training with exercise in dual-task training has been demonstrated to enhance cognitive function (Hong et al., 2024; Wollesen et al., 2020) and mitigate specific risk factors associated with falls (Lipardo et al., 2017).

Furthermore, the ability to perform two tasks simultaneously is impaired in older adults (Bohle et al., 2019). One illustrative example from everyday life may be having a conversation while walking. As a result of the combined effects of cognitive and physical decline, the act of walking is no longer an automated process as it is in younger individuals, attempting to perform the two tasks of walking and talking simultaneously is cognitively demanding and prone to errors. Older adults who stop walking when answering to a question are at a greater risk of falling than the older adults who are able to perform both tasks simultaneously (Lundin-Olsson et al., 1997). Therefore, a potential strategy for addressing this issue may be a combined training of cognitive and physical tasks. This approach may be advantageous since dual task performance is most effectively trained when both tasks are trained simultaneously, rather than each individually (Anguera et al., 2013; Yogev et al., 2008).

1.3 Exergaming as combined physical and cognitive training

1.3.1 Exercise as video game

One method of integrating physical and cognitive training simultaneously is exergaming. Physical activity in an interactive and cognitively demanding digital, augmented, or virtual game-like environment combines exercise with computer-based gaming, and has gained significant popularity in recent decades under the term exergames (Stojan & Voelcker-Rehage, 2019).

Computer-based games controlled by whole body movements became popular as dancing simulator games. They were introduced into homes for personal use in 2004 with the release of the PlayStation-based game Dance Dance Revolution, which was promoted as a weight loss tool (Bogost, 2005). Nintendo Wii, released two years later, became arguably the most popular exergaming system, as it opened up exergames for everyday life as a game console for enjoyment and fun at home. The use of a handheld motion controller with three-axis accelerometers and a high-speed infrared camera enabled the player to control the games by moving the remote controller within a range of 10 meters (J. C. Lee, 2008). Additionally, the Wii balance board enabled the player to control games by changing their center of pressure (Clark et al., 2010). Subsequent gaming systems, such as the Microsoft Kinect, employed infrared cameras and depth cameras that were capable of detecting body movements, thereby enabling participants to move freely without a board or remote controller in front of the screen (Zhang, 2012). With continued advancement of technology, virtual reality glasses have further expanded the possibilities of exergaming. The use of a head-mounted display allowed the user to be immersed in a 3D virtual reality environment, which increased the effect of immersion and allowed for a higher level of ecological validity (Tieri et al., 2018). It is important to note that scientific literature often confuses the terms virtual reality and exergaming. In this thesis, exergaming will be discussed as a screen-based intervention.

Originally designed for entertainment and as a weight loss tool, exergames of various types share the main advantage of being a fun activity. They employ the concept of gamification, which transforms a repetitive and otherwise potentially boring task into a game, thereby motivating the user (Hamari et al., 2014). In the context of rehabilitation, exergames may offer alternative forms of therapy that require good adherence but often involve repetitive movements.

1.3.2 Potential benefits for older adults

When Mr. Smith talks to his therapist about the repetitive nature of the senior exercise class, he recommends contacting a colleague who also offers exergaming training. The combination of physical activity and interactive gaming could motivate Mr. Smith to be more physically active while also training his cognitive functions. Combining physical activity with interactive video games has been shown to have a range of cognitive and physical benefits, particularly for older adults (Stanmore et al., 2017; Suleiman-Martos et al., 2022). These benefits may originate from the simultaneous engagement of both physical movement and cognitive processing, which appears to stimulate both physical and cognitive functions in a distinctive manner.

The physical benefits for older adults include increased physical activity and fitness (Suleiman-Martos et al., 2022). Exergaming has been demonstrated to encourage moderate physical activity, which can lead to improvements in cardiovascular health, muscle strength, and endurance. A meta-analysis demonstrated that exergaming enhanced gait speed and the outcome of the Time Up and Go test to a greater extent than a control group. However, no significant differences were observed between the groups with regard to outcomes such as the 6-minute walk, Berg Balance Scale, cadence or velocity (Suleiman-Martos et al., 2022). In addition, many exergames are designed to improve balance and coordination through activities that require players to move in various directions and maintain postural stability. It has been demonstrated that exergames have a beneficial impact on balance (Donath et al., 2016; Van Diest et al., 2013), stepping (Schoene et al., 2013), and gait parameters (Swanenburg et al., 2018), which in turn can influence the risk of falling and may be beneficial in the context of fall prevention (Chen et al., 2021; Sturnieks et al., 2024). Overall, exergames have been found to be as effective as – or even more effective than – traditional exercise programs for older adults (Skjæret et al., 2016; Suleiman-Martos et al., 2022).

The interactive nature of exergames presents a challenge to cognitive functions, requiring quick decision-making, planning, and memory recall. Previous reviews have demonstrated that exergames are capable of enhancing overall cognition as well as specific domains of executive function, attentional processing, and visuospatial skills (Jiang et al., 2022; Stanmore et al., 2017; Stojan & Voelcker-Rehage, 2019; Wollesen et al., 2020). For example, Zhao and colleagues demonstrated that a 12 week exergaming intervention had a beneficial impact on both executive function and working memory, as measured using neuropsychological tests such as the stroop test and the n-back test (Zhao et al., 2022). Furthermore, there is evidence that exergaming enhances attentional control and processing speed (Wollesen et al., 2020). This is likely due to the necessity of focusing on visual and auditory cues while moving in coordination with the game, which exercises cognitive processing skills. In conclusion, the ability to simultaneously train both physical and cognitive functions makes exergames a promising intervention to prevent age-related functional decline.

Exergames may be a promising tool to motivate older adults to physical activity. However, the results of studies are heterogeneous and not all studies have shown positive effects on all physical outcomes (Zheng et al., 2020). One reason for the inconsistencies may be that people respond differently to prescribed physical activity. Mr. Smith tries exergaming and likes it. First, he plays at the same level as a friend in the group. But he is already 80 years old, so after a short period of getting used to the games, they are no longer challenging enough for Mr. Smith. The trainer increases the difficulty level for Mr. Smith so that both men can train with the right training load. Traditional exercise prescriptions impose a constant load across individuals. Due to the heterogeneity of health conditions among older people, the same exercise prescription may result in a variable training dose for each individual, leading to heterogeneity in individual responses and thus in the training outcomes. To address this issue, exercise prescriptions should be tailored to a comparable dose for each participant, resulting in a lower degree of heterogeneity in individual exercise responses and training outcomes (Herold et al., 2019). Indeed, over time, individualized and tailored training protocols appear indeed to result in larger training effects than training with constant demands (Wollesen & Voelcker-Rehage, 2014). To achieve this, it is essential to not only investigate the impact of exergaming interventions, but also to monitor the effects over the course of the intervention itself.

In addition to the longitudinal approach that employs pre- and post-measurements to assess the efficacy of exergaming, there are investigations that examine the acute effects of exergaming on physical function while exergaming. With regard to physical activity, for instance, HR measurements during exergaming indicate that a game played on a bicycle results in comparable HR activity to that of an traditional interval training protocol (Moholdt et al., 2017). Additionally, participants' movement strategies during gameplay, such as step length and velocity, were evaluated using reflective markers and accelerometers. This approach was employed to compare movement patterns across different stepping exergames in older adults (Skjæret-Maroni et al., 2016; Skjæret-Maroni & Bardal, 2018). The cognitive impact of exergaming is typically measured through cognitive tests following the completion of an exergaming session (Stanmore et al., 2017). One potential avenue for measuring the cognitive activity associated during exergaming play is through neurophysiological techniques such as EEG or functional near-infrared spectroscopy (fNIRS). Early studies have demonstrated the feasibility of employing these methods during exergaming (Anders et al., 2018; Eggenberger et al., 2016). However, further investigation, particularly in older adults, is needed.

1.4 Neuroscientific basis of cognitive engagement

1.4.1 Mobile EEG as a promising tool

Traditional physiological approaches to measuring human brain activity were relatively static, often simulated experiments conducted in laboratory settings, typically in sitting or lying positions. To measure brain activity in a more ecologically valid environment or in situations that contain bodily movements, like exergaming, mobile approaches are necessary (Ladouce et al., 2017). Improvements in technology have facilitated the portability of research methods that were previously limited to the laboratory due to limitations such as weight, size, or battery life. Both EEG and fNIRS have evolved rapidly and now closely match the standards of the high-density non-mobile versions in spatial and temporal resolution (Ladouce et al., 2017). The methodology of fNIRS employs near-infrared light to image the alterations in blood hemoglobin concentration, assuming that blood flow is correlated with the metabolic needs of neural populations (Logothetis et al., 2001). This approach offers a high spatial resolution, but the hemoglobin concentration dynamics are relatively slow, resulting in a temporal resolution of several seconds (Irani et al., 2007). In contrast, mobile EEG has a lower spatial resolution but a much a higher temporal resolution (Mehta & Parasuraman, 2013), enabling the measurement of brain dynamics associated with goal-directed movements and fast cognitive processes. Furthermore, EEG has been used extensively in laboratory-based settings, allowing for the comparison of the results of mobile studies to the gold standard of non-mobile studies (Ladouce et al., 2017).

In general, non-invasive EEG measures the electrical activity on the surface of the scalp of the participant by describing voltage changes between pairs of electrodes. This activity arises from synaptic excitation of the dendrites of many pyramidal neurons in the cerebral cortex. However, since the signal of one neuron is too weak to be measured through the scalp, an EEG signal depicted at the surface always includes the synchronous activation of thousands of neurons, summed up to one larger surface signal (Bear et al., 2016).

The rhythm of the synchronous activation, which indicates functional human EEG rhythms, can vary from 1 to 90 Hz. The primary EEG rhythms are classified according to their frequency bands and correspond to specific behavioral states (e.g. sleep or attention) or pathological conditions (e.g. seizures or coma). The most common definition of frequency bands is as follows: delta (<4 Hz), theta (4-7 Hz), alpha (8-13 Hz), beta (15-30 Hz), and gamma (30-90 Hz). A recent scoping review identified several frequency bands and locations that are affected by cognitive demands. In states of attention allocation, alpha and theta frequencies were observed to increase in the frontal and prefrontal areas, while beta and gamma frequencies declined. Similarly, theta frequencies were increased in the fronto-parietal and occipital areas (Souza & Naves, 2021). The majority of studies have focused on alpha and theta frequencies, which are associated with cognitive processes (Cavanagh & Frank, 2014; Gevins et al., 1997; Klimesch, 1999, 2012; McEvoy et al., 2001; Sauseng et al., 2005). Frontal theta was found to increase with increasing cortical demand (Cavanagh & Frank, 2014; Gevins et al., 1997; Sauseng et al., 2005). The origin of frontal theta is associated with the anterior cingulate cortex (ACC) and the medial prefrontal cortex (Gevins et al., 1997; Ishii et al., 2014; Petersen & Posner, 2012). These two regions have been linked to executive control and working memory processes (Niendam et al., 2012; Shenhav et al., 2013). Furthermore, the ACC has been identified as an important component of the human attentional system (Luks et al., 2002). Conversely, alpha activity is described as related inversely to neural activation and thus decreasing with increasing cognitive demand (Klimesch, 2012; Pfurtscheller & Lopes Da Silva, 1999). However, alpha frequency often yields inconsistent results as other studies found opposite findings of increasing alpha activity (Michels et al., 2010; Palva & Palva, 2007). Klimesch et al. (2007) proposed that alpha synchronization may be associated with the inhibition of non-relevant information. This would indicate that areas engaged in processing the task experience decrease alpha power, while areas that are not involved are inhibited and thus experience an increase in alpha power (Klimesch et al., 2007). Collectively, increasing theta power appears to be the most sensitive and least debated parameter to describe higher cognitive demands, while alpha power may be inversely related to increasing cognitive demands and thus decrease (Chikhi et al., 2022).

1.4.2 Investigating brain activity during exergaming utilizing EEG

To date, there have been only a few studies investigating brain activity in the field of exergaming. The positive effect of exergaming interventions on cognitive functioning is largely based on cognitive test performance, which serves as proxy measure for cognitive processing (Stanmore et al., 2017). In addition, some studies employed EEG to measure brain activity during cognitive tests (O'Leary et al., 2011; Schättin et al., 2016) or in a resting position (Adcock et al., 2020; Amjad et al., 2019) before and after an exergaming intervention. Nevertheless, the aforementioned studies indicated activity alterations in the frontal cortex. However, due to the differing EEG parameters that were analyzed, the transferability of the findings is limited. Moreover, by measuring pre- and post-intervention, the studies did not monitor cognitive demands during the intervention itself. A limited number of studies have employed neuroimaging techniques to assess brain activity during exergame play (Anders et al., 2018; Baumeister et al., 2010; Ghani et al., 2021; Knols et al., 2017; Ko et al., 2020).

Baumeister and colleagues were the first to utilize EEG to examine brain activity while playing exergames. A comparison was made between brain activity during real-world golf putting and the Wii golf game. The researchers observed an increase in frontal theta activity and parietal alpha-2 activity during real-world putting. The results were discussed in the context of the concept of working memory, with increased frontal theta being interpreted as higher focused attention and information processing in the real world as the participants were already accustomed to the task in the real world. The increased alpha-2 activity was discussed as diminished cortical activation in the parietal regions during real world putting. This signifies that the participants actively processed the unfamiliar stimuli in the virtual setting, consequently processing a higher amount of sensory information in the virtual world (Baumeister et al., 2010).

In a recent study, Anders and colleagues investigated brain activity during a balance exergame. They compared playing the game at two distinct levels of difficulty with performing the game's leaning movement in front of a black screen. The researchers found an increase in frontal theta activity in challenging gaming conditions relative to the self-paced leaning movement, accompanied by a reduction in central alpha-2 power in the exergaming condition. The increased frontal theta activity was discussed as higher cognitive demand during exergaming, while the enhanced central alpha-2 activity was interpreted as an indication of improved automation of the motor task, thereby allowing for greater focus on the cognitive performance. (Anders et al., 2018). In a similar approach, Ko and colleagues compared a ski simulator with and without a game. They observed increased sensorimotor rhythm waves during exergaming, which are associated with higher concentration (Ko et al., 2020).

Ghani and colleagues compared different levels of difficulty within an exergame. In contrast to the previously mentioned studies, the researchers employed the amplitude of the N1 event-related potential (ERP) rather than power spectral analysis. However, the feasibility of measuring cognitive workload using this approach was demonstrated as the amplitude of N1 decreased significantly with increasing task difficulty (Ghani et al., 2021). All these studies were conducted with young participants. The only study with older adults was conducted using a bedside video console while measuring brain activity over the left and right prefrontal cortex using EEG and fNIRS. The study indicated positive effects on prefrontal cortical involvement (Knols et al., 2017).

The results of the studies mentioned above are difficult to compare and generalize due to the different methodologies employed to collect and analyze the data. EEG systems with 2-64 channels were used, with data analyzed using power spectral analysis based on channel measures or source-based analysis, as well as an event related approach. Moreover, only one study was conducted with older adults (Knols et al., 2017). However, these studies did demonstrate that EEG measurement during exergaming is a viable approach, and they suggest that frontal theta activity and parietal alpha-2 activity may be sensitive to cognitive demands during exergaming. This is consistent with previous findings of EEG power spectral measures that reflect cognitive involvement (Chikhi et al., 2022).

1.5 Rationale of the thesis

Exergaming has been demonstrated to enhance cognitive and physical functioning in older adults, thereby mitigating the age-related decline. Nevertheless, despite mounting evidence that exergaming can improve both physical and cognitive performance (Jiang et al., 2022; Suleiman-Martos et al., 2022), some studies have yielded inconsistent findings that do not corroborate this effect (Zheng et al., 2020). One potential explanation for these inconsistencies is the lack of individualization in exergames. Older adults exhibit a wide range of health conditions, and the same exercise prescriptions may yield varying training outcomes in different individuals. Consequently, individualized and tailored training protocols appear to result in more pronounced training effects (Wollesen & Voelcker-Rehage, 2014).

To achieve this, it is essential to not only assess physical and cognitive functioning before and after the intervention, but also to gain insight into the intervention itself and to describe the player's behavior during the intervention. While the physical activity of exergaming was previously quantified using HR measures (Moholdt et al., 2017), marker-based motion capture systems (Skjæret-Maroni et al., 2016), or accelerometers (Skjæret-Maroni & Bardal, 2018), the extent of cognitive involvement remains largely uninvestigated. Mobile EEG measurements may prove a viable option. The number of studies investigating the impact of exergames on brain activity in older adults is limited and employs a variety of methodological approaches. However, frontal theta and central and parietal alpha-2 activity may serve as potential parameters for describing cognitive involvement during exergaming.

In order to develop an exergaming intervention that is tailored to the individual, it is essential to have a clear understanding of how to tailor exergames in a way that ensures an effective exergaming intervention for older adults. While planning this intervention, a number of decisions must be made. The initial decision pertains to the selection of the game to be played. As the content and the movements required to control the game may vary considerably, it is crucial to select a game that will provide beneficial but safe movement patterns for older adults. Furthermore, an appropriate level of challenge for the participants should be chosen. As players may demonstrate improvement in their abilities within the game, it is important to determine the point at which the difficulty level should be modified.

To address these questions and plan an effective exergaming intervention, it is important to monitor the intervention and measure the participants' performance while they are playing. This allows for a more comprehensive understanding of the gameplay across the intervention, which is vital for the planning and tailoring of the intervention.

1.6 Objective of the thesis

The overarching objective of this thesis is to investigate the impact of exergaming on cognitive and physical activity in older adults, with a particular focus on the influence of varying game characteristics, such as difficulty level or game speed, on brain activity, physical performance, and perceived exertion, both in short-term (single session) and the long-term (four-week intervention). The research examines both the immediate and evolving impacts of exergames on cognitive demand, physical function, and perceived exertion, aiming to gain insight into the individual response to exergaming and to investigate the relationship between exergaming and healthy aging.

