DEVELOPING AND VALIDATING A DYNAMIC BARRIER FRAMEWORK (DBF) FOR OLDER ADULTS' ENGAGEMENT AND ATTRITION IN IMMERSIVE EXERGAMES

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MEMBANGUNKAN RANGKA KERJA HALANGAN DINAMIK (DBF) BAGI PENGLIBATAN DAN KECICIRAN WARGA EMAS DALAM EXERGAMES IMERSIF

XIACHENG SONG

TESIS YANG DIKEMUKAKAN UNTUK MEMPEROLEH
IJAZAH DOKTOR FALSAFAH

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

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MEMBANGUNKAN RANGKA KERJA HALANGAN DINAMIK (DBF) BAGI PENGLIBATAN DAN KECICIRAN WARGA EMAS DALAM EXERGAMES IMERSIF

Exergame imersif yang disampaikan melalui Realiti Maya (VR) dan Realiti Campuran (MR) boleh menyokong kesihatan dan kesejahteraan warga emas, namun penglibatan berterusan kekal sukar kerana ramai pengguna menghentikan penggunaan tidak lama selepas kontak awal. Kajian terdahulu menekankan kebolehgunaan dan hasil jangka pendek tetapi memberikan penjelasan peringkat proses yang terhad tentang bila pengunduran berlaku dan bagaimana halangan berubah mengikut masa. Tesis ini menangani jurang tersebut dengan mengenal pasti halangan khusus mengikut peringkat yang membawa kepada pengunduran serta mencadangkan dan mengesahkan Kerangka Halangan Dinamik (Dynamic Barrier Framework, DBF) bagi exergame imersif dalam kalangan warga emas. Objektif kajian adalah untuk mengenal pasti dan mengkategorikan halangan utama merentasi peringkat penggunaan (RO1), mengintegrasikan dapatan empirikal ke dalam kerangka penjelasan yang peka fasa (RO2), dan mengesahkan kerangka tersebut melalui penilaian pakar (RO3). Kajian ini menggunakan metodologi berbilang peringkat yang menggabungkan dua eksperimen pengguna dengan pembangunan kerangka dan pengesahan pakar. Eksperimen A (Kontak Awal, RO1) meneliti pengalaman kontak pertama serta mendokumentasikan masa dan sebab pengunduran dalam keadaan VR dan MR. Eksperimen B (Pendedahan Berulang, RO1) menggunakan protokol longitudinal ringkas untuk menilai sama ada prestasi berkaitan penglibatan berubah merentasi hari dalam kalangan peserta yang meneruskan penggunaan. Dapatan menunjukkan pengunduran yang ketara dan bergantung pada peringkat: 86 peserta menyertai Eksperimen A, 70 menamatkannya (81.4%), 40 meneruskan ke Eksperimen B (57.1% daripada peserta yang menamatkan Eksperimen A), dan 35 menamatkan semua peringkat (40.7% keseluruhan). Sebab pengunduran berkembang daripada kekangan fisiologi semasa kontak awal, kepada kebimbangan sosio-psikologi pada keputusan untuk meneruskan, dan kepada faktor motivasi semasa pendedahan berulang. Berdasarkan dapatan ini, DBF mengkonseptualisasikan pengunduran merentasi Fasa 1 Penyesuaian Fizikal, Fasa 2 Pembinaan Kepercayaan, dan Fasa 3 Mengekalkan Nilai dan Minat, dan semakan pakar menyokong kejelasan serta kerelevanan kerangka tersebut.

ABSTRACT

Immersive exergames delivered through Virtual Reality (VR) and Mixed Reality (MR) can support older adults' health and well-being, yet sustained engagement remains difficult because many users discontinue soon after initial contact. Prior work has emphasized usability and short-term outcomes, but it provides limited process-level explanation of when attrition occurs, why barriers shift across usage stages, and how these shifts can be translated into design guidance. This thesis addresses this gap by identifying stage-specific barriers to attrition and by proposing the Dynamic Barrier Framework (DBF), a phase-sensitive explanatory framework for older adults' engagement with immersive exergames. The objectives were to identify and categorize key barriers across usage stages (RO1), integrate empirical findings into a phase-sensitive framework (RO2), and validate the framework through expert evaluation (RO3). The study adopted a multistage methodology combining two user experiments, framework construction, and expert validation. Experiment A (Initial contact, RO1) examined first-contact experiences and documented dropout timing and reasons in VR and MR conditions. Experiment B (Repeated Exposure, RO1) used a six-session repeated-exposure protocol to examine whether engagement-related performance and experience changed among participants who continued. Results showed substantial and stage-dependent attrition: 86 participants entered Experiment A, 70 completed it (81.4%), 40 proceeded to Experiment B (57.1% of Experiment A completers), and 35 completed all stages (40.7% overall). Dropout reasons progressed from physiological constraints during initial contact, to socio-psychological concerns at the decision-to-continue stage, and to motivational factors during repeated exposure. Based on these findings, the DBF conceptualizes attrition across Phase 1 Physical Adjustment, Phase 2 Developing Trust, and Phase 3 Maintaining Value and Interest. Expert validation supported the framework's content validity and practical relevance, indicating that the DBF contributes a novel staged account of attrition and offers actionable guidance for designing safer, more adaptive, and more sustainable immersive exergames for older adults.