The thesis consists of three papers. The first paper employs in a cross-sectional approach the effect of exergaming and its game characteristics on several measures of physical activity and brain activity. Based on those results, the second and third papers describe the changes observed longitudinally across the intervention with respect to the movements of the players and the brain activity, respectively. The specific aims were as follows (Figure 2):

The aim of **Paper 1** was to examine the impact of varying levels of difficulty in two exergames (a step game and a balance game) on brain activity and physical activity of older adults while playing a single exergaming session. Specifically, theta power and alpha-2 power were measured to describe the cognitive involvement, HR and acceleration to describe the physical activity, and participants' self-rated perceived exertion.

The primary aim of **Paper 2** was to investigate the impact of repeated exergaming sessions over four weeks and two game settings (difficulty level and game speed) on gameplay (performance, physical activity, and perceived exertion) in older adults over a four-week exergaming intervention. The secondary aim was to investigate whether there is a change in physical function and fear of falling after the exergaming intervention.

The main aim of **Paper 3** was to monitor frontal theta change throughout a four-week exergaming intervention in a group of healthy elderly individuals. The secondary aims were to explore the potential effects of intervention duration and game characteristics (game type and difficulty level) on changes in frontal theta power as an indicator of cognitive involvement.

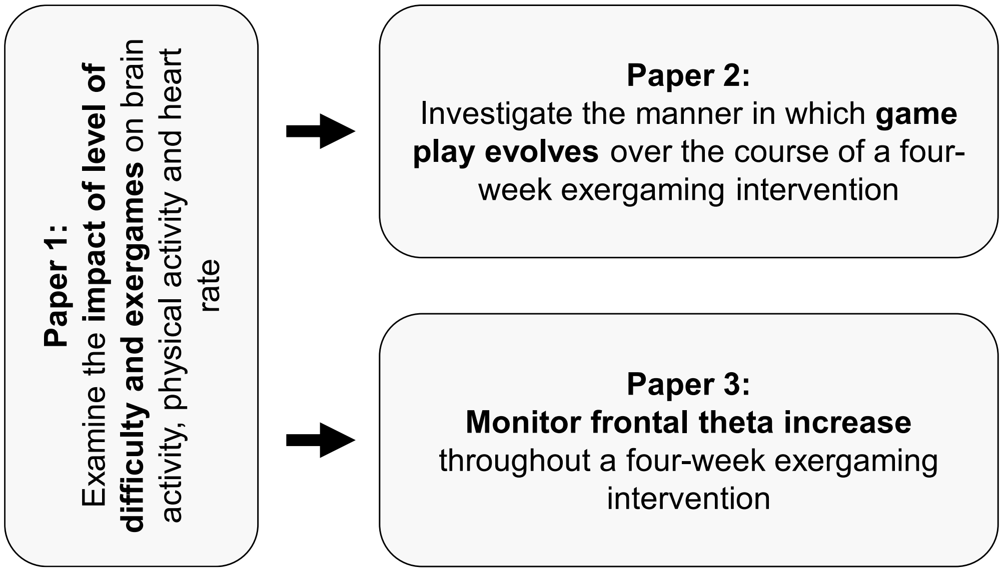

Figure 2: *Schematic overview of the aims of the three included papers.*

2 Methods

The following chapter provides an overview of the exergaming study conducted for this thesis. For more detailed information, please refer to the respective manuscripts.

2.1 Study design and ethical considerations

The thesis comprises three papers, all based on data collected during a single exergaming study. The study was approved by the ethical committee of Paderborn University and the research adhered to the principles outlined in the Declaration of Helsinki. It was registered retrospectively at the German Clinical Trial Register (DRKS00034786, 30.07.2024). The study took place at the Exercise and Neuroscience Lab at Paderborn University between August 2019 and April 2020. The study aimed to explore the longitudinal effects of exergames while simultaneously monitoring changes during a four-week intervention. To achieve this, a design was implemented allowing for a high frequency of measurements in the initial week, gradually decreasing across the intervention. This approach was driven by the general assumption that significant changes, attributed to learning and habituation, would occur primarily within the first week. Thus, to streamline efforts for both participants and the investigator, only one measurement per week was conducted during week two to four.

2.2 Sample characteristics

A total of 42 older adults initially responded to recruitment efforts through local newspaper advertisements and word-of-mouth referrals. Following an information session, in which individuals underwent a comprehensive screening process to determine their eligibility, 28 participants (mean age 74.57 ± 0.78 years, mean height 172.04 ± 1.86 cm, mean weight 76.85 ± 2.26 kg; 14 females) were deemed eligible and provided written informed consent. In accordance with the inclusion criteria, participants were independently living individuals aged 70 years or older, without prior experience in exergaming. Exclusion criteria included a history of neurodegenerative or neurological diseases, acute physical or mental impairments preventing safe exergaming participation for four weeks, or any surgical or injury-related conditions affecting pain-free movement during the study. All participants attended all training sessions as scheduled. Due to the presence of missing or artifact-contaminated data, some datasets were excluded from analysis. Consequently, the number of participants included in the three papers varies. All 28 participants were included in papers 1 and 2. In paper 3, 21 participants (mean age 74.80 years; 8 females) were included in the analysis.

2.3 Experimental procedure

The four-week exergaming intervention consisted of six training sessions and six testing sessions. During all 12 sessions, participants performed the same exergaming training, while additional measurements were taken in the test sessions. All sessions were conducted individually for each participant under the supervision of the first author.

Each exergaming session lasted approximately 45 minutes and included two different exergames (Puzzle and Fox) at varying difficulty levels (Easy and Hard) in a counterbalanced order. In the Puzzle game, participants were required to lean sideways, while in the Fox game, they were instructed to step sideways within a designated range. Prior to engaging in exergaming, participants performed reference movements for each game, executing the leaning or stepping movement self-paced in front of a black screen. Following each exergaming session, participants rated their perceived physical and cognitive exertion on visual analog scales.

Throughout the intervention, data on participants' movements and brain activity were recorded while exergaming at sessions 1, 2, 3, 6, 9, and 12. On these testing days, the participants were equipped with an active 64-channel EEG system, a chest belt for HR measurement, and an accelerometer placed on the lower back (L3), which recorded data continuously during the exergaming session. In addition, cognitive and physical perceived exertion was assessed after each game. Furthermore, cognitive and physical function, fear of falling, and everyday physical activity levels were evaluated before the first and after the last sessions. A flow diagram of the experimental protocol can be seen in Figure 3.

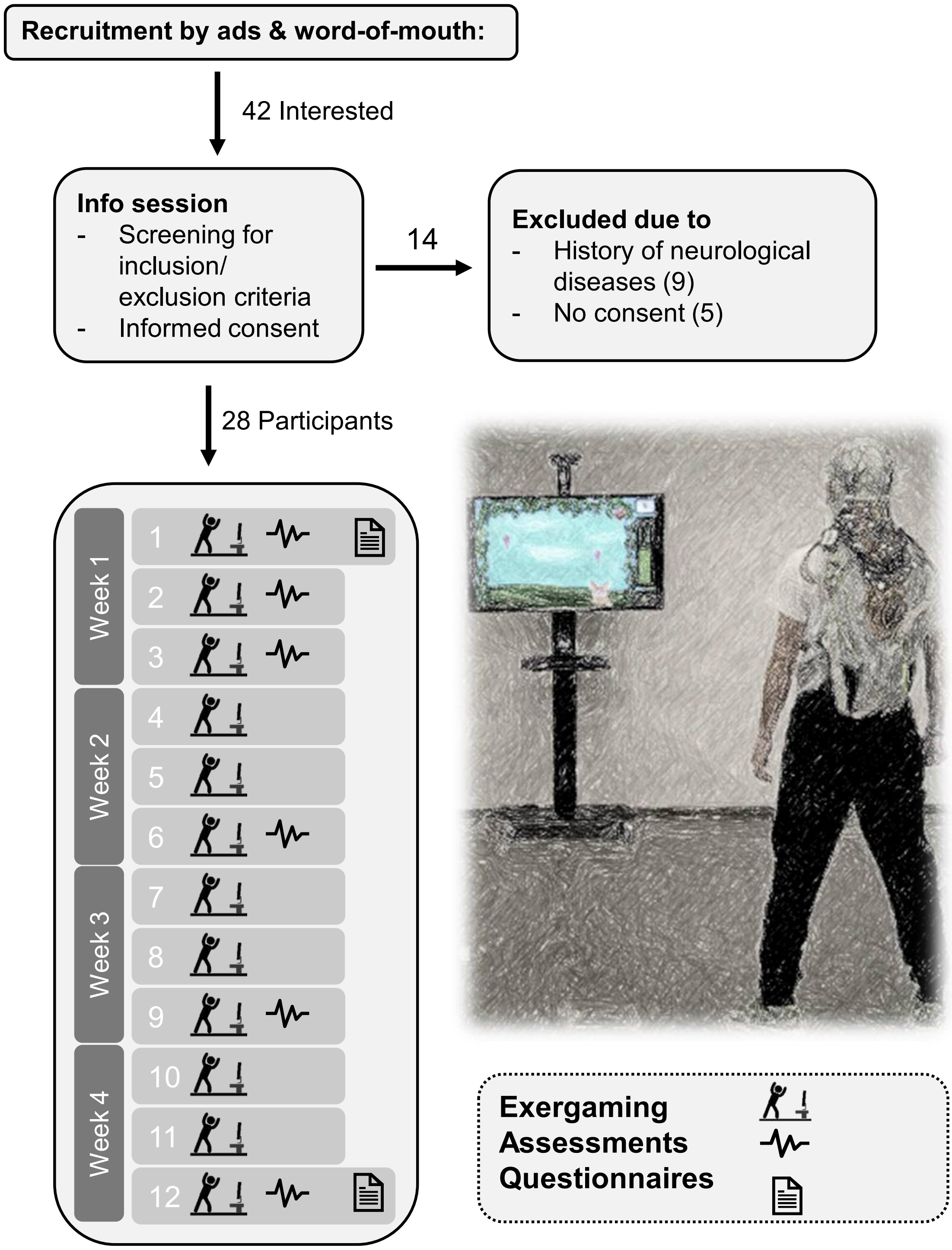

Figure 3: *Experimental Procedure. Prior to the exergaming intervention, all participants were invited to an info session for further information, familiarization with the laboratory, and screening for inclusion criteria. 28 participants started the intervention that consisted of 12 training sessions where two exergames were played at each session for 45 minutes. Furthermore, in session 1, 2, 3, 6, 9, and 12 EEG, acceleration, RPE, and HR were recorded; before and after the intervention, physical and cognitive function and fear of falling were assessed.*

2.4 Exergames

Two exergames were selected from the Silverfit System (SilverFit BV 3D, The Netherlands), a screen-based exergaming system that employs a time-of-flight camera to record players' body movements in three dimensions within a 5x5-meter game area, corresponding to a 176x144-pixel array (Rademaker et al., 2009). Both games required movements sideways that challenged balance while being relatively simple movements to minimize movement artifacts during EEG recording. Screenshots of both games are shown in Figure 4.

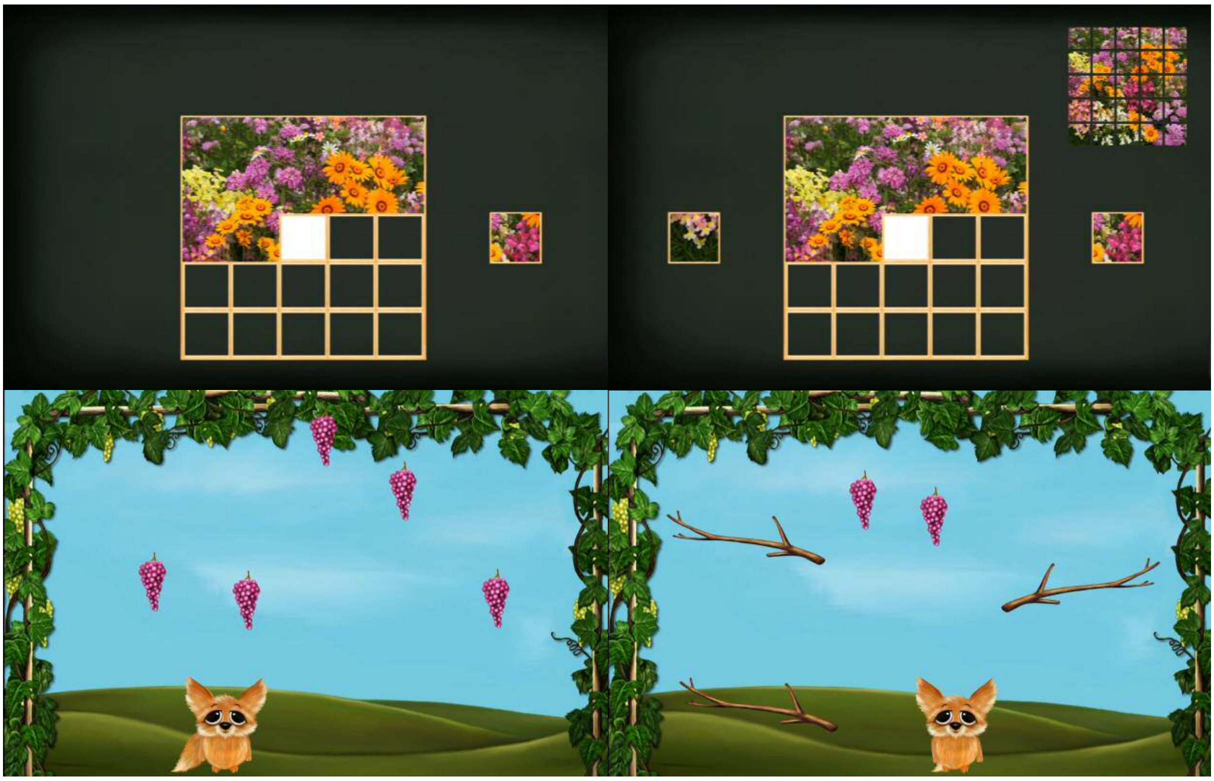

Figure 4: *Screen capture of the exergames.* ***Top****: The puzzle game was controlled by leaning sideways with feet in place; left the easy condition with only one puzzle piece, right the hard difficulty level with two puzzle pieces.* ***Bottom****: the Fox game was played by taking steps sideways, in the easy condition (left), the player aimed to catch as many grapes as possible, in the hard version, the player additionally needs to avoid the branches.*

In the Puzzle game, players control the game by leaning their upper body sideways without taking steps, with the objective of solving a 5x5 jigsaw puzzle. In the Easy condition (Puzzle Easy), a puzzle piece was presented on either the left or right side. Players were required to select the piece by leaning in the corresponding direction. In the Hard condition (Puzzle Hard), puzzle pieces appeared on both sides, requiring that players select the appropriate piece by leaning in the correct direction. The participants solved seven images in each condition per session.

In the Fox game, participants controlled a fox avatar on the screen by stepping left and right. In the Easy condition (Fox Easy), grapes descended from the top of the screen, and players had to catch as many grapes as possible by adjusting the position of the fox avatar accordingly. In the Hard version (Fox Hard), additional branches fell across the screen that players had to avoid while catching grapes. In the first session, all participants played the Fox game at the same game speed level (3 out of 10), with individual progression depending on performance and perceived effort. In each session, each condition was played twice for four minutes each.

2.5 Monitoring of performance, physical activity, and perceived exertion

Quantitative data about participants' performance during gameplay was obtained from the Silverfit System, exported in the form of game scores. In the Puzzle game, the primary outcome parameter was the time taken to complete one image. In order to obtain a single performance measure for each Puzzle condition, the completion times for all seven images were averaged. Similarly, in the Fox game, the game score was determined by the number of grapes caught by the player. In the Hard condition, a penalty of two points was applied for each collision with branches. To derive a single game score for each Fox condition (Easy and Hard), the mean of the scores from both game rounds at each condition was calculated.

To quantify the physical activity of participants during gameplay, a triaxial accelerometer (AX3, Axivity, United Kingdom) was affixed to the lower back at the L3 position. The triaxial raw acceleration data captured by the accelerometer was processed to derive the vector magnitude using the High-pass Filter followed by Euclidean Norm (HFEN) method with a one-second window length (van Hees et al., 2013). This calculation yielded a comprehensive measure of the overall amount of movement.

The degree of exertion perceived by the participants during the exergaming sessions was evaluated using visual analog scales (VAS). Following each gaming session, participants were asked to rate both their perceived physical and cognitive exertion on the VAS. The scale ranged from 1 indicating "not exhausting at all" to 10 representing "totally exhausting". Participants were instructed to select the point on the scale that best corresponded to their perceived level of exertion separately for the cognitive and physical exertion. To ensure that responses were sufficiently granular, the VAS permitted for increments of 0.5.

2.6 Neurophysiological monitoring

Continuous EEG recordings were obtained using 64 active electrodes (ActiCap, BrainProducts, Germany) and a wireless amplifier (Live Amp 64, BrainProducts, Germany) with a sampling rate set at 500 Hz. The electrode placement adhered to the international 10-20 system (Klem et al., 1999), with the ground electrode located mid-forehead (Pivik et al., 1993) and online referencing to FCz. The tree-dimensional positions of the electrode placements were recorded using the Cap Trak system (Brain Products, Germany). To ensure optimal signal quality, a gel was applied between the scalp and electrodes to achieve impedance levels below 5 kOhm. Prior to data collection, participants were informed of the potential for artifacts and instructed to minimize blinking, teeth clenching, and muscle activity in the face and neck during the exergaming sessions.