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LIST OF ABBREVIATIONS

6DoF	Six Degrees of Freedom
BBS	Berg Balance Scale
Borg-	Borg Rating of Perceived Exertion
CI	Confidence Interval
DBF	Dynamic Barrier Framework
df	Degrees of Freedom
F	F Statistic
GEQ	Game Experience Questionnaire
HCI	Human-Computer Interaction
HMD	Head-Mounted Display
IQR	Interquartile Range
M	Mean
Mdn	Median
MR	Mixed Reality
N	Sample Size
p	p-value
RO	Research Objective
RQ	Research Question
rrb	Rank-biserial Correlation
r_s	Spearman Rank Correlation Coefficient
SD	Standard Deviation
S-CVI	Scale-level Content Validity Index
U	Mann-Whitney U Statistic
VR	Virtual Reality
VRSQ	Virtual Reality Sickness Questionnaire

Z	Z Statistic
α	Cronbach's Alpha
β	Standardized Regression Coefficient
ρ	Spearman's Rho
R^2	Coefficient of Determination
ΔR^2	Change in R^2

CHAPTER I

INTRODUCTION

1.1 Research Background

The 21st century is being shaped by rapid population aging, with the global number of adults aged 60 and over projected to exceed two billion by mid-century ("Decade of healthy ageing" 2021; "World population prospects" 2024). In response, public health paradigms have shifted from reactive disease management toward proactive strategies of "Healthy Aging" and "Aging in Place" that aim to preserve independence and well-being within community settings (Xie et al. 2022). However, this vision is threatened by falls, a leading cause of injury and functional decline that also imposes substantial burdens on health and social care systems (Alexander 2021; Lau-Ng, Caruso & Perls 2020). Falls further trigger a psychological "fear of falling," which can drive activity restriction, physical deconditioning, and social withdrawal, forming a vicious cycle that paradoxically elevates subsequent fall risk (Chen et al. 2023; Dantas et al. 2025; "WHO's work on the UN decade of healthy ageing (2021-2030)" 2025).

To mitigate these risks, the literature consistently highlights sustained physical activity—particularly multicomponent programs targeting balance and strength—as an effective approach for reducing fall risk, with Tai Chi frequently supported as a well-established modality (Lu et al. 2023). Yet, the real-world impact of traditional programs is often constrained by an "adherence dilemma," as long-term participation among community-dwelling older adults remains low (Koufakis, Grammatiki & Kotsa 2021). Both intrinsic barriers (e.g., perceived monotony and limited immediate reward) and extrinsic constraints (e.g., travel demands, scheduling, and instructor availability) commonly impede consistent engagement (Liu et al. 2022).

This gap between proven efficacy and sustained participation has motivated growing interest in immersive technologies, including Virtual Reality (VR) and Mixed Reality (MR) exergames (Ho et al. 2022; Juckett et al. 2021)**.** By leveraging gamification features, such as goal-setting, real-time feedback, and engaging narratives, exergames may enhance the subjective experience of exercise and support continued participation. Moreover, home-based deployment can reduce environmental and logistical barriers, potentially making balance training more accessible and sustainable for an aging population (Aalbers & Peeters 2020).

In practice, the sustained use of immersive exergames is frequently undermined by technological attrition, referring to discontinuation that is primarily driven by technology-related frictions rather than by the exercise principles themselves (Eysenbach 2005; Song et al. 2025; Yoong, Wu & Jiang 2024). For older adults, attrition can arise from cybersickness or discomfort, device weight and fit issues, calibration and tracking instability, interaction complexity, and usability barriers that increase cognitive or physical load during use (Park, Choi & Jeong 2025; Tuena et al. 2020). Safety concerns in home settings (e.g., limited space, fear of losing balance while wearing a headset, or reduced situational awareness) may further accelerate early dropout. As a result, even interventions with strong theoretical and clinical promise may fail to deliver long-term benefits if technology-induced barriers prevent repeated, routine participation (Saragih et al. 2025; Tuena et al. 2020).

Beyond technical barriers, meaningful fall-prevention outcomes depend on engagement factors that support continued participation over time. Engagement in immersive exercise is not limited to momentary enjoyment; it also involves perceived competence and progress, appropriately calibrated challenge, clear goals, and feedback that reinforces self-efficacy and habit formation (Geelen et al. 2025; Ryan, Rigby & Przybylski 2006). For older adults in particular, engagement is shaped by perceived safety and confidence, the degree to which activities feel purposeful and manageable, and whether the experience integrates smoothly into daily routines (Ciemer et al. 2025; Hawley-Hague et al. 2016). Therefore, understanding how engagement is produced and maintained, and how it interacts with technological attrition, is essential for designing immersive exergames that are not only appealing at first use, but also sustainable in real-world, home-based contexts (Chuang et al. 2025; Mehrabi et al. 2022).

1.2 Problem Statement

While immersive exergames show significant potential for promoting healthy aging, a critical gap exists between this potential and their practical adoption by older adults (Beraud-Peigne, Maillot & Perrot 2023; Yoong, Wu & Jiang 2024). Many older users discontinue use, a phenomenon known as attrition, but the specific reasons for this are not fully understood. The problem is not simply a lack of efficacy in the technology, but a more complex issue rooted in the user experience during the adoption process (Beraud-Peigne, Maillot & Perrot 2023; Yoong, Wu & Jiang 2024). This thesis addresses this problem by deconstructing it into three distinct but interconnected gaps in the current research: an empirical gap in understanding early barriers, a theoretical gap in explaining the adoption process, and a methodological gap in validating new frameworks.

A key empirical gap exists in the literature regarding the initial adoption phase (Crane et al. 2023; Dilanchian, Andringa & Boot 2021). While prior studies have focused on general usability and motivation, there is limited quantitative evidence explaining why many older adults experience attrition during their initial or repeated contacts with immersive exergames. The literature reveals a recurring pattern of user drop-off, yet the underlying reasons often remain anecdotal or are examined through the narrow lens of general usability, rather than specific, process-oriented barriers. This specific technological modality is the focus of the investigation because it directly confronts the 'adherence dilemma' by combining the motivational appeal of gaming with the unique affordances of physical embodiment and presence, offering a more potent intervention than traditional screen-based applications (Manser, Poikonen & De Bruin 2023; Yoong, Wu & Jiang 2024). The specific barriers that cause this early attrition such as physiological discomfort like cybersickness or concerns about safety remain underexplored and are not well-measured. Without a clear identification of these initial barriers, it is difficult to design interventions that can effectively improve long-term adherence (Manser, Poikonen & De Bruin 2023; Seinsche et al. 2023). This lack of granular understanding represents a critical failure, as it prevents the development of targeted, evidence-based strategies. Therefore, a foundational challenge is to first deconstruct this attrition process before effective long-term interventions can be designed.

Compounding this empirical gap is a theoretical one. The dominant models used to explain technology adoption, such as the Technology Acceptance Model (TAM), are often insufficient for this context (Perdomo Delgado et al. 2024; Shore et al. 2018). These models typically focus on a single point of user intention and do not adequately explain the dynamic process of adoption and attrition over time. They fail to capture how different types of barriers evolve as a user moves through various phases, from initial physiological challenges to later psychological and motivational ones (Lee & Xie 2018; Wu et al. 2025). This theoretical vacuum is not merely an academic oversight; it has profound practical implications, leading to interventions designed around a flawed, static view of the user. Thus, the primary challenge is to develop a new framework that can bridge this chasm between existing models and the lived, dynamic experience of older adults.

Finally, proposing a new framework is insufficient without rigorous validation. Numerous studies emphasize the importance of validating theoretical models, but existing validation methods in this field are often limited (Li et al. 2020; Manser & De Bruin 2021). There is little guidance on how to validate a dynamic framework that integrates physiological, psychological, and motivational barriers over multiple phases (Bruns & Wallhoff 2022; Crane et al. 2023). A significant methodological problem, therefore, is the need to establish a clear and robust process to develop and subsequently validate the proposed framework, ensuring its clarity, coherence, and practical relevance for designing more effective exergames for older adults.

Importantly, these adoption challenges are tightly coupled with the current limitations of VR/MR (head-mounted immersive) technologies when deployed for home-based exercise with older adults. VR/MR exergames typically rely on head-mounted displays and real-time motion tracking, which can introduce modality-specific frictions such as cybersickness and visual discomfort, device weight and fit issues, tracking instability or latency, and interaction complexity that increases cognitive and physical load during movement (Healy et al. 2022; Schaumburg et al. 2025). In addition, immersive engagement can reduce situational awareness, amplifying perceived and actual safety risks (e.g., balance loss in constrained spaces), which may precipitate early withdrawal even when the underlying training principles are evidence-based (Liston et al. 2021; Schaumburg et al. 2025). As a result, attrition in VR/MR contexts cannot be explained by generic usability alone; it requires a barrier-focused account that explicitly considers these VR/MR-specific physiological and safety-related constraints (Ramalho et al. 2024; Rojo et al. 2023).

At the same time, VR/MR remains a compelling modality precisely because its affordances differ qualitatively from other commonly used technologies for fall prevention, such as screen-based applications, instructional videos, or non-immersive games (Levin, Weiss & Keshner 2015; Mirelman et al. 2016). Unlike conventional approaches that often struggle to sustain engagement and deliver embodied practice at adequate intensity, VR/MR can combine presence and embodiment with adaptive, real-time feedback, enabling users to rehearse balance-relevant movements in more interactive and motivating formats (Alhasan et al. 2025; Song et al. 2025). Moreover, MR-style passthrough or mixed-reality designs can potentially support home deployment while maintaining some environmental awareness, suggesting a pathway to reduce logistical barriers without fully sacrificing safety (Nishchyk et al. 2021; Thuilier et al. 2025). This dual reality, that VR/MR offers distinctive potential yet also introduces distinctive attrition risks, underscores the need to systematically characterize the adoption process and develop a phase-sensitive framework that can guide more sustainable VR/MR exergame design for older adults (Greenhalgh et al. 2017; Mehrabi et al. 2022).

1.3 Research Questions

The following are the three (3) research questions investigated in this study (labelled as RQ1, RQ2, RQ3).

RQ1. What specific barriers lead to attrition during initial and repeated contacts with immersive exergames and reduce sustained engagement?

RQ2. How to construct a Dynamic Barrier Framework that explains how different types of barriers evolve across stages of attrition and engagement during adoption?

RQ3. How can the Dynamic Barrier Framework be validated for adoption, engagement, and attrition?

1.4 Research Objectives

RO1. To identify key barriers that lead to attrition during initial and repeated contacts with immersive exergames and undermine sustained engagement.

RO2. To construct a Dynamic Barrier Framework that explains how different types of barriers evolve across stages of attrition and engagement during adoption.

RO3. To validate the Dynamic Barrier Framework.

The following Figure 1 visualizes the relationship between the research questions and research objectives of this thesis.

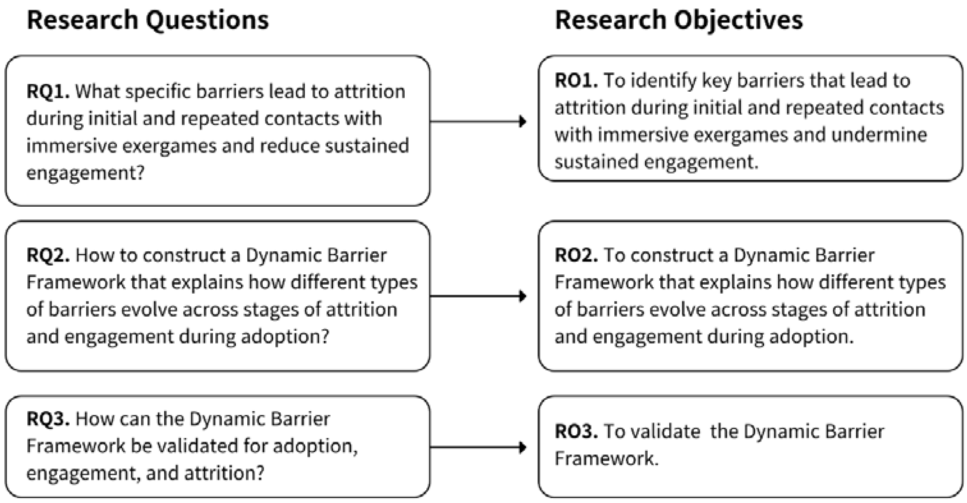

Figure 1 The research objectives and corresponding research questions

1.5 Research Scope

The research conducted in this doctoral thesis is framed by the following scope and boundaries:

In addition to these scope boundaries, the study assumes that participants were functionally able to perform basic movements safely, that all VR/MR sessions were conducted in a controlled and supervised environment, and that short-term repeated exposure can provide meaningful evidence for constructing the phase-sensitive DBF.

a) The Participant Population: The study focuses on community-dwelling older adults aged 60 and above. In this thesis, community-dwelling refers to older adults who live in ordinary home or community settings rather than in institutionalized care facilities. This population was selected because the thesis examines the early adoption, engagement, and attrition of VR/MR exergames as a potential community-based healthy ageing intervention, rather than as a clinically supervised rehabilitation programme. Participants were therefore expected to be functionally independent and generally healthy enough to complete basic movement tasks in a controlled VR/MR environment. The findings are most applicable to this non-clinical “healthy ageing” population and may not be generalizable to older adults in institutionalized care or those with significant cognitive or physical impairments, who may require different safety protocols, clinical supervision, and intervention designs.

b) The Target Behavior: The research investigates the dynamic, multi-stage process of older adults adoption, engagement, and attrition in the context of immersive (VR/MR) exergames. The focus is not on the long-term health outcomes, but on understanding the user journey and identifying the specific barriers (physiological, psychological, and motivational) that older adults encounter during initial and sustained engagement with the technology.

c) The Research Approach: The study employs a multi-phase, sequential exploratory design, including an initial usability study and a multi-session longitudinal study. The theoretical lens is grounded in theories of intrinsic motivation, primarily Self-Determination Theory (SDT) and Flow Theory. The ultimate aim is to synthesize the findings into a new proposed model: the "Dynamic Barrier Framework", rather than applying existing technology acceptance models.

1.6 Organization Of The Thesis

This thesis is organized into five chapters.

Chapter 1 contains the introduction. It presents the research background, the problem statement, the research questions, and the research objectives. It also defines the scope of the study and outlines the organization of the thesis.

Chapter 2 provides the literature review. It follows a "narrative funnel" structure, beginning with the context of healthy aging and physical activity challenges. The chapter then reviews immersive exergames as a technological solution, analyzes the barriers to their adoption, and evaluates existing theoretical models to identify the research gaps.

Chapter 3 details the methodology used in this research. It describes the two-stage, sequential exploratory research design, which includes an initial usability study (Experiment A) and a longitudinal study (Experiment B). The chapter also explains the participant recruitment, the development of the Tai Chi exergame intervention, and the methods for data collection and analysis.

Chapter 4 presents the results and discussion. The findings are structured to align with the research objectives. It first reports the findings from the initial and longitudinal studies (RO1). It then uses this evidence to construct the "Dynamic Barrier Framework" (RO2). The chapter concludes by validating the proposed framework using the study's empirical findings (RO3).

Chapter 5 provides the conclusion. This chapter summarizes the key findings in relation to the research questions. It then details the theoretical and practical contributions of the study, discusses its limitations, and proposes directions for future research.

The research framework has been applied as the steps taken during the research. Figure 2 below illustrates the research framework used in this thesis.