EEG data processing was conducted using the EEGLAB toolbox v2020_0 (Delorme & Makeig, 2004) in MATLAB (Version R2019b, Mathworks Inc., United States). Initially, sinusoidal noise was removed using the Cleanline plug-in (Mullen, 2011), followed by FIR filtering between 3 Hz and 30 Hz. Subsequently, the data were referenced to a common average and downsampled to 256 Hz. Channels connected via electrical bridges were identified and removed using the eBridge plug-in (Alschuler et al., 2014), along with additional noisy channels using the EEGLAB pop_rejchan function. Further data cleaning was conducted using the clean_rawdata plug-in (Miyakoshi & Kothe, 2014), which was employed to eliminate non-stereotypical artifacts or extreme noise. Large-amplitude artifact transients were interpolated using automated artifact subspace reconstruction (ASR) with a cutoff value of 7 standard deviations (Jacobsen et al., 2021; Nordin et al., 2020). Independent component analysis (ICA) (AMICA - Palmer, 2015) was employed to decompose the clean signal into independent components (IC). Each IC was associated with a corresponding dipole using the DIPFIT toolbox (Oostenveld & Oostendorp, 2002) and classified as a brain signal or non-brain signal (e.g., muscle activity, eye activity) using the ICLabel plug-in (Pion-Tonachini et al., 2019).

Only ICs with a high probability (>90%) of being brain components, located within cortical layers, and with a low residual variance (<15%) were retained for further analysis and clustered into five clusters based on spatial (dipole location and orientation, scalp maps) and temporal (power spectra) information. The absolute power of functional ICs within a specific cluster was calculated as the area under the curve (Pivik et al., 1993) for predefined frequency bands. For example, theta (4-7 Hz) was used for the frontal cluster and alpha-2 (10-12 Hz) for the central and parietal areas. Spectral power for each frequency bin (1 Hz) per component in each frequency per component in each condition and session was exported for further analysis. In Paper 3, the change in frontal theta was calculated as the difference between the theta spectral power of the respective game condition and the associated reference measure (e.g. Δ Puzzle Easy = Puzzle Easy - Puzzle Reference). Accordingly, positive delta values indicate an increased activation of the frontal cortex.

2.7 Physical function, cognitive function, and fear of falling

The participants underwent a comprehensive assessment of various aspects related to physical and cognitive function. The cognitive ability of the participants was evaluated at the information session using the Montreal Cognitive Assessment (MoCA), which is a one-page 30-point test that is administered in 10 minutes. It was designed to assess multiple cognitive domains, including short-term memory, visuospatial abilities, executive functions, attention, concentration, working memory, language, and orientation in time and place (Nasreddine et al., 2005). A higher score indicates a better cognitive function. Physical function was assessed using the Community Balance and Mobility Scale (CBMS), which consists of 13 tasks evaluating higher-level balance and mobility skills (Weber et al., 2018). Tasks such as unilateral stance, tandem walking, and descending stairs were scored on a scale from 0 to 5, with higher scores indicating better balance and mobility. Additionally, participants completed the German version of the 16-item Falls Efficacy Scale–International (FES-I) questionnaire, which measures the level of concern about falling on a 4-point scale (Yardley et al., 2005). The scale ranges from 16 to 64 points where higher scores on the FES-I indicate greater concern about falling. Physical function and FES-I were assessed at the beginning and end of the intervention to track changes in balance, mobility, and fear of falling over time.

Following the training intervention, participants completed the German version of the Physical Activity Scale for the Elderly (PASE) questionnaire (Washburn et al., 1993). The PASE questionnaire provided insight into the level of physical activity that participants engaged in during the previous week, considering the frequency, duration, and intensity of the activities. A higher PASE score indicates a higher level of physical activity among older adults.

In addition, cognitive function was assessed before and after the intervention using the Flanker task (Eriksen & Eriksen, 1974) to describe the inhibitory control of the participants. However, the resulting reaction times of many participants were significantly higher than expected for this age group (Verhaeghen, 2011), exceeding the range of valid results. Therefore, this data was not included in further analysis.

2.8 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics (IBM Corp., USA). Normality of the data distribution was assessed using the Shapiro-Wilk test, QQ plots, and histograms. All outcome measures were presented as mean with standard error (± SE) and the significance level for all tests was set at $p < 0.05$. Descriptive analysis of participant characteristics (age, height, weight, MoCA, CBMS, and FES-I) was performed.

2.8.1 Paper 1

For the cross-sectional comparison in paper 1, the data were not normally distributed for game score, RPE, and EEG. Therefore, further analysis was conducted using non-parametric tests. Potential differences in game score and RPE were tested using the Wilcoxon signed-rank test and the effects of the different games and conditions on brain activity using Friedman-ANOVA with Bonferroni corrections for post hoc comparisons.

The acceleration data was evaluated using a two-way repeated measures ANOVA on Game (Puzzle, Fox) × Condition (Reference, Easy, Hard), with Mauchley's test of sphericity and Greenhouse–Geisser correction if necessary. Bonferroni corrections were employed for post hoc comparisons. For post hoc analyses and significant paired comparisons, the effect size (r) was calculated.

2.8.2 Paper 2

To assess changes in mean game score, physical activity, and perceived exertion over a 4-week period and/or across difficulty level, a linear mixed model (LMM) was used. The model included Subject as a random factor to account for repeated measures (random intercept model), while Session (6 occasions) and Difficulty Level (Easy, Hard) were fixed effects. For perceived exertion, only Session was included as a fixed effect since difficulty was not differentiated by the RPE score. Likelihood ratio tests provided p-values for each main and interaction effect, with the three-way interaction tested using the difference in the -2 likelihood values between models with main and interaction effects. The degree of freedom (DF) is the additional number of regression parameters.

Distributions of the CBMS and FES-I data were skewed and potential changes between the pre- and post-measurement were assessed using the non-parametric Wilcoxon signed-rank test.

2.8.3 Paper 3

In examining the performance (game score) for paper 3, a repeated measures ANOVA was conducted for each exergame, with the factors Difficulty Level (2 levels) and Session (6 levels). If necessary, the Greenhouse-Geisser correction was applied following Mauchly's test of sphericity. For post-hoc comparisons, Bonferroni correction was employed, and the effect size was reported as the partial eta squared (part. $\eta 2$).

The analysis of brain activity (EEG) was conducted using a linear mixed-effects model. Participants were included as random effects to account for the repeated measures effects. The fixed effects were Game (2 levels), Difficulty Level (2 levels), and Session (6 levels). Bonferroni correction was employed for post-hoc comparisons.

3 Results

The following chapter presents a concise overview of the main findings of the three studies, which are of significance to the overarching objective of this thesis. The detailed results, including statistical details and secondary analyses, can be found in the original manuscripts. An overview of the results is found in Figure 5.

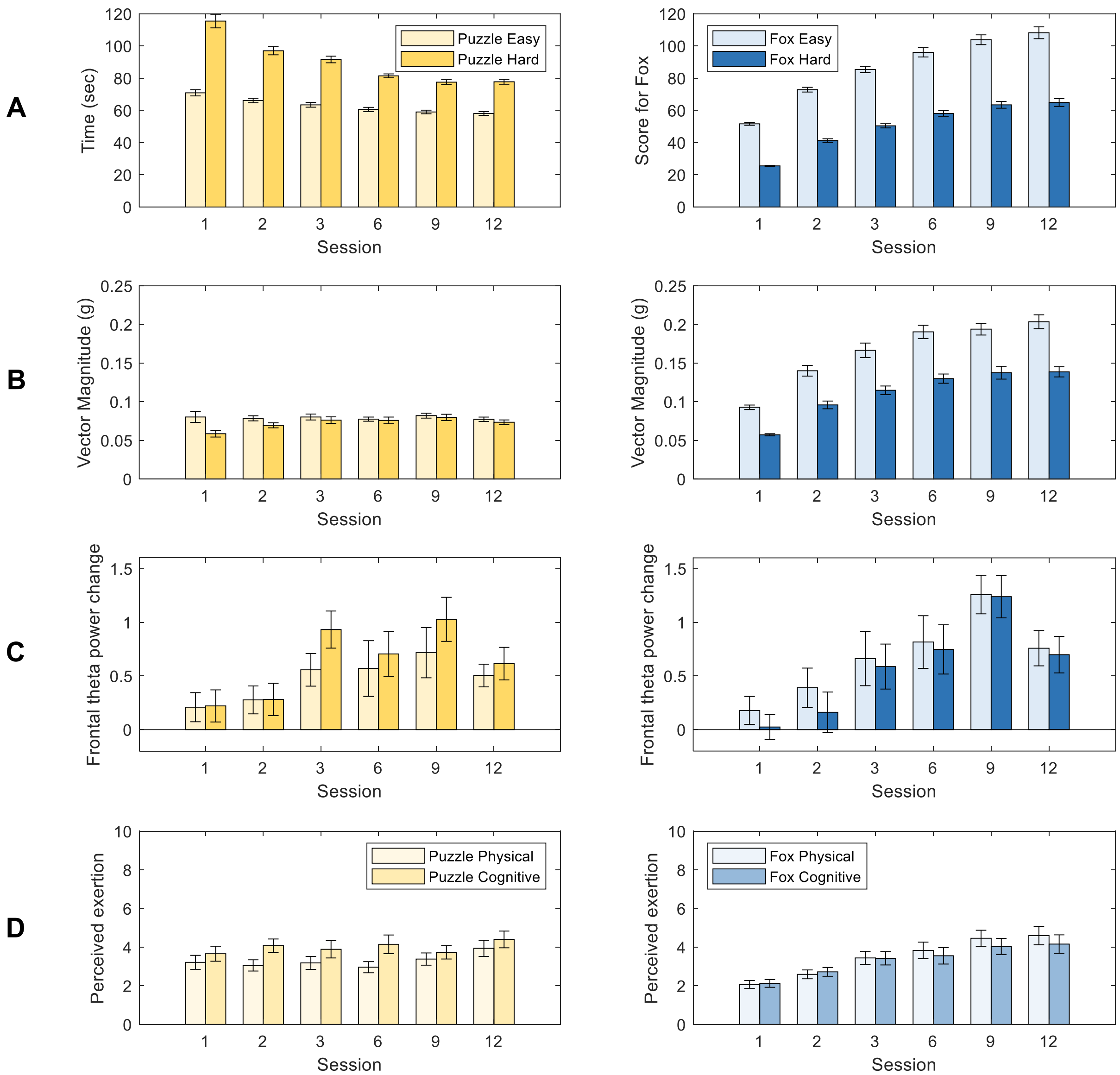

***Figure 5**: Overview of the main results across all training sessions. Mean across participants and SE are displayed, the Puzzle game in yellow, the Fox game in blue. **A**: Performance: better performance in the Puzzle game is indicated by a shorter playing time, in the Fox game by a higher score. **B**: Physical activity measured with accelerometer. **C**: Change in frontal theta from the reference movement to the corresponding game. Positive values show a training stimulus above reference. **D:** Perceived physical and cognitive exertion.*

3.1 Paper 1: Effects of game characteristics on brain activity and physical activity

The primary objective of the first paper was to examine the immediate effect of two different exergames at two levels of difficulty on brain activity and physical activity in older adults. Therefore, brain activity in terms of theta power and alpha-2 power and physical activity in terms of HR and acceleration during exergaming and reference movement were analyzed from session 1 in a cross-sectional design.

The participants demonstrated significantly better performance in the easy condition compared to the hard condition. In addition, they perceived a higher exertion during the Puzzle game compared to the Fox game, but experienced similar levels of physical and cognitive exertion.

Physical activity parameters, as measured by vector magnitude from acceleration sensors, revealed that the participants moved significantly more during the Fox game compared to the Puzzle game. Further analysis of each game demonstrated that the participants moved less with increasing complexity of the conditions. In both games, the vector magnitude was significantly higher during the reference movement compared to the exergaming. Furthermore, the vector magnitude was lower in the hard condition compared to the easy condition. HR was not further analyzed because 12 of 28 participants used medication with a potential impact on HR, thereby rendering the results invalid.

Brain activity revealed five different clusters: one frontal cluster, two central clusters, and two parietal clusters. The frontal theta showed an overall increase during both games compared to the reference movement, with no further significant differences between the easy and hard levels of difficulty. In contrast, alpha-2 power exhibited more diverse patterns for the central and parietal clusters.

3.2 Paper 2: Gameplay throughout an exergaming intervention

The second paper examined the physical activity of older adults during a four-week exergaming intervention. The primary aim was to investigate how difficulty level and game speed affect gameplay in older adults during a four-week exergaming intervention.

Performance, progression of game speed level, physical activity, and perceived exertion were analyzed from six measurement sessions across a four-week exergaming intervention.

The games speed level of the Fox game was tailored individually for each participant throughout the exergaming intervention. All participants demonstrated an increase in their game speed level and rated it as appropriate at the end of the intervention. Concurrently, participants exhibited a significant improvement in their performance across the intervention in both games and difficulty levels. Additionally, participants demonstrated superior performance in the easy condition compared to the hard condition for all time points and both games.

As with performance, physical activity during the exergaming intervention increased across the intervention for both games and difficulty levels. When comparing the games, the increase for the Fox game was higher than for the Puzzle game. These results are consistent with those of Paper 1, in which participants moved more in the easy condition compared to the hard condition in both games, illustrating that this is maintained over repeated sessions. This effect was larger for the Fox game than for the Puzzle game.

When asked to rate their perceived exertion, participants rated the Fox as increasing over the intervention period, consistent with the observed increase in performance and physical activity. In contrast, the rated exertion for the Puzzle game remained consistent throughout the intervention. A comparison of the games revealed that the Fox game was perceived as significantly more physically exhausting than the Puzzle game, while cognitive exhaustion was rated similarly.

The potential effect of the four-week intervention was evaluated by measuring fear of falling and physical function using the Community Balance and Mobility Scale at the initial and final sessions. Participants showed a significant improvement in physical function throughout the intervention, while fear of falling did not change significantly, but was already low before the intervention. In addition, participants were more physically active than their peers in the same age group.

3.3 Paper 3: Monitoring cognitive demand during an exergaming intervention

The third paper focused on the cognitive demand during a four-week exergaming intervention. The primary aim was to monitor cognitive demand and explore the potential effects of intervention duration and level of difficulty. The game performance and cognitive demand in terms of frontal theta activity were explored at six time points throughout a four-week exergaming intervention.

Consistent with and extending the cross-sectional results from Paper 1, frontal theta was significantly increased during exergaming compared to the reference movement at all time points for both games, illustrating that the increased cognitive involvement does not disappear due to habituation or learning across the four-week exergaming intervention. Moreover, the difference between exergaming and reference movement continued to increase significantly over the course of the intervention. However, no effect of game type or difficulty level on frontal theta activity was found.

4 Discussion

This chapter provides an overall interpretation of the findings from the three papers included in this thesis and a further discussion of the overall significance of the findings. First, the main findings of the studies will be summarized and interpreted in the context of the overall objective of this thesis. A more detailed discussion of all findings can be found in the manuscripts. Furthermore, methodological considerations regarding the chosen approaches will be discussed and potential areas of research and application will be elaborated.

The overarching objective of this thesis was to investigate the effects of exergaming on cognitive and physical activity in older adults during a four-week exergaming intervention. Additionally, the impact of game characteristics on gameplay was studied. Those collective findings are a crucial step towards individualized tailoring of exergaming interventions.

Paper 1 examined the immediate effect of game characteristics on cognitive demand and physical activity in a single exergaming session. Regarding physical activity, a reduction in the amount of movement was observed in conjunction with an increase in complexity. The HR measurements could not be used in this cohort of participants due to the potential influence of medication on HR, which was reported by a significant proportion of the study participants. Theta waves in the frontal region were elevated during exergaming compared to similar movements in front of a black screen without cognitive stimuli, regardless of the game and level of difficulty. This suggests that exergaming places a greater cognitive demand on the brain than the performance of the movement itself. Given the consistent results, theta waves in the frontal region were deemed a promising biomarker for cognitive involvement during exergaming. In contrast, inconsistent and diverging patterns were observed in central and parietal alpha-2 activity. Consequently, only frontal theta activity was analyzed in the longitudinal data of paper 3 and is discussed in greater detail further below.

Paper 2 confirmed and extended the findings of the cross-sectional study regarding the effect of difficulty level on physical activity over a four-week period. Furthermore, it was demonstrated that game performance, physical activity, and perceived exertion increased more for the individually tailored game than for a game played with the same settings across the intervention period. Additionally, comparing the first and initial session, the participants increased their physical function (as indicated by the CBMS) while their fear of falling was not affected by the exergaming intervention. This confirms the positive effects of exergaming on fall risk factors such as balance and mobility, as was also found in previous studies (Chen et al., 2021; Donath et al., 2016; Gomes et al., 2018).

Paper 3 examined the cognitive demands across a four-week exergaming intervention. Extending the findings in Paper 1, frontal theta activity was increased during exergaming at all time points for both games and difficulty levels, indicating that exergaming effects do not disappear due to habituation but reflect sustained activation of the brain. Moreover, as performance improved throughout the intervention period as well, the cognitive involvement relative to the reference movement increased, suggesting a training effect based on automatization and improved focusing on the game.

The following sections present a detailed discussion on monitoring physical load and cognitive demand during exergaming and the impact of exergaming, game characteristics, and intervention duration on those measures. A detailed discussion of the chosen methodology, considerations and implications for individually tailored exergame sessions in older adults and future research fields will be presented based on the study findings.

4.1 Impact of exergaming on cognitive involvement

Exergaming is a form of exercise that combines physical and cognitive training within a digital environment. As a first step in this thesis, the impact of exergaming on physical activity and cognitive involvement was evaluated by comparing exergaming to conducting similar movements (stepping or leaning sideways) in front of a black screen without cognitive stimuli as a reference movement.