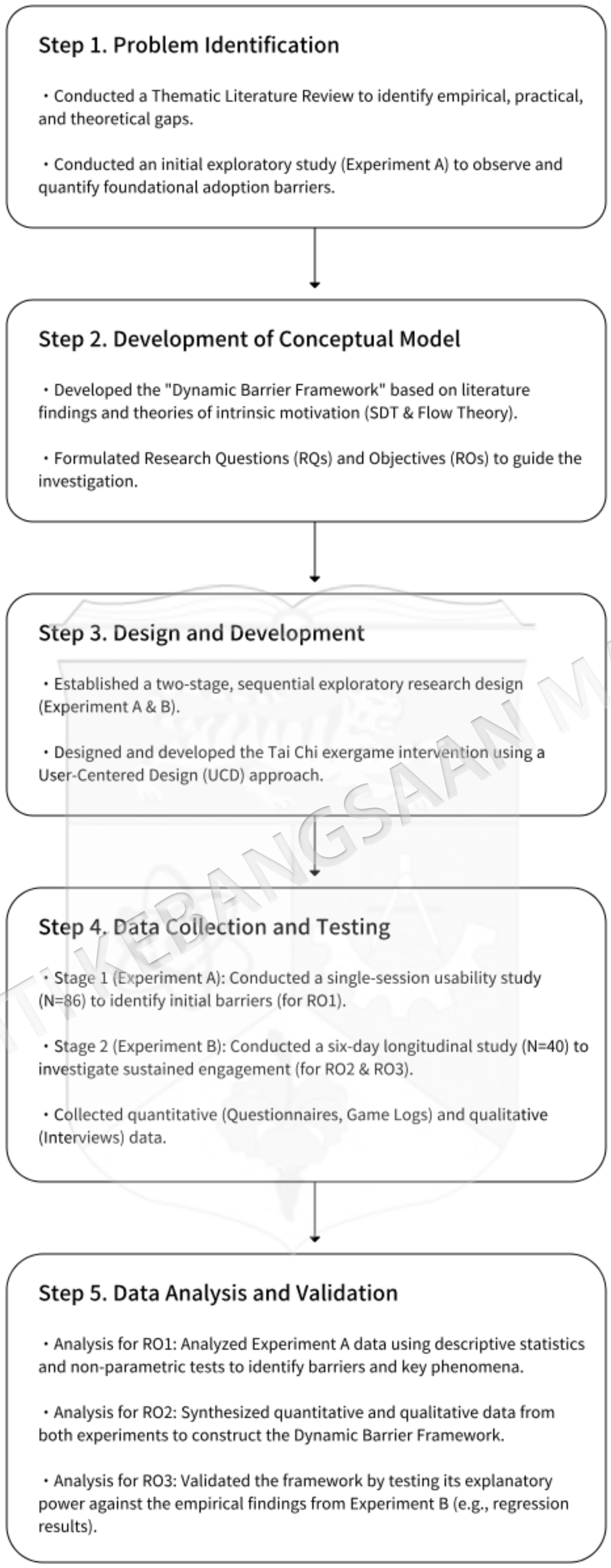

Figure 2 Research framework

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter provides a theoretical and empirical foundation for this doctoral thesis. The preceding chapter established the central research problem: the persistent gap between the promising potential of immersive exergames for promoting healthy aging and the practical reality of their low adoption rates and high user attrition among older adults. To better understand the nuances of this "potential-practice gap" and to ground the current investigation within the existing scholarly landscape, a careful engagement with the relevant bodies of literature is needed. The purpose of this chapter, therefore, is to conduct this systematic review. It aims to deconstruct the key concepts, synthesize the existing evidence, critically analyze the prevailing challenges, and evaluate the suitability of current theoretical models, thereby establishing a clear and evidence-based rationale for the research questions and objectives of this thesis.

Accordingly, this chapter evaluates the limitations of prior work rather than treating the literature only as descriptive background, with particular attention to where existing models fail to explain embodied and phase-dependent attrition.

The review therefore moves from the broader context of healthy aging and fall prevention to the more specific problem of sustained engagement with immersive exergames. It first examines the limitations of existing physical activity and fall-prevention approaches, then reviews VR/MR exergames as a possible but imperfect response to these limitations. The chapter then synthesizes evidence on usability, cybersickness, technology anxiety, trust, and motivation to show why older adults' engagement cannot be explained by single-factor adoption models alone. This progression leads to the empirical, practical, and theoretical gaps that motivate the Dynamic Barrier Framework.

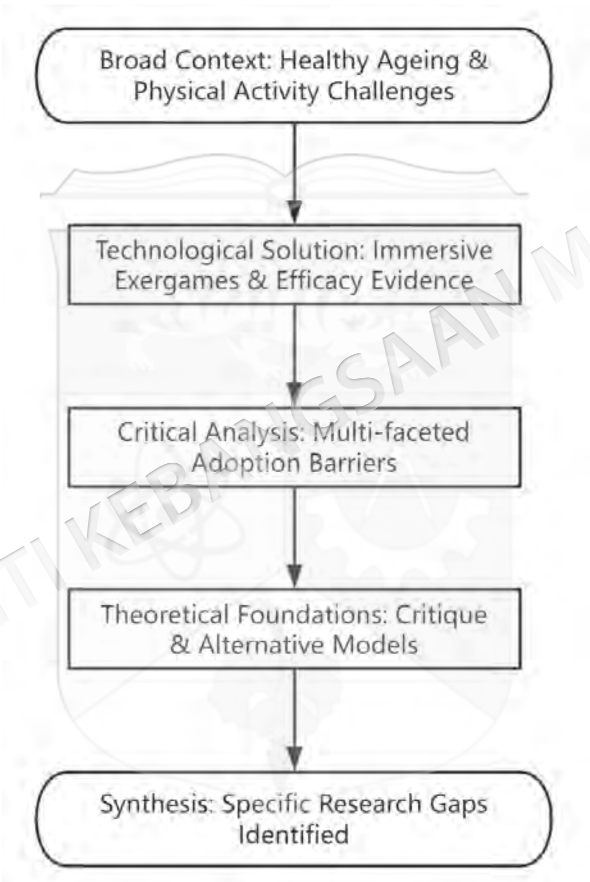

Figure 3 The Narrative Funnel Structure of Chapter 2

2.2 Healthy Aging And The Challenge Of Physical Activity

The pursuit of "Healthy Aging" has emerged as a paramount global priority, representing a paradigm shift from merely extending lifespan to enhancing the quality of those extended years. Central to this pursuit is the profound and well-documented challenge of promoting and sustaining physical activity among older adults (Smith et al. 2022). This section establishes the real-world context for the research problem, systematically exploring the intersection of global demographic trends and the critical need for effective physical interventions. It will lay the foundational argument for why innovative approaches to exercise are not just beneficial, but essential for the well-being of the world's rapidly growing older population (Bernardes et al. 2025).

This exploration will unfold in three parts (Sung et al. 2021). First, the sheer scale of the demographic transition towards an older global population will be detailed, establishing the urgency and scope of the issue. Second, the discussion will narrow to focus on fall prevention, a critical public health goal that crystallizes the life-altering importance of maintaining physical function. Finally, this section will delve into the persistent "adherence dilemma" associated with traditional exercise modalities, identifying the key bottleneck that necessitates the novel technological solution investigated in this thesis.

2.2.1 The Global Trend Of Population Aging And The Imperative Of Healthy Aging

The twenty-first century is defined by an unprecedented demographic transformation: the rapid and accelerating aging of the global population (Sy et al. 2023). This is not a localized phenomenon but a worldwide trend that poses significant and multifaceted challenges to public health systems, social welfare structures, and economic stability. The scale of this demographic transformation, as highlighted by major international bodies, is detailed in Table 1. According to projections from the World Health Organization (WHO), the number of people aged 60 and over is expected to more than double, reaching 2 billion by the year 2050 ("Ageing" 2025; *World population prospects 2022* 2022), (see Figure 4, Figure 5). Similarly, the United Nations forecasts that by 2050, individuals aged 65 and over will constitute 16.4 percent of the world's population, with a particularly sharp increase in the cohort of the "oldest-old" (those aged 80 and above) (Jakovljevic et al. 2020; Sy et al. 2023). This profound demographic shift necessitates a fundamental re-evaluation of societal approaches to health, well-being, and care for older persons, urging a move away from reactive, disease-focused models towards proactive, preventative, and holistic strategies.