At all time points during the intervention, frontal theta activity was increased during exergaming compared to the reference movement. Increased frontal theta activity is associated with cognitive demands, which have been described as reflecting attentional control processes (Gevins et al., 1997; McEvoy et al., 2001; Sauseng et al., 2005). Although the participants performed the same movement in the reference condition as in the exergames, they had to focus their attention on the game, process visual information, react to the demands of the game, and use their body to play the game with the appropriate movements. The findings suggest that exergaming addresses the attentional system and increases cognitive demands in older adults. Frontal theta has been linked to attentional processes in numerous previous studies, including those investigating cognitive (Cavanagh & Frank, 2014; Sauseng et al., 2010) and sensorimotor (Baumeister et al., 2008; Büchel, Lehmann, Ullrich, et al., 2021; Jacobsen et al., 2021) tasks. Previous studies have indicated that the ACC may be the origin for frontal theta activity (Gevins et al., 1997; Ishii et al., 2014; Petersen & Posner, 2012). This has been identified as an important component of the human attentional system in neuroimaging and brain lesion studies (Karni et al., 1998; Luks et al., 2002).

Enhanced cognitive involvement underscores that exergaming is more than merely performing specific movements. For instance, the player must control the fox avatar on the screen by coordinating sideways steps while simultaneously attending to the game to detect falling grapes and branches and planning the next steps to catch all grapes before they touch the ground without being hit by falling branches. Even such a simple mini-game thus combines movement coordination, attention, planning, and inhibition to assess how grapes can be caught without being hit by branches. The simultaneous nature of these tasks demonstrates that playing an exergame is an inherent cognitive-motor dual task. Previous research has demonstrated that older adults exhibit enhanced frontal theta when performing a dual task compared to single task conditions (Bohle et al., 2019; Ozdemir et al., 2016). The current findings indicate that similar mechanisms may be employed during exergaming compared to equivalent physical movements.

In the field of exergaming, a few initial studies have also indicated a correlation between frontal brain activity and exergaming. In young participants, increased frontal theta during exergaming was observed in comparison to a similar reference movement in a balance game and a ski simulator (Anders et al., 2018; Ko et al., 2020). Papers 1 and 3 extend these findings, illustrating that exergames address cognitive involvement in older adults as well.

Paper 3 demonstrated that the increased cognitive demands were present throughout all six time points of the intervention. This is the first study to describe the progression of cognitive demands throughout an exercise intervention. Prior studies that examined brain activity in exergame interventions measured it as proxy pre- and post-intervention while the subjects were seated or engaged in cognitive tasks, but not during the intervention (Schättin et al., 2016; Stojan & Voelcker-Rehage, 2019). This does not allow for conclusions about whether the training load during the intervention was appropriate to expect training adaptations. In contrast, the constant increase of frontal theta activity throughout the intervention in the current study indicates that even simple mini-games played repeatedly for 12 sessions over four weeks in a highly standardized environment continue to address cognitive demands in older adults. These findings indicate that this cognitive demand does not disappear due to a habituation effect but persists over time, even after four weeks of playing the same games. This finding underlines the potential of exergames to be utilized in longer interventions. The increased cognitive involvement may not be traced back to the fact of novelty and learning a new game but remains present what may be the result of the cognitive demands the exergaming is putting on the player.

4.2 Impact of game type and difficulty level

The variety of exergame systems, types of games, and game settings that are available provide countless opportunities for exergaming variation. However, to ensure effective exergaming intervention, it is essential to understand the impact of game characteristics on the gameplay, both in terms of physical load and cognitive demands. This thesis examined the influence of game type and level of difficulty on gameplay.

The Fox game and the Puzzle game differ in terms of both content and the objective of the game, as well as in the way the game is played (leaning versus stepping sideways). Participants moved extensively more during the Fox game, as stepping sideways requires a higher degree of movement than leaning sideways. In line with this, the participants rated their perceived physical exertion higher for the Fox game overall. It is important to note that this difference was not present at the start of the intervention, as the intensity of the Fox game started at a very low level. However, as the intensity of the Fox game increased as participants became more skilled, this difference became more apparent. In contrast, the type of game selected did not influence the cognitive demands as measured by the perceived cognitive exertion and the frontal theta power. These were comparable for both games, indicating that exergaming itself appears to influence frontal theta power.

Both games were played at two difficulty levels, with an additional cognitive element applied to increase the level of difficulty. In the Puzzle game, the participants had to decide between two puzzle pieces, and in the Fox game, they needed to avoid falling branches. This cognitive element increased the level of difficulty, as evidenced by the decreased game performance in the harder gaming conditions. Furthermore, the amount of movement decreased in the harder conditions for both games as well. This confirms the findings of previous studies that cognitive elements increase the difficulty level and influence the overall movement (Anders, Bengtson, et al., 2020; Skjæret-Maroni et al., 2016; Skjæret-Maroni & Bardal, 2018). The additional cognitive elements in the exergames place higher cognitive demand on the participants as they need to make a choice between puzzle pieces or inhibit the catching of grapes to prevent an accidental collision with branches. The capacity to perform cognitive and motor tasks simultaneously is generally diminished with age, and may result in a reduction in motor performance if the cognitive task becomes more demanding (Brustio et al., 2017).

However, the increased cognitive complexity did not result in a change in frontal theta activity in older adults, which stands in contract to observations in younger adults, where increased difficulty is accompanied by increased theta power in cognitive tasks (Cavanagh & Frank, 2014; Sauseng et al., 2005) as well as exergaming tasks (Anders et al., 2018). Other studies found that frontal theta increases with difficulty in young adults but not in older adults when testing working memory or coordination tasks (Depestele et al., 2023). The CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008) posits that older brains must exert greater effort to achieve comparable results to younger brains, thus requiring more neural resources. Should demands be further increased, the neural resources of older adults may reach their limit, resulting in inadequate processing and poorer outcomes. In the current study, frontal activity did not increase further in the difficult conditions, yet performance decreased in both games. This suggests that the neural capacity of older adults may have reached the maximal limit already in the easy games, with little opportunity for frontal theta to increase further in the harder condition.

In conclusion, the choice of game type and level of difficulty appear to exert influence on physical load in terms that the player’s movements were reduced when cognitive complexity was increased in both games, and they moved less during the Puzzle compared to the Fox. No influence of game type or level of difficulty was found on the cognitive demands in terms of frontal theta activity. To increase the challenge in a game and to prevent monotony, it may be important to increase the level of difficulty. However, it is important to be aware that the participants may move less in the more complex games, which would be disadvantageous if the players aim is to improve their physical activity. Furthermore, the type of game determines the kind of movement and in return the amount of movement. If the aim is to enhance stepping abilities, a game like the Fox game may prove more advantageous than the Puzzle game. In training balance and displacement of the center of mass, a game that demands movements that challenge balance, similar to the Puzzle game, may be the right choice. This thesis indicates that game characteristics need to be considered in general and their effect has to be carefully studied before employing them in a meaningful way in interventions. Those findings represent a further step towards understanding the impact of game characteristics on the player's gameplay.

4.3 Impact of repeated exergaming sessions and individual tailoring

This thesis included two games: the Puzzle game, which was played with the same setting throughout the four-week intervention period, and the Fox game, which had individually tailored game speed. Repeated measurements during the intervention period enable to quantify the impact of tailoring one game to the individual abilities of the player.

Both games demonstrated improvements in the performance across the intervention, indicating a training effect. However, both games reached a plateau, after session 6 for the Puzzle game and session 9 for the Fox game, indicating that they may have reached their level of mastery (Hardon et al., 2021; McConville & Virk, 2012). Further tailoring would be necessary from this point onwards to induce a training stimulus. Simultaneously, the relative cognitive involvement increased throughout the intervention period. The training effects can be interpreted based on research on skill level expertise. Higher frontal theta activity in experts compared to novices during goal-directed sports movements such as shooting or golf putting has been interpreted as an indicator for higher focused attention (Baumeister et al., 2008; Luchsinger et al., 2016). Due to increased automated gameplay across the intervention, older adults may be able to focus their attention (Haufler et al., 2000) on the essential elements of the game that improve their performance, in contrast to the beginning of the intervention when the focus was on understanding the game and being able to play it at all. In sum, automatization and improved game focus may be the results of a four-week exergaming intervention. This study indicates that these adaptations may be reflected by improved game performance and increased cognitive involvement.

All parameters showed a larger increase in the Fox game compared to the Puzzle game across the intervention. This effect might be attributable to the tailoring of the game speed during the intervention according to the participants’ performance and their perception of the game speed level. These findings are consistent with the assertion that training demands, which adapt over time to the evolving skills of the player, achieve more substantial training effects than constant demands (Wollesen & Voelcker-Rehage, 2014). As a result, games should be personalized to each player's skills in order to maximize effectiveness. Tailoring the game speed level based on a combination of performance and subjective assessment of their perceived appropriateness appears to be an effective approach for tailoring an intervention individually to each player. All players found their preferred game speed level throughout the intervention, which was higher than in the first session. Higher game speed resulted in increased physical activity and thus in increased perceived exertion of the participants in contrast to the Puzzle game that had constant demands across the sessions and showed no changes in the perceived exertion.

4.4 Methodological considerations

This thesis employed a variety of research methods to achieve the overarching objective of monitoring the physical and cognitive demands of an exergaming intervention. Pursuing this objective from multiple points may yield more robust and compelling results. However, each methodology possesses both strengths and limitations, which will be discussed in detail in the following paragraphs.

4.4.1 Strengths and limitations of the chosen study design

The main objective of this thesis was to monitor the physical and cognitive load of an exergaming intervention in older adults during a longer period of play. Consequently, a study design was developed with six measurement points during the four-week intervention in order to assess what happens during the entire intervention period, rather than merely before and after the intervention. A review of existing literature reveals no other exergame studies employing repeated measures of both physical and cognitive outcomes during the intervention period while participants were engaged in exergaming. In a recent randomized controlled trial, the perceived exertion and performance of the players were assessed at each training session of an exergaming intervention and published as secondary data (Bakker et al., 2020), but when using RPE it is only possible to assess the training load retrospectively after the task is finished.

Therefore, EEG, acceleration, and HR were measured in this study while the participants played exergames. This enables monitoring of physical load and cognitive involvement during the training itself instead of measuring or asking for the training load when the training is finalized which may increase the accuracy of the monitoring. EEG allows to measure brain activity while the participant is playing the exergame and can be used to monitor cognitive involvement. However, when using EEG, it is necessary to consider the time the participants are willing to dedicate to the study. The preparation time for EEG was scheduled with approximately 45 minutes, and the training intervention itself was 45 minutes as well. The study design of this thesis followed the recommendations that balance training for older adults should contain three sessions per week with 31-45 minutes of a single training session (Lesinski et al., 2015). However, with a study duration of four weeks, measuring EEG each session would be very time-consuming for the participants. Consequently, the focus was on the initial week, as habituation and training effects are typically most pronounced during the start of an intervention. The frequency of measurements was then reduced to once a week over the subsequent three weeks. This sampling rate was still sufficiently high to monitor the changes during the intervention. However, a limitation of this study design was the relatively short duration of four weeks, which may be insufficient to find significant effects of the intervention on physical and cognitive functions (Jiang et al., 2022; Lesinski et al., 2015). Furthermore, a control group was absent. To investigate the effects of exergaming interventions, a randomized controlled trial is necessary. However, in this thesis, the primary objective was not to investigate the effect of exergames on cognitive and physical function over time, but rather to monitor the load of exergames throughout an intervention.

It should be highlighted that this study was conducted with older adults as participants, which is the target group of this exergaming intervention. However, they enrolled for this study actively after newspaper advertisements intending that they were inherently interested in the topic of exergaming and fall prevention. Furthermore, the participants were highly active as evidenced by a higher PASE score than their average age group and minimal concerns about falling as indicated by the FES-I prior to the intervention. Therefore, it can be postulated that this sample of active older adults may not be representative of their peers, which may have influenced the results. For instance, the ceiling effect observed in the Fox game during the first session, where most participants caught all grapes, might indicate that the game speed was too low for the participant group. It is recommended that future studies do not commence with a fixed game speed level for all participants but rather individualize this as well. To manage this, participants could for instance have gotten the opportunity to try the game at the information session, allowing them to commence their training with a suitable training load from the first session onwards. This might enhance the efficacy of an intervention.

The physical activity during gameplay was assessed using vector magnitude, which quantifies the amount of movement per second as a function of time. In the Puzzle game, participants consistently performed the same movement sequence (leaning to the side 25 times). However, as they solved the puzzles more quickly over the course of the exergaming intervention, the movement per unit of time increased, although the total amount of movement during gameplay remained approximately constant. In contrast, the Fox game featured a fixed duration of eight minutes, divided into two four-minute segments per condition. To maximize the number of grapes caught within this time, participants were required to take more and faster steps, leading to a higher total movement output. Thus, the applicability of accelerometers depends on the nature of the games and their respective motion requirements. In this study, the accelerometer was positioned on the lower back to represent the center of gravity. For step-based games, such as the Fox game, it is possible to extract information about the steps by placing additional accelerometers on both feet (Skjæret-Maroni & Bardal, 2018).To detect the movement of the puzzle game, a placement on the higher back or neck may be more susceptible to the leaning movement. More detailed methods for describing movement characteristics, as employed in previous studies, are motion capture-based tracking (Anders, Bengtson, et al., 2020). However, for the purpose of expeditious application to monitor physical activity during exergaming, the accelerometer has been demonstrated to be viable.

During the intervention, participants were asked to rate their perceived exertion for each game at every session. However, they rated both levels of difficulty as one score, which may have introduced a bias into the results. Although participants were instructed to rate the overall exertion of both difficulty levels, some participants asked which difficulty level they should rate. Therefore, the order of difficulty levels played may have influenced the results, as participants may have rated the last difficulty level played. Future studies should ask participants to rate each condition separately. This would allow to investigate the effect of complexity on perceived exertion and strengthen the informative value of the perceived exertion data. However, a distinction was made between physical and cognitive exertion. During the data collection, it became evident that some participants had problems in differentiating between cognitive and physical exertion, which may have influenced the outcomes. Previous studies have demonstrated that RPE during exergaming may result in a reduced RPE compared to traditional exercise due to the gamification and distraction from the exertion itself (Hassan et al., 2023; Luiz de Brito Gomes et al., 2023). This should be considered when employing RPE during exergaming.

4.4.2 Strengths and limitations of the exergaming system

Exergaming offers a motivating and enjoyable way to engage in physical activity. But to do so, it is important that the exergame intervention is designed properly to enable the player to reach their training goals. In this thesis, participants were only permitted to play two games each session. This was due to the need for standardization, although in a practical clinical setting, it could be preferable to allow for greater variety. The feedback from the participants indicated that they would have preferred to play other games to increase variety and prevent boredom. Furthermore, including a variety of games would allow for different movement patterns that may in turn provide different training effects. In this thesis, the movements were only sideways, which was specified by the games. However, to reach the potential in exergames, it should be considered to accommodate different movement patterns, including those played in a seated position for participants with limited mobility. Furthermore, the selected games should be adjustable to tailor the exergaming intervention to the individual abilities of the player and contain a higher variability so that the intervention is a fun way to train and not monotonous.

Nevertheless, regardless of the variety in the games, motivation and fun quickly disappear if difficulties with the game appear. In this study, the game occasionally encountered difficulties identifying the player, even when they remained within the designated playing area. Potential causes included the use of black clothing, reflecting materials, or sunlight reflections that interfered with the camera recognition. If the system failed to recognize the player, gameplay was interrupted, disrupting the player's flow, and potentially leading to frustration. Without a clear understanding of the underlying problem, this could have a negative impact on players' motivation and enjoyment. This underscores the need for exergaming systems to be stable, as a lack of stability can lead to a lack of motivation and a reduced likelihood of long-term engagement with the games.

However, even if the system functions properly, participants do not always play the games as intended. Sometimes players find creative ways to solve the game without performing the movements as intended, which might decrease their training effect. For the Puzzle game, the leaning movement was not intuitive for all players, and in the initial sessions, they attempted taking steps and used their hands to solve the puzzle. The intention of the game is to challenge the player’s balance by performing a leaning movement of the whole body. However, most participants performed a bending of the upper body which might not accomplish the same effects on training balance. Furthermore, the game design occasionally constrains the movement of the participants. In the Fox game, several participants’ avatars got stuck on the edge of the screen for some time due to their initial strategy to avoid the branches. They opted for missing grapes on the opposite side of the screen and lingered in the corner of the screen, waiting for the branches to pass. As the point of the games is to encourage movement, it would be advantageous to provide participants with a solution to circumvent the branches, rather than requiring them to wait.

The decision to wait was often not optimal in terms of performance and game score, as more grapes were missed than the penalty would have been when hit by branches. However, in general, the game score was important for the motivation of the players. They often asked about the high score of the other participants and competed against their own results from previous sessions. This demonstrates that the game score provides high motivation due to the comparison to others and enables the monitoring of one’s own results and the receipt of feedback regarding the training.

Moreover, exergames are an appropriate alternative to traditional gym or group training sessions, offering a convenient and accessible option for training at home. This enables individuals who are not able to get outside in all kinds of weather or who are not mobile enough to get to a rehabilitation center, to train independently. Furthermore, home use allows for training to be conducted between appointments with therapists. The game score enables the therapist to verify whether and how the patient performed the exercises at home. However, exergames may be an addition to regular supervised training and should not be a replacement.

Potential disadvantages may include safety issues or cheating, which could result in the games not being played as intended. This research has shown that supervision, at least at the beginning, is advised to ensure proper application.

If used at home, exergames need to meet different criteria than for use in a laboratory, a gym or even at a rehabilitation center which are supervised conditions. In this thesis, the Silverfit system was used that was specifically designed for older adults. Once set up, it is relatively simple to use. The game starts as soon as the computer starts, the mouse is replaced with a handheld controller that simplifies the interaction with the system, and each game is explained by short videos. However, the settings of the games are not that intuitive to find and to change. Those who are less familiar with computers may require assistance in adapting the game to their specific needs and abilities.

The system is dependent upon a camera that detects the movement of the player. This enables the player to move freely in front of the screen without the use of a controller or balance board. However, the playing area in front of the screen is 5x5 m, which is quite large. This is beneficial in terms of allowing the player to move freely, but this makes the Silverfit system unsuitable for use at home, as most living rooms do not provide that much space in front of the screen. Furthermore, it is important that the space in front of the screen should be free from any obstacles such as furniture and carpets, as they might increase the risk of collision and falling. This is a risk factor that can lead to injury, especially in older adults. Additionally, the player may not be able to observe their surroundings, as they are focused on the game. This phenomenon of immersion was also observed in this study in a laboratory setting. A significant number of participants exhibited a tendency to approach the screen while playing. However, if they moved too close to the screen, the camera was unable to detect them accurately, resulting in a warning on the screen and an interruption of the game until the player moved back to the starting position. This interruption resulted in a disruption of the intended immersion and the flow of the game. It would be preferable if the participants were guided back into the playing area by game elements within the game that encourage the player to take steps backwards.

4.4.3 Strengths and limitations of mobile EEG

The rapid development of technology has enabled the use of mobile brain imaging technology to measure brain activity in more complex and dynamic situations (Ladouce et al., 2017). Due to its portability and high temporal resolution, mobile EEG has been considered the superior application in mobile movement protocols (Gramann et al., 2014). However, EEG in general, and the mobile approach in particular, is subject to inherent limitations in study design and data analysis that must be addressed.

One inherent limitation of EEG is its poor spatial resolution. The activity generated in any brain region creates far-field potentials that are distributed widely via the brain tissue and skull across the scalp surface by passive volume conduction. Consequently, the EEG signal at a single electrode is the sum of activities from various brain sources, as well as artifacts from muscles, eyes, electrodes, movements, or the electrical environment (Onton & Makeig, 2006). Brain activity itself is a weak electromagnetic signal that is easily disturbed by larger signals, such as larger movements from the participant or the muscle activity itself, which induces artifacts. Consequently, addressing artifacts is an inherent aspect of EEG measurement, encompassing the design of the study and the processing of the EEG signals, particularly in mobile brain imaging (Niso et al., 2023).

In designing this study and selecting the exergames, it was considered that it would be possible to measure EEG while playing these two particular games. Both games chosen for the study involved movement of the lower extremities, with leaning or stepping sideways. The feasibility of playing the Puzzle game while measuring EEG was demonstrated in a previous study (Anders et al., 2018). However, the movement intensity for the Fox game was higher. Nevertheless, mobile brain imaging has been successfully applied in previous studies involving walking and running (Gwin et al., 2010). Therefore, it can be assumed that the methods for mobile brain imaging can be transferred to stepping exergames. Furthermore, in the Fox game, the possibility of gaining additional points by making the Fox jump to catch chickens by lifting the arms (Anders, Bengtson, et al., 2020) was excluded to prevent movement artifacts. Additionally, participants were informed of the importance of not clenching their teeth or speaking during the game in order to minimize artifacts. This thesis confirms that it is feasible to measure mobile EEG during exergaming under these conditions.

However, EEG measurement during exergaming always results in EEG data contaminated with artifacts, despite the implementation of all available precautions. Previous studies have raised concerns about the origin of time-frequency results from mobile measurements due to insufficient artifact removal (Jacobsen et al., 2021; Kline et al., 2015). Since the frequency band of artifacts and functional brain activity overlap in studies involving movement, a simple approach using band pass filtering is not sufficient. In addition to traditional filtering techniques, a variety of methods have been developed to remove non-brain activity. An initial overview of these methods proposes a combination of techniques, for example combining automated cleaning (ASR) with separation of the mixed signal (ICA) (Gorjan et al., 2022). In this study, a bandpass filter, ASR, and ICA were selected to remove non-brain artifacts and to decompose the functional brain activity from the mixed signal, thereby counteracting volume effects.

Prior to the application of an ICA, it is recommended that a high pass filter with a cut-off frequency just below the frequency of interest is applied in conjunction with a low pass filter to enhance the effectiveness of the artifact separation (Frølich & Dowding, 2018). In the context of this thesis, a cut-off frequency of 3 Hz was selected for the high-pass filter, with the objective of retaining the theta frequency range (4-7 Hz) while simultaneously filtering out slow drifts in the EEG signal, which may be induced by sweating.

The ASR method has previously been used in walking studies as part of the preprocessing pipeline before the ICA (Bulea et al., 2014). This method has been demonstrated to enhance the ICA decomposition and involves the automated removal to misclassifying (Chang et al., 2020). The ASR is based on a principal component analysis that decomposes the multi-channel EEG data using a sliding window. First, clean reference data is automatically selected from the raw data. Next, a threshold for identifying artifact components is calculated, and the ASR rejects artifact components in each time window that exceed the rejection threshold. Finally, the remaining clean data is reconstructed (Chang et al., 2020). Determining the appropriate rejection threshold is a crucial aspect of this process. The standard deviation across the principal component space of all windows is multiplied by the cut-off parameter k, which must be defined manually. Lower k values result in a stricter ASR. While previous studies have recommended default values of 5-7 (Gorjan et al., 2022), other studies have proposed values of 20-30, arguing that the default would be too aggressive (Chang et al., 2020). Additionally, a study evaluating single leg stance and fast walking has suggested a cut-off value above 10 (Anders, Müller, et al., 2020). In a systematic literature review on studies during high-intensity locomotion, Gorjan et al. (2022) recommended a cut-off value of approximately 10. For this investigation, a cut-off value of 7 was chosen, following previous studies (Jacobsen et al., 2021; Nordin et al., 2020). This implies that the ASR is highly selective in rejecting artifacts, which may result in a high percentage of data being reconstructed. A comparison of different cut-off values and a manual inspection of the cleaned data indicated that a cut-off value of 7 was the most suitable for the signal-to-noise ratio in this data set. Nevertheless, it is important to consider the high percentage of potentially reconstructed data, particularly given that the ASR rejects eye blinks and eye movements that are picked up in the frontal electrodes simultaneously with the frontal theta activity, which was the frequency of interest in this investigation.

To counteract the volume conduction, the ICA was applied to the cleaned data after ASR. ICA is the most popular method for removing artifacts in EEG studies, particularly when involving movements. Furthermore, it addresses the issue of one electrode picking up a mixture of signals due to volume conduction (Gorjan et al., 2022). The approach of the ICA is to extract independent EEG signals and their sources. The assumption is that the mixture of signals that arise from statistically independent sources are associated with different physiological activities and artifacts. ICA decomposes the signals into their components (ICs) (Onton & Makeig, 2006). In this investigation, only the functional brain components were analyzed further. The labeling process was conducted using an EEGLAB plugin (IClabel) to enhance the objectivity of the study. This was followed by a manual verification to ensure that only functional brain components were included in the subsequent analysis.

The number of ICs obtained from the data is equal to the number of channels in the dataset. Exploratory studies and fundamental research will benefit from increased head coverage and a high number of channels, particularly if data-driven methods such as ICA or ASR are to be employed (Niso et al., 2023). Furthermore, as the movement intensity increases, the number of channels should be increased to provide a higher number of degrees of freedom for the ICA to decompose the increasing number of potential artifacts in the data. A minimum of 64 channels is recommended (Gorjan et al., 2022), which was the case for the current investigation. To enhance the data quality, future studies may opt to increase the number of channels further, particularly in instances where the intensity may be expected to increase (Gorjan et al., 2022). However, it is crucial to consider the increased preparation time that this entails. For 64 channels, a preparation time of approximately 30-45 minutes is required, and the time required for preparation increases with the number of electrodes. It is important to note that not all participants are able to remain still for an hour to ensure proper electrode placement and a sufficient level of impedance (e.g. children or individuals with diseases or cognitive decline). Therefore, the number of channels should be determined carefully, with the number of channels depending heavily on the intended use of the system.

In contrast to the inherent disadvantage of poor spatial resolution of EEG, the temporal resolution is superior, allowing for the investigation of fast cognitive processes. However, the current investigation did not exploit this advantage since the EEG data was analyzed based on power spectral analysis. The recorded EEG data of one condition was averaged, resulting in one value per condition per frequency band. Consequently, both phases of decision-making (deciding which puzzle piece is correct) and less cognitive involvement (waiting until the new puzzle piece appears) were included, making it challenging to ascertain whether theta activity represents specific control-related processes (Ghani et al., 2021). One potential solution could be an event-related analysis of the EEG data, which focuses on the brief period surrounding the stimuli that elicit cognitive involvement (Olyaei et al., 2022). However, for event-related analysis, a substantial number of stimuli is necessary to ensure reliable results, which may not be feasible for older adults playing exergames. Furthermore, the precise stimuli (e.g. the appearance of the puzzle piece) must be exported from the exergame. Ghani et al. (2021) was one of the first studies to investigate cognitive involvement during exergaming, demonstrating that the N1 ERP component is an effective measure of cognitive involvement during exergaming with random auditory stimuli. However, to accurately measure the cognitive involvement around a specific decision-making stimulus, it requires precise information when this stimulus occurs. Power spectral analysis, as applied in this thesis, can be used to measure frontal theta power without synchronizing the exergaming system to the EEG system. For a simple and fast application to measure cognitive demand, it would be important that the EEG system works independently so that it can be applied to all games instead of being dependent on the stimulus information of the game. Nevertheless, future studies should compare these two approaches and assess the reliability of the N1 ERP as a potential biomarker for monitoring cognitive demand throughout an intervention.

Repeated measurements of EEG were uncommon in previous studies. However, a high degree of repeatability for all frequency bands was found in a study examining resistance training repeatedly using a similar preprocessing approach involving ASR and ICA (Domingos et al., 2023). Moreover, good repeatability was observed for the alpha and beta bands after submaximal running periods (Büchel, Lehmann, Sandbakk, et al., 2021). The preprocessing pipeline in the present thesis, which included bandpass filtering, ASR, and ICA, was automated to the greatest extent possible to ensure objective and consistent data processing for all data sets and to minimize potential bias in the data. Concurrently, the outcomes of the ASR and of the IClabel were evaluated manually to guarantee optimal data quality. Nevertheless, the reproducibility of frontal theta activity should be validated in future studies.

4.5 Lessons learned - practical considerations for exergaming with older adults

This thesis confirms the findings of previous research and suggests that it is important to monitor an exergaming intervention and that tailoring it to the individual is a crucial aspect of an effective intervention (Herold et al., 2019; Wollesen & Voelcker-Rehage, 2014). Following the general adaptation syndrome, it is important that the training stimulus is appropriate to achieve training adaptation and progression. If the training load is too low, no training effect is reached. Conversely, if the training stimulus is too high, fatigue can be the consequence (Cunanan et al., 2018). The training load model allows for the monitoring of a training process (Bourdon et al., 2017). It distinguishes between external and internal loads, with external load representing the objective measures (e.g. distance and speed of running) that an individual has completed, and the internal load representing the individual's response to a given external load (e.g. HR or RPE) (Cormack & Coutts, 2022). Consequently, the internal load can be adjusted by modifying the external load. To describe the dose of a training process, it is recommended to use specific markers of the internal load as a proxy (Herold et al., 2019). For instance, in endurance training it is common practice to monitor HR as an internal load to control the external load. The training aim could be to run for one hour at 60% of the maximum HR, which would result in different speeds for each individual. However, in an exergaming intervention, the external load can be controlled using game settings, but the practitioners need biomarkers for the training load.

In this thesis, physical activity was measured using acceleration and HR measures, the cognitive demand using EEG. Furthermore, the participants were asked to rate their perceived exertion after the game and the performance was depicted as game score. Our study showed that it was feasible to record acceleration, EEG and HR during exergaming as objective measures. Although being one of the most used physical measures, the HR measures in this study were not reliable in this cohort of older adults. Although only including older adults without acute diseases, the use of medication in this age group in general is increased and more than 40% of them reported to use antihypertensives. Previous research supports that HR is not a reliable indicator of exercise intensity in individuals taking beta-blockers (Izquierdo et al., 2021), as these medications significantly lower both resting and maximal HR (Arena et al., 2010; Han et al., 2022). Consequently, studies should interpret HR data with caution and ensure that the types of medications used by participants are reported to accurately assess the results of exergame activity. Furthermore, physical activity was measured using accelerometers and the vector magnitude reflecting the amount of movement during exergaming. This approach was used before to measure the physical activity during dance (Jeffries et al., 2017), netball (Graham et al., 2020) or basketball (Vázquez-Guerrero et al., 2019) and stepping games (Skjæret-Maroni & Bardal, 2018). This study confirmed that using accelerometer measures during exergaming was feasible and easily applicable. However, a disadvantage is that the training load is calculated after the intervention, for immediate feedback, a simultaneous analysis of the data would be necessary.

Similar disadvantages are present when using mobile EEG to measure cognitive demand. On the one hand, EEG allows for neurophysiological measures directly related to the brain, on the other hand, it is -as conducted in this study- time consuming due to preparation and does not give immediate feedback about the training load. For future implementation, a reduced number of electrodes may reduce the preparation time and make the neurophysiological measures more applicable. However, it is an objective direct measure to describe the cognitive demand during exergaming and was shown feasible in this study. Alternative physiological measures for cognitive demand indicators like HR, blood pressure or pupil eye tracking (Perrey, 2022) may be easily applicable but are often biased by physical activity, what make is not suitable for exergaming since the increased HR of physical activity may cover the increased HR of cognitive demands. Behavioral indicators for cognitive demands as the performance (Perrey, 2022) were measured in this thesis as well. But as with physiological measures, the game score represents a combined physical and cognitive performance and does not clearly represent the cognitive demands of exergaming. However, the game score is a straightforward way to give brief feedback to the participants and was experienced as motivating to improve the own game score throughout the exergaming intervention. Furthermore, cognitive demand can be recorded using subjective self-rating (Perrey, 2022). In comparison to EEG and accelerometer measures, the RPE is an easy implementation and a proven method that does not need much equipment and shows the internal training load immediately. However, this method is dependent on the ability of the participants to judge their exertion retrospectively. Results from this study indicate that the subjective RPE measures underpin the objective measures. For example, the participants rated the Fox game as more physically exhausting than the Puzzle game, which was reflected in the objective acceleration data.

Based on the training load model in the context of exergaming, possible biomarkers for the external load could be described using accelerometer measurements and for the internal load using EEG and RPE. It is important to exercise caution when interpreting HR measurements in older adults who may be taking medication. The training load can be adjusted by selecting appropriate games and modifying their game characteristics. This research highlights the importance of monitoring the training load repeatedly throughout an intervention and provides a foundation for tailoring the intervention to the individual.

4.6 Implications – potentials in the field of exergaming in older adults

This thesis posits that screen-based exergaming can be a viable means of integrating physical and cognitive training into the lives of older adults in a manner that is both enjoyable and effective. However, as technology continues to evolve in the gaming field, there may emerge new avenues to combine gamification and fall prevention interventions. Currently, most people have access to various technologies in their homes, which could be leveraged for this purpose. Each mobile phone, tablet, or smartwatch already incorporates a multitude of sensors that present a wealth of potential for being implemented in exergames. At the same time, mobile phones are improving in detecting people: social media filters recognize faces, and webcams can follow speakers in online meetings. Furthermore, machine learning and artificial intelligence are becoming more available and open for innovative solutions. One popular option for markerless tracking of body positions from a video is the open source model OpenPose (Cao et al., 2021). It allows to track human posture and joint angles from a video or a picture. With similar solutions, the standard mobile phone camera rather than a sophisticated depth camera may represent a cost-effective option for use at home. First examples of exergames using a standard camera are Ergofox (Hamburg, Germany) or different games from Nex (San Jose, USA) that use a mobile phone or webcam to allow gamification of basketball training, dance games, and party games to motivate the player for physical activity that is easy applicable. While these technologies may not have the same level of precision and capabilities as screen-based exergaming systems for rehabilitation, they may be suitable for use in a domestic setting which may increase usability. Pokémon Go showed that it is not always necessary to implement complex solutions. The concept behind Pokémon Go was relatively simple but highly effective in encouraging people to go outside and be physically active (J. E. Lee et al., 2021). The prospect of catching Pokémon with a mobile phone in a park may be a more motivating activity than simply going for a walk in the park. Simple and accessible solutions, such as mobile phones, should be considered in the future. Such games have the potential to motivate individuals to become more physically active, thereby preventing the onset of a sedentary lifestyle and the subsequent downward spiral of functional decline (Whitehead, 2019).

Searching for monsters in the park may enhance physical activity but is insufficient in more specific rehabilitation settings. To accomplish more specific training goals in a clinical application, the games need to instruct specific exercises in a rehabilitation context. A more sophisticated approach regarding the cognitive component of exergaming could be to use brain activity to control the cognitive demand of an exergame. In conjunction with recent research in the field of brain-computer interfaces (BCI) and neurofeedback training (NFT), a reliable biomarker for cognitive involvement could serve as a foundation for future research aimed at developing a game that can regulate cognitive demand automatically. BCI enables the bypassing of the body’s neuromuscular pathways by measuring brain activity that is associated with the user’s intent and translating it into an electronic device as an executive body, only by means of voluntary changes in the brain activity. Thereby BCI allows to control for example a cursor on a screen or moving forward and backwards in a virtual reality using EEG activity (Alchalabi & Faubert, 2019). NFT actively trains specific frequency bands, for example aiming to actively increase theta activity, by providing feedback about the amount of theta activity on a screen. NFT was shown to improve memory in older adults (Laborda-Sánchez & Cansino, 2021). In the field of exergaming, a mixture of those technologies might serve as a control mechanism of the exergame. Brain activity could be measured while playing the exergame, and the cognitive complexity of the game could be tailored in real-time based on the cognitive involvement measured using EEG. This would allow to keep the cognitive demand at a level that is suitable for cognitive training. Similar approaches have been employed using HR during a bicycle exergame. The game was able to regulate the intensity of the physical activity in a way that the player performed a high intensity interval training (Moholdt et al., 2017). This thesis suggests frontal theta activity as a possible measure for cognitive involvement during exergaming. Further knowledge is needed to establish what is a suitable level of cognitive involvement as a threshold and how cognitive involvement can be measured as simple as possible but with reliable results. As a next step, games need to be designed that can be tailored based on the EEG data.