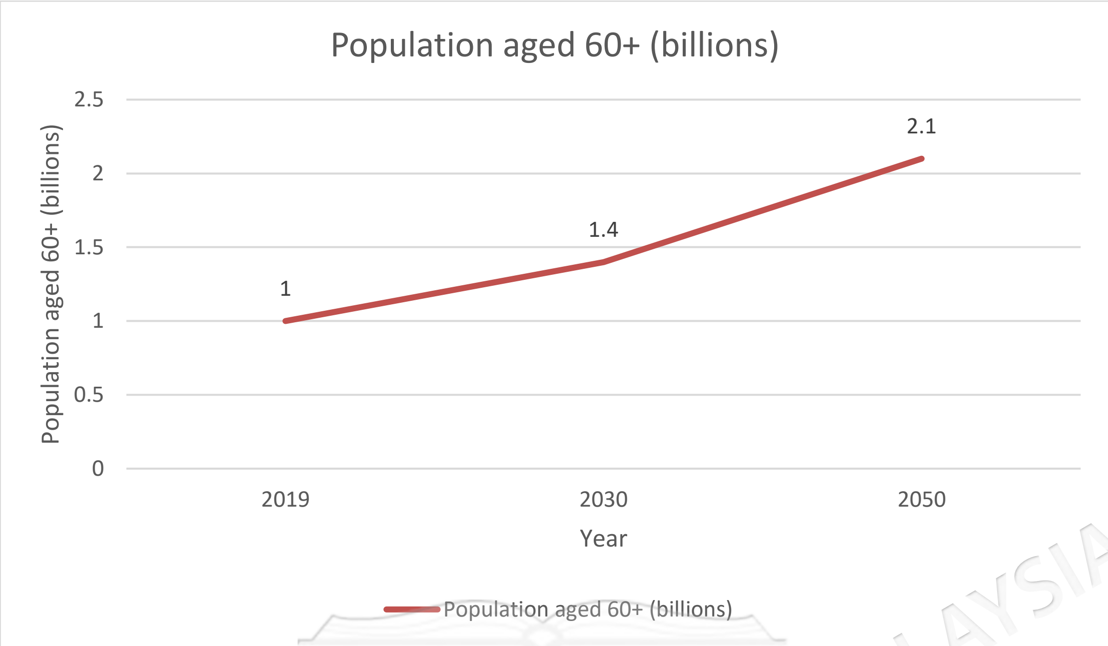

Figure 4 Global population aged 60 years and above, 2019-2050, in billions (WHO, 2019)

Table 1 Key Projections of Global Population Aging

Organization	Key Statistic / Projection	Target Year
World Health Organization (WHO) ("Decade of healthy ageing" 2021)	The number of people aged 60 and over is expected to more than double, reaching 2 billion.	2050
United Nations (UN) (*World population prospects 2022* 2022)	Individuals aged 65 and over will constitute 16.4 percent of the world's population.	2050
	A particularly sharp increase is expected in the "oldest-old" cohort (those aged 80 and above).	2050

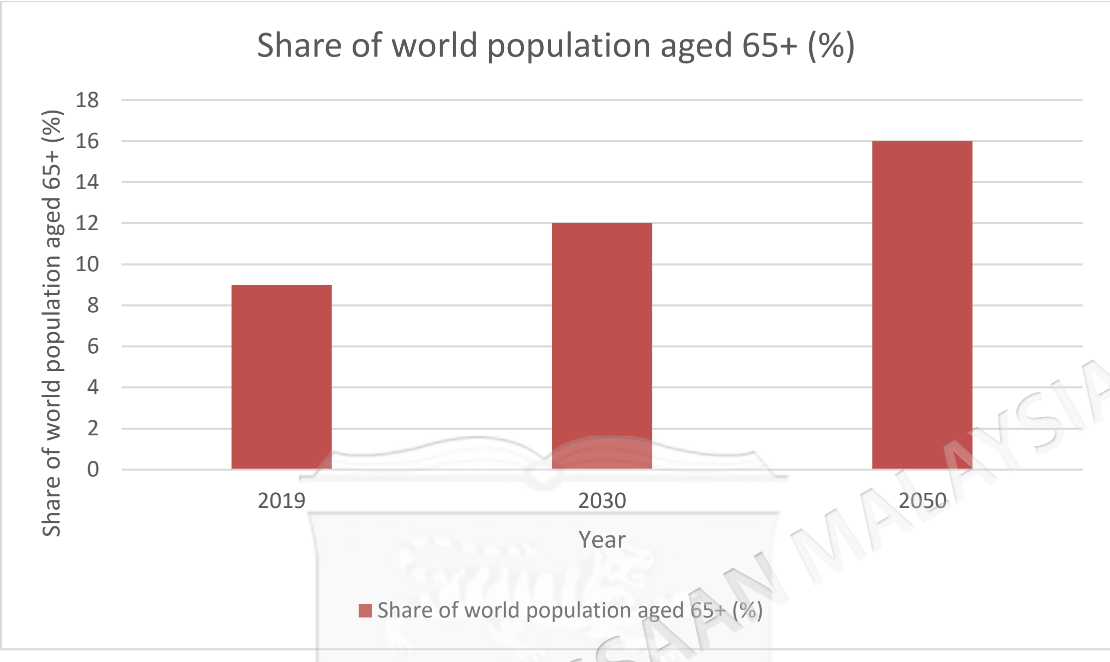

Figure 5 Share of world population aged 65 years and above, 2019-2050 (%)
(World population prospects 2022)

The ramifications of this demographic shift extend far beyond the realm of public health, creating profound socioeconomic pressures on a global scale. Economically, nations face the dual challenge of rising healthcare expenditures associated with age-related chronic conditions and a shrinking ratio of working-age individuals to retirees, placing unprecedented strain on pension funds and social security systems (Sy et al. 2023). Socially, this trend necessitates new models for community support, long-term care, and intergenerational engagement. This complex interplay of health, social, and economic factors underscores that promoting health and maintaining function in older age is not merely a quality-of-life concern for individuals; it is a critical strategy for ensuring societal sustainability and resilience in the face of this historic demographic transition (Thinley 2021).