4.7 Future research – to reach the potential of exergaming

To further implement exergames in clinical settings, high-quality randomized controlled studies are necessary to validate the effectiveness of exergaming on both physical and cognitive functions. These studies should also explore whether the positive effects of exergaming can be transferred to everyday function and fall prevention for participants. Additionally, research is needed to identify the factors that contribute to sustaining long-term benefits from exergaming interventions. Furthermore, it is essential to identify the specific components that comprise an effective exergaming intervention. It is necessary to investigate the potential effects of modifiers, such as exercise type, intensity, and training frequency, on the effectiveness of exergaming and to monitor the physical and cognitive training load during the intervention.

This thesis used acceleration and HR to monitor the physical training load. Especially HR was not found reliable in the cohort of older adults and alternatives need to be found. With vector magnitude, an easy approach was chosen for the acceleration data. It was able to describe the overall movement, but it always displayed the amount of movement per time and no absolute values. Furthermore, small movements like shifting weight in the puzzle game result in extremely low amounts of movement. Future research should focus on more detailed measures like stepping strategies or the area of movement (Skjæret-Maroni & Bardal, 2018) to being able to describe the physical load of exergaming more detailed.

This thesis utilized frontal theta activity to describe cognitive involvement while exergaming using EEG. This approach requires effort and expertise to apply the EEG electrodes properly what is a barrier if this method should be applied outside the laboratory setting. A total of 64 channels covering the entire scalp were used during this investigation, allowing to explore brain activity during exergaming in general and to be able to analyze the data in source space using ICA and ASR. However, only the frontal cluster was analyzed further. Based on the results indicating that frontal theta may serve as a potential biomarker for cognitive demands during exergaming, it may be sufficient to limit the analysis to the frontal area and reduce the number of electrodes. Future studies should verify whether the findings can be replicated with a reduced number of electrodes, for instance, by only recording frontal brain activity from the outset. Ghani and colleagues demonstrated that comparable results could be obtained regarding the cognitive involvement during exergames, as measured through N1 RPE analysis, using data obtained with 64 channels and with three midline electrodes (Fz, Cz, Pz) with a ground and reference electrode (Ghani et al., 2020, 2021). Further studies should be conducted to determine the minimum number of electrodes required to accurately assess absolute frontal theta power.

One downside of reducing the number of electrodes to the frontal area is that analysis in source space is not possible. An alternative approach to improving the spatial resolution of EEG data would be to combine EEG measurements with fNIRS. By recording both simultaneously, it is possible to combine the advantages of both technologies to gain a more holistic understanding of brain activity. This approach allows for the study of the interaction between neuronal and hemodynamic phenomena, which can inform conclusions about alterations in neurovascular coupling (Yeung & Chu, 2022). Moreover, the concurrent measurement of EEG and fNIRS would allow for validation of each system. The high spatial resolution of the fNIRS enables the validation of EEG source localization methods based on fNIRS results (Steinmetzger et al., 2020). The combined EEG-fNIRS approach has been most frequently employed in studies of sensory and motor function (Yeung & Chu, 2022). However, it has not yet been utilized in a mobile setting that encompasses larger movements than those of the fingers. Given that both EEG (Anders et al., 2018) and fNIRS (Eggenberger et al., 2016) have already been employed in movement protocols within the field of exergaming, a combined application may prove beneficial for future studies.

5 Conclusion

This thesis demonstrates the potential of exergames as a versatile tool for enhancing both physical and cognitive functions in older adults. For people like Mr. Smith, such games offer an opportunity to counteract age-related functional decline and promote healthy aging. This research has provided valuable insights into how these interventions affect physical activity and cognitive involvement by being the first to repeatedly measure both physical activity and cognitive engagement during exergaming sessions for older adults. The consistent cortical involvement throughout the intervention underscores the cognitive engagement inherent to exergaming. Moreover, game characteristics, including game speed and difficulty level, significantly influence the physical activity and perceived exertion of the player. Therefore, it can be posited that game characteristics may serve as a means of tailoring the exergame individually for each player, thereby providing an optimal training stimulus. The findings highlight the direct impact of exergames on the physical and cognitive demands placed on the player, emphasizing the importance of monitoring both aspects to effectively manage the training load. This research not only contributes to the optimization of exergame design for more effective outcomes but also establishes a foundation for future studies exploring the neurophysiological effects of exergaming. Such insights are critical for advancing exergaming as a targeted tool in older adults, offering a promising approach to mitigating age-related physical and cognitive functional decline. This thesis is a major step toward realizing the potential of exergaming in individually tailored, structured interventions to support healthy aging.

References

Adcock, M., Sonder, F., Schaettin, A., Gennaro, F., & de Bruin, E. D. (2020). A usability study of a multicomponent video game-based training for older adults. *EUROPEAN REVIEW OF AGING AND PHYSICAL ACTIVITY*, *17*(1). https://doi.org/10.1186/s11556-019-0233-2

Alchalabi, B., & Faubert, J. (2019). A Comparison between BCI Simulation and Neurofeedback for Forward/Backward Navigation in Virtual Reality. *Computational Intelligence and Neuroscience*, *2019*, 2503431. https://doi.org/10.1155/2019/2503431

Alschuler, D. M., Tenke, C. E., Bruder, G. E., & Kayser, J. (2014). Identifying electrode bridging from electrical distance distributions: A survey of publicly-available EEG data using a new method. *Clinical Neurophysiology*, *125*(3), 484–490. https://doi.org/10.1016/j.clinph.2013.08.024

Amjad, I., Toor, H., Niazi, I. K., Pervaiz, S., Jochumsen, M., Shafique, M., Haavik, H., & Ahmed, T. (2019). Xbox 360 Kinect Cognitive Games Improve Slowness, Complexity of EEG, and Cognitive Functions in Subjects with Mild Cognitive Impairment: A Randomized Control Trial. *Games for Health Journal*, *8*(2), 144–152. https://doi.org/10.1089/g4h.2018.0029

Anders, P., Bengtson, E. I., Grønvik, K. B., Skjæret-Maroni, N., & Vereijken, B. (2020). Balance Training in Older Adults Using Exergames: Game Speed and Cognitive Elements Affect How Seniors Play. *Frontiers in Sports and Active Living*, *2*(May), 1–11. https://doi.org/10.3389/fspor.2020.00054

Anders, P., Lehmann, T., Müller, H., Grønvik, K. B., Skjæret-Maroni, N., Baumeister, J., & Vereijken, B. (2018). Exergames Inherently Contain Cognitive Elements as Indicated by Cortical Processing. *Frontiers in Behavioral Neuroscience*, *12*(2), 102. https://doi.org/10.3389/fnbeh.2018.00102

Anders, P., Müller, H., Skjæret-Maroni, N., Vereijken, B., & Baumeister, J. (2020). The influence of motor tasks and cut-off parameter selection on artifact subspace reconstruction in EEG recordings. *Medical & Biological Engineering & Computing*, *58*(11), 2673–2683. https://doi.org/10.1007/s11517-020-02252-3

Andrews-Hanna, J. R., Snyder, A. Z., Vincent, J. L., Lustig, C., Head, D., Raichle, M. E. E., & Buckner, R. L. (2007). Disruption of Large-Scale Brain Systems in Advanced Aging. *Neuron*, *56*(5), 924–935. https://doi.org/10.1016/j.neuron.2007.10.038

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., Kong, E., Larraburo, Y., Rolle, C., Johnston, E., Gazzaley, A., J.A., A., J., B., J.L., R., O., A.-H., F., F., J., J., E., K., Y., L., … E., J. (2013). Video game training enhances cognitive control in older adults. *Nature*, *501*(7465), 97–101. https://doi.org/http://dx.doi.org/10.1038/nature12486

Arena, R., Myers, J., Abella, J., Peberdy, M. A., Bensimhon, D., Chase, P., & Guazzi, M. (2010). The prognostic value of the heart rate response during exercise and recovery in patients with heart failure: Influence of beta-blockade. *International Journal of Cardiology*, *138*(2), 166–173. https://doi.org/10.1016/j.ijcard.2008.08.010

Bakker, J., Donath, L., & Rein, R. (2020). Balance training monitoring and individual response during unstable vs. stable balance Exergaming in elderly adults: Findings from a randomized controlled trial. *Experimental Gerontology*, *139*(July), 111037. https://doi.org/10.1016/j.exger.2020.111037

Baumeister, J. (2013). Sensorimotor control and associated brain activity in sports medicine research. *Paderborn: Universitat Paderborn*, *July 2013*, 237. https://doi.org/10.13140/2.1.3261.0249

Baumeister, J., Reinecke, K., Cordes, M., Lerch, C., & Weiß, M. (2010). Brain activity in goal-directed movements in a real compared to a virtual environment using the Nintendo Wii. *Neuroscience Letters*, *481*(1), 47–50. https://doi.org/10.1016/j.neulet.2010.06.051

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology*, *104*(4), 625–631. https://doi.org/10.1007/s00421-008-0811-x

Bear, M., Connors, B., & Paradiso, M. (2016). *Neoroscience Exploring the Brain* (4th ed.). Wolters Kluwer.

Bogost, I. (2005). The Rhetoric of Exergaming. *Proceedings of the Digital Arts and Cultures (DAC)*, 10.

Bohle, H., Rimpel, J., Schauenburg, G., Gebel, A., Stelzel, C., Heinzel, S., Rapp, M., & Granacher, U. (2019). Behavioral and neural correlates of cognitive-motor interference during multitasking in young and old adults. *Neural Plasticity*, *2019*. https://doi.org/10.1155/2019/9478656

Bourdon, P. C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M. C., Gabbett, T. J., Coutts, A. J., Burgess, D. J., Gregson, W., & Cable, N. T. (2017). Monitoring athlete training loads: Consensus statement. *International Journal of Sports Physiology and Performance*, *12*, 161–170. https://doi.org/10.1123/IJSPP.2017-0208

Brustio, P. R., Magistro, D., Zecca, M., Rabaglietti, E., & Liubicich, M. E. (2017). Age-related decrements in dual-task performance: Comparison of different mobility and cognitive tasks. A cross sectional study. *PLoS ONE*, *12*(7), 1–15. https://doi.org/10.1371/journal.pone.0181698

Büchel, D., Lehmann, T., Sandbakk, Ø., & Baumeister, J. (2021). EEG-derived brain graphs are reliable measures for exploring exercise-induced changes in brain networks. *Scientific Reports*, *11*(1), 20803. https://doi.org/10.1038/s41598-021-00371-x

Büchel, D., Lehmann, T., Ullrich, S., Cockcroft, J., Louw, Q., & Baumeister, J. (2021). Stance leg and surface stability modulate cortical activity during human single leg stance. *Experimental Brain Research*, *239*(4), 1193–1202. https://doi.org/10.1007/s00221-021-06035-6

Bulea, T. C., Kim, J., Damiano, D. L., Stanley, C. J., & Park, H. S. (2014). User-driven control increases cortical activity during treadmill walking: An EEG study. *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2014*, 2111–2114. https://doi.org/10.1109/EMBC.2014.6944033

Cao, Z., Hidalgo, G., Simon, T., Wei, S. E., & Sheikh, Y. (2021). OpenPose: Realtime Multi-Person 2D Pose Estimation Using Part Affinity Fields. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *43*(1), 172–186. https://doi.org/10.1109/TPAMI.2019.2929257

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*, *18*(8), 414–421. https://doi.org/10.1016/j.tics.2014.04.012

Chang, C. Y., Hsu, S. H., Pion-Tonachini, L., & Jung, T. P. (2020). Evaluation of Artifact Subspace Reconstruction for Automatic Artifact Components Removal in Multi-Channel EEG Recordings. *IEEE Transactions on Biomedical Engineering*, *67*(4), 1114–1121.

https://doi.org/10.1109/TBME.2019.2930186

Chen, Y., Zhang, Y., Guo, Z., Bao, D., & Zhou, J. (2021). Comparison between the effects of exergame intervention and traditional physical training on improving balance and fall prevention in healthy older adults: a systematic review and meta-analysis. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–17. https://doi.org/10.1186/s12984-021-00917-0

Chikhi, S., Matton, N., & Blanchet, S. (2022). EEG power spectral measures of cognitive workload: A meta-analysis. *Psychophysiology*, *59*(6), e14009. https://doi.org/10.1111/psyp.14009

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K., & Hunt, M. (2010). Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait and Posture*, *31*(3), 307–310. https://doi.org/10.1016/j.gaitpost.2009.11.012

Cormack, S., & Coutts, A. J. (2022). Training Load Model. In D. French & L. Torres Ronda (Eds.), *NSCA's Essentials of Sport Science* (pp. 13–26). Human Kinetics.

Cunanan, A. J., DeWeese, B. H., Wagle, J. P., Carroll, K. M., Sausaman, R., Hornsby, W. G., Haff, G. G., Triplett, N. T., Pierce, K. C., & Stone, M. H. (2018). The General Adaptation Syndrome: A Foundation for the Concept of Periodization. *Sports Medicine*, *48*(4), 787–797. https://doi.org/10.1007/s40279-017-0855-3

Cunningham, C., O' Sullivan, R., Caserotti, P., & Tully, M. A. (2020). Consequences of physical inactivity in older adults: A systematic review of reviews and meta-analyses. *Scandinavian Journal of Medicine & Science in Sports*, *30*(5), 816–827. https://doi.org/10.1111/sms.13616

Daun, F., & Kibele, A. (2019). Different strength declines in leg primary movers versus stabilizers across age—Implications for the risk of falls in older adults? *PLoS ONE*, *14*(3), 16–18. https://doi.org/10.1371/journal.pone.0213361

de Vos, A. J., Asmus-Szepesi, K. J., Bakker, T. J., de Vreede, P. L., van Wijngaarden, J. D., Steyerberg, E. W., Mackenbach, J. P., & Nieboer, A. P. (2012). Integrated approach to prevent functional decline in hospitalized elderly: the Prevention and Reactivation Care Program (PReCaP). *BMC Geriatrics*, *12*(1), 7. https://doi.org/10.1186/1471-2318-12-7

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Depestele, S., van Dun, K., Verstraelen, S., Van Hoornweder, S., & Meesen, R. (2023). Midfrontal Theta and Cognitive Control During Interlimb Coordination Across the Adult Lifespan. *Journal of Motor Behavior*, *0*(0), 1–11. https://doi.org/10.1080/00222895.2023.2183178

Distefano, G., & Goodpaster, B. H. (2018). Effects of exercise and aging on skeletal muscle. *Cold Spring Harbor Perspectives in Medicine*, *8*(3). https://doi.org/10.1101/cshperspect.a029785

Domingos, C., Marôco, J. L., Miranda, M., Silva, C., Melo, X., & Borrego, C. (2023). Repeatability of Brain Activity as Measured by a 32-Channel EEG System during Resistance Exercise in Healthy Young Adults. *International Journal of Environmental Research and Public Health*, *20*(3). https://doi.org/10.3390/ijerph20031992

Donath, L., Rössler, R., & Faude, O. (2016). Effects of Virtual Reality Training (Exergaming) Compared to Alternative Exercise Training and Passive Control on Standing Balance and

Functional Mobility in Healthy Community-Dwelling Seniors: A Meta-Analytical Review. *Sports Medicine*, *46*(9), 1293–1309. https://doi.org/10.1007/s40279-016-0485-1

Eggenberger, P., Wolf, M., Schumann, M., & de Bruin, E. D. (2016). Exergame and balance training modulate prefrontal brain activity during walking and enhance executive function in older adults. *Frontiers in Aging Neuroscience*, *8*(APR), 1–16. https://doi.org/10.3389/fnagi.2016.00066

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Ferrucci, L., Gonzalez-Freire, M., Fabbri, E., Simonsick, E., Tanaka, T., Moore, Z., Salimi, S., Sierra, F., & de Cabo, R. (2020). Measuring biological aging in humans: A quest. *Aging Cell*, *19*(2), 1–21. https://doi.org/10.1111/acel.13080

Fjordside, S., & Morville, A. (2016). Factors influencing older people′s experiences of participation in autonomous decisions concerning their daily care in their own homes: a review of the literature. *International Journal of Older People Nursing*, *11*(4), 284–297. https://doi.org/10.1111/opn.12116

Fleg, J. L., Morrell, C. H., Bos, A. G., Brant, L. J., Talbot, L. A., Wright, J. G., & Lakatta, E. G. (2005). Accelerated longitudinal decline of aerobic capacity in healthy older adults. *Circulation*, *112*(5), 674–682. https://doi.org/10.1161/CIRCULATIONAHA.105.545459

Fragala, M. S., Cadore, E. L., Dorgo, S., Izquierdo, M., Kraemer, W. J., Peterson, M. D., & Ryan, E. D. (2019). Resistance training for older adults: Position statement from the national strength and conditioning association. *Journal of Strength and Conditioning Research*, *33*(8), 2019–2052. https://doi.org/10.1519/jsc.0000000000003230

Frølich, L., & Dowding, I. (2018). Removal of muscular artifacts in EEG signals: a comparison of linear decomposition methods. *Brain Informatics*, *5*(1), 13–22. https://doi.org/10.1007/s40708-017-0074-6

García Piqueras, J., García Mesa, Y., Cárcaba, L., Feito, J., Torres Parejo, I., Martín Biedma, B., Cobo, J., García Suárez, O., & Vega, J. A. (2019). Ageing of the somatosensory system at the periphery: age related changes in cutaneous mechanoreceptors. *Journal of Anatomy*, *234*(6), 839–852. https://doi.org/10.1111/joa.12983

Gevins, A., Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: Effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, *7*(4), 374–385. https://doi.org/10.1093/cercor/7.4.374

Ghani, U., Signal, N., Niazi, I. K., & Taylor, D. (2020). A novel approach to validate the efficacy of single task ERP paradigms to measure cognitive workload. *International Journal of Psychophysiology*, *158*(March), 9–15. https://doi.org/10.1016/j.ijpsycho.2020.09.007

Ghani, U., Signal, N., Niazi, I. K., & Taylor, D. (2021). Efficacy of a Single-Task ERP Measure to Evaluate Cognitive Workload During a Novel Exergame. *Frontiers in Human Neuroscience*, *15*(September), 1–9. https://doi.org/10.3389/fnhum.2021.742384

Gomes, G. C. V., Simões, M. do S., Lin, S. M., Bacha, J. M. R., Viveiro, L. A. P., Varise, E. M., Carvas Junior, N., Lange, B., Jacob Filho, W., & Pompeu, J. E. (2018). Feasibility, safety, acceptability, and functional outcomes of playing Nintendo Wii Fit PlusTM for frail older adults: A randomized feasibility clinical trial. *Maturitas*, *118*(October), 20–28. https://doi.org/10.1016/j.maturitas.2018.10.002

Gorjan, D., Gramann, K., De Pauw, K., & Marusic, U. (2022). Removal of movement-induced

EEG artifacts: Current state of the art and guidelines. *Journal of Neural Engineering*, *19*(1). https://doi.org/10.1088/1741-2552/ac542c

Graham, S., Zois, J., Aughey, R., & Duthie, G. (2020). The peak player load™ of state-level netball matches. *Journal of Science and Medicine in Sport*, *23*(2), 189–193. https://doi.org/10.1016/j.jsams.2019.09.014

Gramann, K., Ferris, D. P., Gwin, J., & Makeig, S. (2014). Imaging natural cognition in action. *International Journal of Psychophysiology*, *91*(1), 22–29. https://doi.org/10.1016/j.ijpsycho.2013.09.003

Gwin, J. T., Gramann, K., Makeig, S., & Ferris, D. P. (2010). Removal of movement artifact from high-density EEG recorded during walking and running. *Journal of Neurophysiology*, *103*(6), 3526–3534. https://doi.org/10.1152/jn.00105.2010

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does gamification work? - A literature review of empirical studies on gamification. *Proceedings of the Annual Hawaii International Conference on System Sciences*, 3025–3034. https://doi.org/10.1109/HICSS.2014.377

Han, S. H., Choi, M. S., Kim, Y. M., Kim, D. M., Park, H. E., Hong, J. W., Kim, S. H., Shin, Y. B., & Lee, B. J. (2022). Is Age-Predicted Maximal Heart Rate Applicable in Patients With Heart or Lung Disease? *Annals of Rehabilitation Medicine*, *46*(3), 133–141. https://doi.org/10.5535/arm.21181

Hardon, S. F., van Gastel, L. A., Horeman, T., & Daams, F. (2021). Assessment of technical skills based on learning curve analyses in laparoscopic surgery training. *Surgery (United States)*, *170*(3), 831–840. https://doi.org/10.1016/j.surg.2021.04.024

Hassan, M. A., Ryu, S., Tao, K., Wang, R., Quan, M., & Gao, Z. (2023). Young adults' rating of perceived exertion and mood in exergaming dance and aerobic dance. *Brain Behavior and Immunity Integrative*, *2*(March), 100007. https://doi.org/10.1016/j.bbii.2023.100007

Haufler, A. J., Spalding, T. W., Santa Maria, D. L., & Hatfield, B. D. (2000). Neuro-cognitive activity during a self-paced visuospatial task: Comparative EEG profiles in marksmen and novice shooters. In *Biological Psychology* (Vol. 53, Issues 2–3). https://doi.org/10.1016/S0301-0511(00)00047-8

Henry, M., & Baudry, S. (2019). Age-related changes in leg proprioception: Implications for postural control. *Journal of Neurophysiology*, *122*(2), 525–538. https://doi.org/10.1152/jn.00067.2019

Herold, F., Müller, P., Gronwald, T., & Müller, N. G. (2019). Dose–Response Matters! – A Perspective on the Exercise Prescription in Exercise–Cognition Research. *Frontiers in Psychology*, *10*(November), 1–17. https://doi.org/10.3389/fpsyg.2019.02338

Hong, X. L., Cheng, L. J., Feng, R. C., Goh, J., Gyanwali, B., Itoh, S., TAM, W. S. W., & Wu, X. V. (2024). Effect of physio-cognitive dual-task training on cognition in pre-ageing and older adults with neurocognitive disorders: A meta-analysis and meta-regression of randomized controlled trial. *Archives of Gerontology and Geriatrics*, *116*(August 2023), 105161. https://doi.org/10.1016/j.archger.2023.105161

Irani, F., Platek, S. M., Bunce, S., Ruocco, A. C., & Chute, D. (2007). Functional near infrared spectroscopy (fNIRS): An emerging neuroimaging technology with important applications for the study of brain disorders. *Clinical Neuropsychologist*, *21*(1), 9–37. https://doi.org/10.1080/13854040600910018

Ishii, R., Canuet, L., Ishihara, T., Aoki, Y., Ikeda, S., Hata, M., Katsimichas, T., Gunji, A., Takahashi, H., Nakahachi, T., Iwase, M., & Takeda, M. (2014). Frontal midline theta rhythm and gamma power changes during focused attention on mental calculation: An MEG beamformer analysis. *Frontiers in Human Neuroscience*, *8*(JUNE), 1–10. https://doi.org/10.3389/fnhum.2014.00406

Izquierdo, M., Merchant, R. A., Morley, J. E., Anker, S. D., Aprahamian, I., Arai, H., Aubertin-Leheudre, M., Bernabei, R., Cadore, E. L., Cesari, M., Chen, L.-K., de Souto Barreto, P., Duque, G., Ferrucci, L., Fielding, R. A., García-Hermoso, A., Gutiérrez-Robledo, L. M., Harridge, S. D. R., Kirk, B., … Singh, M. F. (2021). International Exercise Recommendations in Older Adults (ICFSR): Expert Consensus Guidelines. *The Journal of Nutrition, Health & Aging*, *25*(7), 824–853. https://doi.org/10.1007/s12603-021-1665-8

Jacobsen, N. S. J., Blum, S., Witt, K., & Debener, S. (2021). A walk in the park? Characterizing gait related artifacts in mobile EEG recordings. *European Journal of Neuroscience*, *54*(12), 8421–8440. https://doi.org/10.1111/ejn.14965

Jeffries, A. C., Wallace, L., & Coutts, A. J. (2017). Quantifying training loads in contemporary dance. *International Journal of Sports Physiology and Performance*, *12*(6), 796–802. https://doi.org/10.1123/ijspp.2016-0159

Jiang, J., Guo, W., & Wang, B. (2022). Effects of exergaming on executive function of older adults: a systematic review and meta-analysis. *PeerJ*, *10*, 1–16. https://doi.org/10.7717/peerj.13194

Karni, A., Meyer, G., Rey-Hipolito, C., Jezzard, P., Adams, M. M., Turner, R., & Ungerleider, L. G. (1998). The acquisition of skilled motor performance: Fast and slow experience-driven changes in primary motor cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *95*(3), 861–868. https://doi.org/10.1073/pnas.95.3.861

Khan, S. S., Singer, B. D., & Vaughan, D. E. (2017). Molecular and physiological manifestations and measurement of aging in humans. *Aging Cell*, *16*(4), 624–633. https://doi.org/10.1111/acel.12601

Klem, G. H., Lüders, H. O., Jasper, H. H., & Elger, C. (1999). The ten-twenty electrode system of the International Federation. The International Federation of Clinical Neurophysiology. *Electroencephalography and Clinical Neurophysiology. Supplement*, *52*(2–3), 3–6. https://doi.org/10.1016/0022-510x(84)90023-6

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a rKlimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Research Reviews, 29(2-3), 169–195. doi:10.1016/S016. *Brain Research Reviews*, *29*(2–3), 169–195. https://doi.org/10.1016/S0165-0173(98)00056-3

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007

Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition-timing hypothesis. *Brain Research Reviews*, *53*(1), 63–88. https://doi.org/10.1016/j.brainresrev.2006.06.003

Kline, J. E., Huang, H. J., Snyder, K. L., & Ferris, D. P. (2015). Isolating gait-related movement artifacts in electroencephalography during human walking. *Journal of Neural Engineering*, *12*(4). https://doi.org/10.1088/1741-2560/12/4/046022

Knols, R. H., Swanenburg, J., De Bon, D., Gennaro, F., Wolf, M., Krüger, B., Bettex, D., & de Bruin, E. D. (2017). Investigating the Usability and Acute Effects of a Bedside Video

Console to Prefrontal Cortical Activity Alterations: A Preclinical Study in Healthy Elderly. *Frontiers in Systems Neuroscience*, *11*(November), 1–14. https://doi.org/10.3389/fnsys.2017.00085

Ko, J., Jang, S.-W., Lee, H. T., Yun, H.-K., & Kim, Y. S. (2020). Effects of Virtual Reality and Non–Virtual Reality Exercises on the Exercise Capacity and Concentration of Users in a Ski Exergame: Comparative Study. *JMIR Serious Games*, *8*(4), e16693. https://doi.org/10.2196/16693

Laborda-Sánchez, F., & Cansino, S. (2021). The Effects of Neurofeedback on Aging-Associated Cognitive Decline: A Systematic Review. *Applied Psychophysiology Biofeedback*, *46*(1), 1–10. https://doi.org/10.1007/s10484-020-09497-6

Ladouce, S., Donaldson, D. I., Dudchenko, P. A., & Ietswaart, M. (2017). Understanding minds in real-world environments: Toward a mobile cognition approach. *Frontiers in Human Neuroscience*, *10*(January), 1–14. https://doi.org/10.3389/fnhum.2016.00694

Lee, J. C. (2008). Hacking the Nintendo Wii remote. *IEEE Pervasive Computing*, *7*(3), 39–45. https://doi.org/10.1109/MPRV.2008.53

Lee, J. E., Zeng, N., Oh, Y., Lee, D., & Gao, Z. (2021). Effects of Pokémon GO on Physical Activity and Psychological and Social Outcomes: A Systematic Review. *Journal of Clinical Medicine*, *10*(9), 1860. https://doi.org/10.3390/jcm10091860

Lesinski, M., Hortobágyi, T., Muehlbauer, T., Gollhofer, A., & Granacher, U. (2015). Effects of Balance Training on Balance Performance in Healthy Older Adults: A Systematic Review and Meta-analysis. *Sports Medicine*, *45*(12), 1721–1738. https://doi.org/10.1007/s40279-015-0375-y

Lipardo, D. S., Aseron, A. M. C., Kwan, M. M., & Tsang, W. W. (2017). Effect of Exercise and Cognitive Training on Falls and Fall-Related Factors in Older Adults With Mild Cognitive Impairment: A Systematic Review. *Archives of Physical Medicine and Rehabilitation*, *98*(10), 2079–2096. https://doi.org/10.1016/j.apmr.2017.04.021

Logothetis, N. K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A. (2001). Neurophysiological investigation of the basis of the fMRI signal. *Nature*, *412*(6843), 150–157. https://doi.org/10.1038/35084005

Lord, S. R., Delbaere, K., & Gandevia, S. C. (2016). Use of a physiological profile to document motor impairment in ageing and in clinical groups. *The Journal of Physiology*, *594*(16), 4513–4523. https://doi.org/10.1113/JP271108

Lord, S. R., Delbaere, K., & Sturnieks, D. L. (2018). Aging. In *Handbook of Clinical Neurology* (Vol. 159, pp. 157–171). https://doi.org/10.1016/B978-0-444-63916-5.00010-0

Luchsinger, H., Sandbakk, Ø., Schubert, M., Ettema, G., & Baumeister, J. (2016). A comparison of frontal theta activity during shooting among biathletes and cross-country skiers before and after vigorous exercise. *PLoS ONE*, *11*(3), 1–11. https://doi.org/10.1371/journal.pone.0150461

Luiz de Brito Gomes, J., Soltani, P., Barbosa, R. R., Gomes, J. A. F., & Costa, M. da C. (2023). Is rating of perceived exertion a valid method for monitoring exergaming intensity in type-1 diabetics? A cross-sectional randomized trial. *Journal of Bodywork and Movement Therapies*, *36*(April), 432–437. https://doi.org/10.1016/j.jbmt.2023.05.018

Luks, T. L., Simpson, G. V., Feiwell, R. J., & Miller, W. L. (2002). Evidence for Anterior Cingulate Cortex Involvement in Monitoring Preparatory Attentional Set. *NeuroImage*, *17*(2), 792–802. https://doi.org/10.1006/nimg.2002.1210

Lundin-Olsson, L., Nyberg, L., & Gustafson, Y. (1997). “Stops walking when talking” as a predictor of falls in elderly people. *The Lancet*, *349*(9052), 617. https://doi.org/10.1016/S0140-6736(97)24009-2

McConville, K. M. V., & Virk, S. (2012). Evaluation of an electronic video game for improvement of balance. *Virtual Reality*, *16*(4), 315–323. https://doi.org/10.1007/s10055-012-0212-7

McEvoy, L. K., Pellouchoud, E., Smith, M. E., & Gevins, A. (2001). Neurophysiological signals of working memory in normal aging. *Cognitive Brain Research*, *11*(3), 363–376. https://doi.org/10.1016/S0926-6410(01)00009-X

Mehta, R. K., & Parasuraman, R. (2013). Neuroergonomics: A review of applications to physical and cognitive work. *Frontiers in Human Neuroscience*, *7*(DEC), 1–10. https://doi.org/10.3389/fnhum.2013.00889

Michels, L., Bucher, K., Lüchinger, R., Klaver, P., Martin, E., Jeanmonod, D., & Brandeis, D. (2010). Simultaneous EEG-fMRI during a working memory task: Modulations in low and high frequency bands. *PLoS ONE*, *5*(4). https://doi.org/10.1371/journal.pone.0010298

Miyakoshi, M., & Kothe, C. A. E. (2014). clean_rawdata. *SCCn, INC, UCSD*.

Moholdt, T., Weie, S., Chorianopoulos, K., Wang, A. I., & Hagen, K. (2017). Exergaming can be an innovative way of enjoyable high-intensity interval training. *BMJ Open Sport & Exercise Medicine*, *3*(1), e000258. https://doi.org/10.1136/bmjsem-2017-000258

Mullen, T. R. (2011). CleanLine. *SCCN/INC/UCSD*.

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x

Niendam, T. A., Laird, A. R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective and Behavioral Neuroscience*, *12*(2), 241–268. https://doi.org/10.3758/s13415-011-0083-5

Niso, G., Romero, E., Moreau, J. T., Araujo, A., & Krol, L. R. (2023). Wireless EEG: A survey of systems and studies. *NeuroImage*, *269*(December 2022). https://doi.org/10.1016/j.neuroimage.2022.119774

Nordin, A. D., Hairston, W. D., & Ferris, D. P. (2020). Faster Gait Speeds Reduce Alpha and Beta EEG Spectral Power from Human Sensorimotor Cortex. *IEEE Transactions on Biomedical Engineering*, *67*(3), 842–853. https://doi.org/10.1109/TBME.2019.2921766

O’Leary, K. C., Pontifex, M. B., Scudder, M. R., Brown, M. L., & Hillman, C. H. (2011). The effects of single bouts of aerobic exercise, exergaming, and videogame play on cognitive control. *Clinical Neurophysiology*, *122*(8), 1518–1525. https://doi.org/10.1016/j.clinph.2011.01.049

Olyaei, G., Khanmohammadi, R., Talebian, S., Hadian, M. R., Bagheri, H., & Najafi, M. (2022). The effect of exergaming on cognition and brain activity in older adults: A motor- related cortical potential study. *Physiology and Behavior*, *255*(July), 113941. https://doi.org/10.1016/j.physbeh.2022.113941

Onton, J., & Makeig, S. (2006). Information-based modeling of event-related brain dynamics. *Progress in Brain Research*, *159*, 99–120. https://doi.org/10.1016/S0079-6123(06)59007-7

Oostenveld, R., & Oostendorp, T. F. (2002). Validating the boundary element method for forward and inverse EEG computations in the presence of a hole in the skull. *Human Brain Mapping*, *17*(3), 179–192. https://doi.org/10.1002/hbm.10061

Oschwald, J., Guye, S., Liem, F., Rast, P., Willis, S., Röcke, C., Jäncke, L., Martin, M., & Mérillat, S. (2020). Brain structure and cognitive ability in healthy aging: A review on longitudinal correlated change. *Reviews in the Neurosciences*, *31*(1), 1–57. https://doi.org/10.1515/revneuro-2018-0096

Osoba, M. Y., Rao, A. K., Agrawal, S. K., & Lalwani, A. K. (2019). Balance and gait in the elderly: A contemporary review. *Laryngoscope Investigative Otolaryngology*, *4*(1), 143–153. https://doi.org/10.1002/lio2.252

Ozdemir, R. A., Contreras-Vidal, J. L., Lee, B. C., & Paloski, W. H. (2016). Cortical activity modulations underlying age-related performance differences during posture–cognition dual tasking. In *Experimental Brain Research* (Vol. 234, Issue 11, pp. 3321–3334). https://doi.org/10.1007/s00221-016-4730-5

Palmer, J. (2015). AMICA. *SCCN/INC/UCSD*.