In response to this global challenge, international health bodies and national governments have championed the paradigm of "Healthy Aging". As defined by the WHO, Healthy Aging is the process of developing and maintaining the functional ability that enables well-being in older age (Patel & Gallagher 2024). This perspective marks a significant departure from a traditional, deficit-oriented view of aging as an inevitable period of decline. Instead, it focuses on optimizing opportunities for health, participation, and security in order to enhance quality of life as people age. Intricately linked to this paradigm is the concept of "Aging in Place," which underscores the goal of enabling older adults to live in their own homes and communities safely, independently, and comfortably for as long as possible (Cesari et al. 2022). Together, these concepts form a guiding philosophy for modern gerontology and public health policy, emphasizing empowerment, autonomy, and the preservation of individual capacity as the primary objectives of care and intervention.

Despite the policy emphasis on healthy aging, implementation remains uneven at the community level, where access, adherence, and sustained support often determine whether recommended activity programs can be maintained.

The concept of "functional ability," central to the Healthy Aging framework, is a composite of two key elements: the intrinsic capacity of the individual and the characteristics of the environment they inhabit. Intrinsic capacity encompasses all the physical and mental capacities that a person can draw upon, including their mobility, sensory function, and cognitive abilities (Cesari et al. 2022). The environment comprises the external world, from the home and community to broader societal attitudes and support systems. Consequently, interventions aimed at promoting Healthy Aging can target two distinct pathways: either by enhancing an individual's intrinsic capacity or by creating enabling and supportive environments. The research presented in this thesis focuses on the former pathway, exploring how technological interventions can be designed to directly build and maintain the intrinsic physical capacities of older adults, thereby empowering them to navigate their environments with greater confidence and independence.

Central to the successful implementation of the Healthy Aging agenda is the promotion of regular physical activity, which is widely recognized in the scientific literature as a cornerstone of health and well-being in later life (Wolff et al. 2025). The benefits of sustained physical engagement for older adults are extensive and well-documented. Physiologically, it is a powerful tool for the primary and secondary prevention of a host of chronic non-communicable diseases, including cardiovascular conditions, type 2 diabetes, and certain cancers (Izquierdo et al. 2025). It is also crucial for maintaining musculoskeletal health, preserving muscle mass (combating sarcopenia), maintaining bone density (combating osteoporosis), and, critically, enhancing balance and coordination (Indrakumar & Silva 2024; Izquierdo et al. 2025). Cognitively, a growing body of evidence links physical activity to improved brain health, with benefits for functions such as memory, attention, and executive function. Psychologically, regular exercise is associated with reduced symptoms of depression and anxiety and improved mood and overall psychological well-being (Nguyen et al. 2024; Rabinowitz et al. 2023). Ultimately, these multifaceted benefits converge to support the core goals of Healthy Aging: fostering independence, enhancing quality of life, and enabling older adults to remain active and engaged members of their communities. These extensive benefits of physical activity across physiological, cognitive, and psychological domains are summarized in Table 2.

Table 2 Documented Benefits of Physical Activity for Older Adults

Domain	**Specific Benefits**
Physiological	- Prevention of a host of chronic non-communicable diseases - Maintenance of musculoskeletal health, including preserving muscle mass and bone density - Enhancement of balance and coordination
Cognitive	- Improved brain health - Benefits for functions such as memory, attention, and executive function
Psychological	- Reduced symptoms of depression and anxiety - Improved mood and overall psychological well-being

Recognizing the pivotal role of physical activity, major public health organizations such as the WHO have established specific guidelines for older adults. These guidelines typically advocate for a multi-component approach to exercise that addresses various facets of physical health (Fukushima et al. 2024). The WHO's multi-component approach advocates for a mix of aerobic, strength, flexibility, and balance training. The key components and their primary goals are summarized in Table 3 , while the specific weekly recommendations for duration and frequency are detailed in Figure 6 and Figure 7 (Bull et al. 2020; *WHO guidelines on physical activity and sedentary behaviour* 2020). The key recommended components include: (1) aerobic activities to maintain cardiovascular health; (2) muscle-strengthening exercises to combat sarcopenia and maintain strength for daily tasks; (3) flexibility training to preserve range of motion; and (4) balance training, which is of paramount importance for this demographic (Fukushima et al. 2024; Makizako et al. 2020). Balance exercises are specifically designed to improve stability and reduce the risk of falls, a leading cause of injury, loss of independence, and mortality among older adults. Therefore, interventions that can effectively and engagingly deliver balance training are considered a high-priority area within the broader strategy of promoting physical activity for Healthy Aging (Gerards et al. 2021).