Palva, S., & Palva, J. M. (2007). New vistas for α-frequency band oscillations. *Trends in Neurosciences*, *30*(4), 150–158. https://doi.org/10.1016/j.tins.2007.02.001

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*, 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Perrey, S. (2022). Training Monitoring in Sports: It Is Time to Embrace Cognitive Demand. *Sports*, *10*(4). https://doi.org/10.3390/sports10040056

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Pfurtscheller, G., & Lopes Da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology*, *110*(11), 1842–1857. https://doi.org/10.1016/S1388-2457(99)00141-8

Pion-Tonachini, L., Kreutz-Delgado, K., & Makeig, S. (2019). ICLabel: An automated electroencephalographic independent component classifier, dataset, and website. *NeuroImage*, *198*(5), 181–197. https://doi.org/10.1016/j.neuroimage.2019.05.026

Pivik, R. T., Broughton, R. J., Coppola, R., Davidson, R. J., Fox, N., & Nuwer, M. R. (1993). Guidelines for the recording and quantitative analysis of electroencephalographic activity in research contexts. *Psychophysiology*, *30*(6), 547–558. https://doi.org/10.1111/j.1469-8986.1993.tb02081.x

Rademaker, A., Linden, S. Van der, & Wiersinga, J. (2009). SilverFit, a virtual rehabilitation system. *Gerontechnology*, *8*(2), 187–211. https://doi.org/10.4017/gt.2009.08.02.012.00

Reinders, I., Murphy, R. A., Koster, A., Brouwer, I. A., Visser, M., Garcia, M. E., Launer, L. J., Siggeirsdottir, K., Eiriksdottir, G., Jonsson, P. V., Gudnason, V., & Harris, T. B. (2015). Muscle quality and muscle fat infiltration in relation to incident mobility disability and gait speed decline: The age, gene/environment susceptibility-reykjavik study. *Journals of Gerontology - Series A Biological Sciences and Medical Sciences*, *70*(8), 1030–1036. https://doi.org/10.1093/gerona/glv016

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*(3), 177–182.

https://doi.org/10.1111/j.1467-8721.2008.00570.x

Ridderinkhof, K. R., & Krugers, H. J. (2022). Horizons in Human Aging Neuroscience: From Normal Neural Aging to Mental (Fr)Agility. *Frontiers in Human Neuroscience*, *16*(June), 1–22. https://doi.org/10.3389/fnhum.2022.815759

Rogers, M. W., & Mille, M.-L. (2018). Balance perturbations. In B. I. Day & S. R. Lord (Eds.), *Handbook of Clinical Neurology* (1st ed., Vol. 159, pp. 85–105). Elsevier B.V. https://doi.org/10.1016/B978-0-444-63916-5.00005-7

Rubenstein, L. Z. (2006). Falls in older people: Epidemiology, risk factors and strategies for prevention. *Age and Ageing*, *35*(SUPPL.2), 37–41. https://doi.org/10.1093/ageing/afl084

Salvi, S. M., Akhtar, S., & Currie, Z. (2006). Ageing changes in the eye. *Postgraduate Medical Journal*, *82*(971), 581–587. https://doi.org/10.1136/pgmj.2005.040857

Sauseng, P., Griesmayr, B., Freunberger, R., & Klimesch, W. (2010). Control mechanisms in working memory: A possible function of EEG theta oscillations. *Neuroscience and Biobehavioral Reviews*, *34*(7), 1015–1022. https://doi.org/10.1016/j.neubiorev.2009.12.006

Sauseng, P., Klimesch, W., Schabus, M., & Doppelmayr, M. (2005). Fronto-parietal EEG coherence in theta and upper alpha reflect central executive functions of working memory. *International Journal of Psychophysiology*, *57*(2), 97–103. https://doi.org/10.1016/j.ijpsycho.2005.03.018

Schättin, A., Arner, R., Gennaro, F., & de Bruin, E. D. (2016). Adaptations of prefrontal brain activity, executive functions, and gait in healthy elderly following exergame and balance training: A randomized-controlled study. *Frontiers in Aging Neuroscience*, *8*(NOV). https://doi.org/10.3389/fnagi.2016.00278

Schoene, D., Lord, S. R., Delbaere, K., Severino, C., Davies, T. A., & Smith, S. T. (2013). A Randomized Controlled Pilot Study of Home-Based Step Training in Older People Using Videogame Technology. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0057734

Seals, D. R., Justice, J. N., & Larocca, T. J. (2016). Physiological geroscience: Targeting function to increase healthspan and achieve optimal longevity. *Journal of Physiology*, *594*(8), 2001–2024. https://doi.org/10.1113/jphysiol.2014.282665

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: An integrative theory of anterior cingulate cortex function. *Neuron*, *79*(2), 217–240. https://doi.org/10.1016/j.neuron.2013.07.007

Silverthorn, D. U. (2010). Human Physiology - An integrated approach. In *Human physiology: an integrated approach, 5ª edição* (5th ed.). Pearson Benjamin Cummings. http://library.wur.nl/WebQuery/clc/1836027%5Cnhttps://bb.tulsacc.edu/bbcswebdav/institution/Syllabus/archives/20092/Metro/Science-Math/BIO_2154_106_30426_20092.doc

Skjæret-Maroni, N., & Bardal, E. M. (2018). Eldre og exergaming – hvordan beveger de seg egentlig? *Fysioterapeuten*, *9*. https://www.fysioterapeuten.no/fagfellevurdert-velferdsteknologi/eldre-og-exergaming--hvordan-beveger-de-seg-egentlig/125291

Skjæret-Maroni, N., Vonstad, E. K., Ihlen, E. A. F., Tan, X. C., Helbostad, J. L., & Vereijken, B. (2016). Exergaming in older adults: Movement characteristics while playing stepping games. *Frontiers in Psychology*, *7*(JUN), 1–11. https://doi.org/10.3389/fpsyg.2016.00964

Skjæret, N., Nawaz, A., Morat, T., Schoene, D., Helbostad, J. L., & Vereijken, B. (2016). Exercise and rehabilitation delivered through exergames in older adults: An integrative review of technologies, safety and efficacy. *International Journal of Medical Informatics*, *85*(1), 1–16. https://doi.org/10.1016/j.ijmedinf.2015.10.008

Souza, R. H. C. e., & Naves, E. L. M. (2021). Attention Detection in Virtual Environments Using EEG Signals: A Scoping Review. *Frontiers in Physiology*, *12*(November), 1–18. https://doi.org/10.3389/fphys.2021.727840

Stanmore, E., Stubbs, B., Vancampfort, D., de Bruin, E. D., & Firth, J. (2017). The effect of active video games on cognitive functioning in clinical and non-clinical populations: A meta-analysis of randomized controlled trials. *Neuroscience and Biobehavioral Reviews*, *78*(February), 34–43. https://doi.org/10.1016/j.neubiorev.2017.04.011

Steinmetzger, K., Shen, Z., Riedel, H., & Rupp, A. (2020). Auditory cortex activity measured using functional near-infrared spectroscopy (fNIRS) appears to be susceptible to masking by cortical blood stealing. *Hearing Research*, *396*, 108069. https://doi.org/10.1016/j.heares.2020.108069

Stojan, R., & Voelcker-Rehage, C. (2019). A Systematic Review on the Cognitive Benefits and Neurophysiological Correlates of Exergaming in Healthy Older Adults. *Journal of Clinical Medicine*, *8*(5), 734. https://doi.org/10.3390/jcm8050734

Sturnieks, D. L., Hicks, C., Smith, N., Ratanapongleka, M., Menant, J., Turner, J., Lo, J., Chaplin, C., Garcia, J., Valenzuela, M. J., Delbaere, K., Herbert, R. D., Sherrington, C., Toson, B., & Lord, S. R. (2024). Exergame and cognitive training for preventing falls in community-dwelling older people: a randomized controlled trial. *Nature Medicine*, *30*(1), 98–105. https://doi.org/10.1038/s41591-023-02739-0

Suleiman-Martos, N., García-Lara, R., Albendín-García, L., Romero-Béjar, J. L., Cañadas-De La Fuente, G. A., Monsalve-Reyes, C., & Gomez-Urquiza, J. L. (2022). Effects of active video games on physical function in independent community-dwelling older adults: A systematic review and meta-analysis. *Journal of Advanced Nursing*, *78*(5), 1228–1244. https://doi.org/10.1111/jan.15138

Swanenburg, J., Wild, K., Straumann, D., & Bruin, E. D. d. (2018). Exergaming in a Moving Virtual World to Train Vestibular Functions and Gait; a Proof-of-Concept-Study With Older Adults. *Frontiers in Physiology*, *9*(July), 1–9. https://doi.org/10.3389/fphys.2018.00988

Tieri, G., Morone, G., Paolucci, S., & Iosa, M. (2018). Virtual reality in cognitive and motor rehabilitation: facts, fiction and fallacies. *Expert Review of Medical Devices*, *15*(2), 107–117. https://doi.org/10.1080/17434440.2018.1425613

Urtamo, A., Jyväkorpi, S. K., & Strandberg, T. E. (2019). Definitions of successful ageing: A brief review of a multidimensional concept. *Acta Biomedica*, *90*(2), 359–363. https://doi.org/10.23750/abm.v90i2.8376

Van Diest, M., Lamoth, C. J., Stegenga, J., Verkerke, G. J., & Postema, K. (2013). Exergaming for balance training of elderly: State of the art and future developments. *Journal of NeuroEngineering and Rehabilitation*, *10*(1), 1. https://doi.org/10.1186/1743-0003-10-101

van Hees, V. T., Gorzelniak, L., Dean León, E. C., Eder, M., Pias, M., Taherian, S., Ekelund, U., Renström, F., Franks, P. W., Horsch, A., & Brage, S. (2013). Separating Movement and Gravity Components in an Acceleration Signal and Implications for the Assessment of Human Daily Physical Activity. *PLoS ONE*, *8*(4), 1–10. https://doi.org/10.1371/journal.pone.0061691

Vázquez-Guerrero, J., Fernández-Valdés, B., Gonçalves, B., & Sampaio, J. E. (2019). Changes in locomotor ratio during basketball game quarters from elite under-18 teams. *Frontiers in Psychology*, *10*(SEP). https://doi.org/10.3389/fpsyg.2019.02163

Verhaeghen, P. (2011). Aging and Executive Control: Reports of a Demise Greatly Exaggerated. *Current Directions in Psychological Science*, *20*(3), 174–180. https://doi.org/10.1177/0963721411408772

Viseux, F. J. F., Delval, A., Defebvre, L., & Simoneau, M. (2020). Postural instability in Parkinson's disease: Review and bottom-up rehabilitative approaches. *Neurophysiologie Clinique*, *50*(6), 479–487. https://doi.org/10.1016/j.neucli.2020.10.013

Washburn, R. A., Smith, K. W., Jette, A. M., & Janney, C. A. (1993). The physical activity scale for the elderly (PASE): Development and evaluation. *Journal of Clinical Epidemiology*, *46*(2), 153–162. https://doi.org/10.1016/0895-4356(93)90053-4

Weber, M., Van Ancum, J., Bergquist, R., Taraldsen, K., Gordt, K., Mikolaizak, A. S., Nerz, C., Pijnappels, M., Jonkman, N. H., Maier, A. B., Helbostad, J. L., Vereijken, B., Becker, C., & Schwenk, M. (2018). Concurrent validity and reliability of the Community Balance and Mobility scale in young-older adults. *BMC Geriatrics*, *18*(1), 1–10. https://doi.org/10.1186/s12877-018-0845-9

Whitehead, B. R. (2019). Investigating the function spiral in later life: Aging attitudes, physical activity, and gait. *Journal of Health Psychology*, *24*(14), 1955–1964. https://doi.org/10.1177/1359105317710814

Wollesen, B., & Voelcker-Rehage, C. (2014). Training effects on motor-cognitive dual-task performance in older adults: A systematic review. *European Review of Aging and Physical Activity*, *11*(1), 5–24. https://doi.org/10.1007/s11556-013-0122-z

Wollesen, B., Wildbredt, A., van Schooten, K. S., Lim, M. L., & Delbaere, K. (2020). The effects of cognitive-motor training interventions on executive functions in older people: a systematic review and meta-analysis. *European Review of Aging and Physical Activity*, *17*(1), 9. https://doi.org/10.1186/s11556-020-00240-y

World Health Organization. (2007). *WHO Global Report on Falls Prevention in Older Age*. https://www.who.int/publications-detail-redirect/%0A9789241563536

World Health Organization. (2015). *World report on ageing and health*. https://www.who.int/publications/i/item/9789241565042

World Health Organization. (2020). WHO Guidelines on physical activity and sedentary behaviour. In *Routledge Handbook of Youth Sport*. https://www.who.int/publications/i/item/9789240015128

Xu, Q., Ou, X., & Li, J. (2022). The risk of falls among the aging population: A systematic review and meta-analysis. *Frontiers in Public Health*, *10*(4). https://doi.org/10.3389/fpubh.2022.902599

Yamasaki, T. (2023). Preventive Strategies for Cognitive Decline and Dementia: Benefits of Aerobic Physical Activity, Especially Open-Skill Exercise. *Brain Sciences*, *13*(3). https://doi.org/10.3390/brainsci13030521

Yardley, L., Beyer, N., Hauer, K., Kempen, G., Piot-Ziegler, C., & Todd, C. (2005). Development and initial validation of the Falls Efficacy Scale-International (FES-I). *Age and Ageing*, *34*(6), 614–619. https://doi.org/10.1093/ageing/afi196

Yeung, M. K., & Chu, V. W. (2022). Viewing neurovascular coupling through the lens of combined EEG–fNIRS: A systematic review of current methods. *Psychophysiology*, *59*(6), 1–34. https://doi.org/10.1111/psyp.14054

Yogev, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders : Official Journal of the Movement Disorder Society*, *23*(3), 329–

342; quiz 472. https://doi.org/10.1002/mds.21720

Zhang, Z. (2012). Microsoft kinect sensor and its effect. *IEEE Multimedia*, *19*(2), 4–10. https://doi.org/10.1109/MMUL.2012.24

Zhao, C., Zhao, C., Zhao, M., Wang, L., Guo, J., Zhang, L., Li, Y., Sun, Y., Zhang, L., Li, Z., & Zhu, W. (2022). Effect of Exergame Training on Working Memory and Executive Function in Older Adults. *Sustainability (Switzerland)*, *14*(17). https://doi.org/10.3390/su141710631

Zheng, L., Li, G., Wang, X., Yin, H., Jia, Y., Leng, M., Li, H., & Chen, L. (2020). Effect of exergames on physical outcomes in frail elderly: a systematic review. *Aging Clinical and Experimental Research*, *32*(11), 2187–2200. https://doi.org/10.1007/s40520-019-01344-x

Scientific Dissemination

Peer-reviewed publications

Anders, P., Lehmann, T., Müller, H., Grønvik, K. B., Skjæret-Maroni, N., Baumeister, J., & Vereijken, B. (2018). Exergames Inherently Contain Cognitive Elements as Indicated by Cortical Processing. *Frontiers in Behavioral Neuroscience, 12(2), 102.* https://doi.org/10.3389/fnbeh.2018.00102

Anders, P., Müller, H., Skjæret-Maroni, N., Vereijken, B., & Baumeister, J. (2020). The influence of motor tasks and cut-off parameter selection on artifact subspace reconstruction in EEG recordings. *Medical & Biological Engineering & Computing*, *58*(11), 2673–2683. https://doi.org/10.1007/s11517-020-02252-3

Müller, H., Baumeister, J., Bardal, E. M., Vereijken, B., & Skjæret-Maroni, N. (2023). Exergaming in older adults: the effects of game characteristics on brain activity and physical activity. *Frontiers in Aging Neuroscience*, *15*(May). https://doi.org/10.3389/fnagi.2023.1143859

Müller, H., Skjæret-Maroni, N., Bardal, E. M., Vereijken, B., & Baumeister, J. (2024). Exergaming interventions for older adults: The effect of game characteristics on gameplay. *Experimental Gerontology*, *197*(October), 112610. https://doi.org/10.1016/j.exger.2024.112610

Other scientific publications

Müller, H. (2024). Spielerisch fit - Exergaming als Trainingsoption auch im Alter. *Pt-Zeitschrift Für Physiotherapeuten*, *76*(7), 20–23.

Oral presentations

Müller, H., Skjæret-Maroni, N., Vereijken, B., & Baumeister, J. (2023). Exergaming in older adults : How game characteristics affect physical activity during exergaming. *Dvs Band 27X*. https://drive.google.com/file/d/1WHhfJ1Y6lM4C7sDGhtiQDsykDFmWe2hC/view

Poster presentations

Anders, P., Blix Grønvik, K., Molde, I., Müller, H., Skjæret-Maroni, N., & Vereijken, B. (2017). P108: Balance exergames improve movement characteristics of body weight transfer. *Gait and Posture*, *57*, 352–353. https://doi.org/10.1016/j.gaitpost.2017.06.462

Anders, P., Lehmann, T., Müller, H., Molde, I., Blix Grønvik, K., Skjæret-Maroni, N., Vereijken, B., & Baumeister, J. (2017). P107 Balance exergames increase cortical activity in frontal areas of the brain. *Gait and Posture*, *57*, 351. https://doi.org/10.1016/j.gaitpost.2017.06.461

Müller, H., Skjæret-Maroni, N., Vereijken, B., & Baumeister, J. (2022). Performance and Brain Activity in Older Adults while Playing Leaning and Stepping Exergames. *ISPGR World Congress, Montreal*

Publications and manuscripts of the included studies

Paper 1

Müller, H., Baumeister, J., Bardal, E. M., Vereijken, B., & Skjæret-Maroni, N. (2023). Exergaming in older adults: the effects of game characteristics on brain activity and physical activity. *Frontiers in Aging Neuroscience*, *15*(May). https://doi.org/10.3389/fnagi.2023.1143859

Paper 2

Müller, H., Skjæret-Maroni, N., Bardal, E. M., Vereijken, B., & Baumeister, J. (2024). Exergaming interventions for older adults: The effect of game characteristics on gameplay. *Experimental Gerontology*, *197*(October), 112610. https://doi.org/10.1016/j.exger.2024.112610

Paper 3 (under Review)

Müller, H., Büchel, D., Skjæret-Maroni, N., Vereijken, B., Baumeister, J. (2025). Monitoring Cognitive Load while Playing Exergames in a Four-Week Intervention for Older Adults: An explorative EEG Study. *Submitted for publication in Scientific Reports*