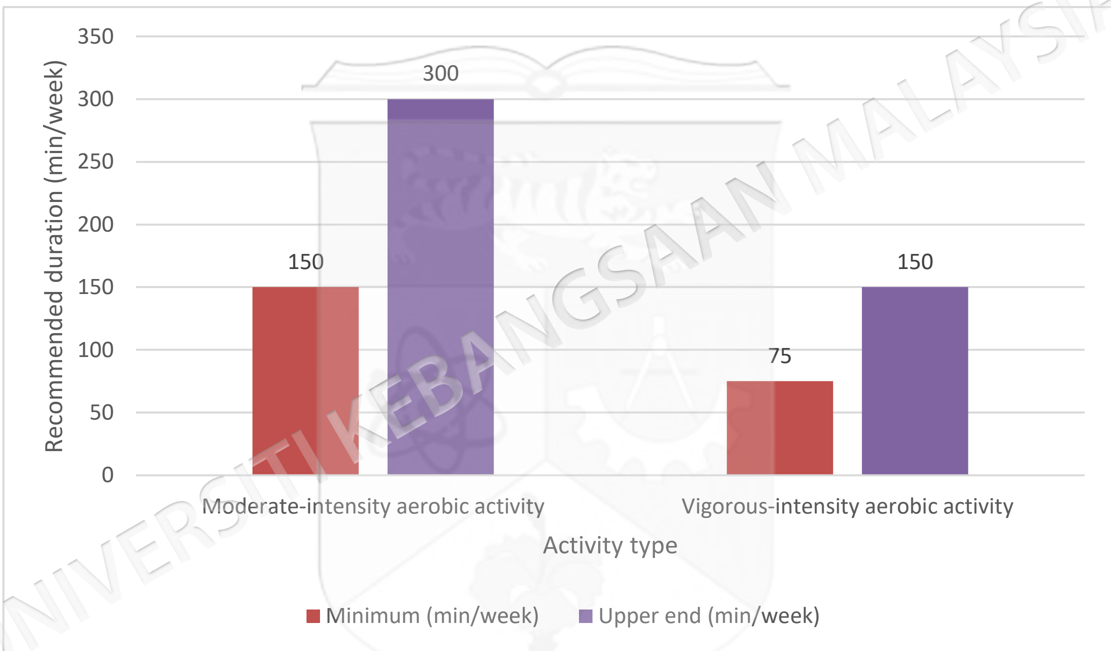

Figure 6 WHO 2020 weekly aerobic activity recommendations for adults aged 65+ (in minutes) (Bull et al. 2020).

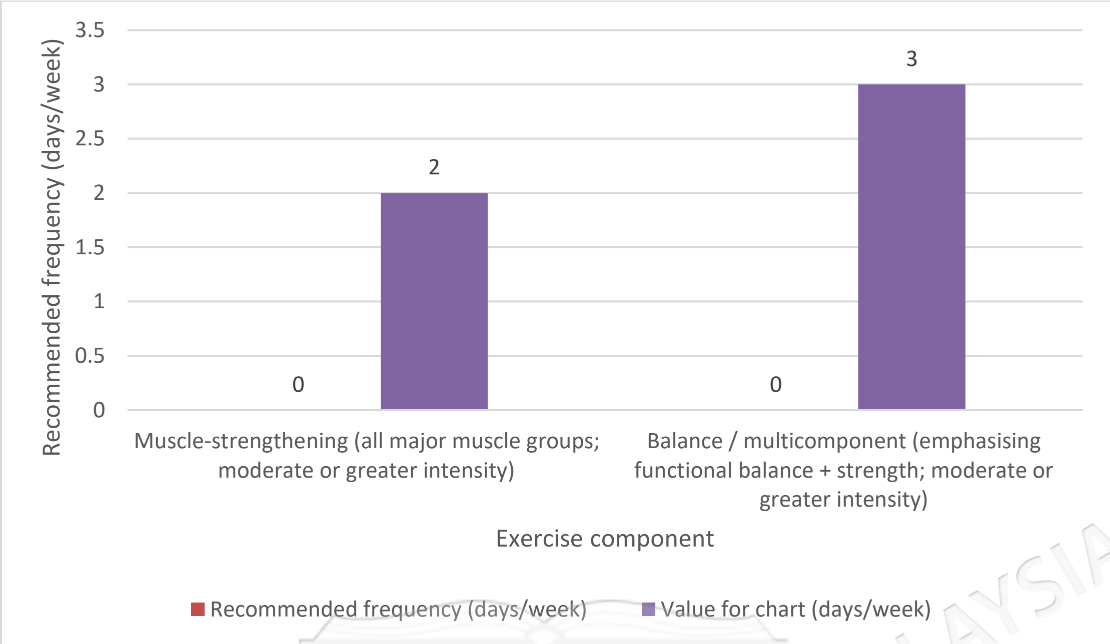

Figure 7 WHO 2020 weekly frequency recommendations for muscle-strengthening and balance-focused exercise for adults aged 65+ (in days) (Bull et al. 2020).

Table 3 WHO Multi-component Exercise Recommendations for Older Adults

Component	**Primary Goal**
Aerobic Activities	To maintain cardiovascular health.
Muscle-strengthening Exercises	To combat sarcopenia and maintain strength for daily tasks.
Flexibility Training	To preserve range of motion.
Balance Training	To improve stability and reduce the risk of falls.

However, despite the overwhelming evidence supporting its benefits, establishing and maintaining adequate levels of physical activity among the older population remains a formidable public health challenge (Yang & Moffatt 2024). Recognizing this gap between knowledge and practice, the research community has increasingly turned its attention toward exploring how emerging technologies can be leveraged to create more engaging, accessible, and sustainable technology-supported exercise programs (Bernardes et al. 2025). The imperative is to move beyond simply prescribing exercise and instead to design experiences that motivate, support, and empower older adults to integrate physical activity seamlessly into their daily lives. Among the various health targets for this demographic, one of the most pressing and impactful is the prevention of falls, an issue that demands targeted and highly effective intervention strategies, and which will be discussed in the subsequent section (Yang 2023).

2.2.2 Fall Prevention As A Critical Public Health Goal For Older Adults

While promoting general physical activity is foundational to the Healthy Aging paradigm, specific health threats demand targeted intervention strategies. Among the most pressing of these is the prevention of falls, an issue that has escalated into a crucial and undeniable public health priority for the elderly population globally (Blain, Miot & Bernard 2021; Lach et al. 2023). Falls are a leading cause of fatal and non-fatal injuries among older adults, and their prevalence and severity are often underestimated. Far from being minor accidents, falls can be life-altering events; research indicates that approximately 20% of falls result in a serious injury, such as a hip fracture or a traumatic brain injury, which can precipitate a rapid decline in health and lead to loss of independence or even death, as shown in Figure 8 (Alamri et al. 2023; Vaishya & Vaish 2020). Compounding the issue, data from the last decade reveals a concerning upward trend in the rate of fall-related fatalities among individuals over 65, indicating that the problem is worsening despite advances in conventional care and support (Vaishya & Vaish 2020).

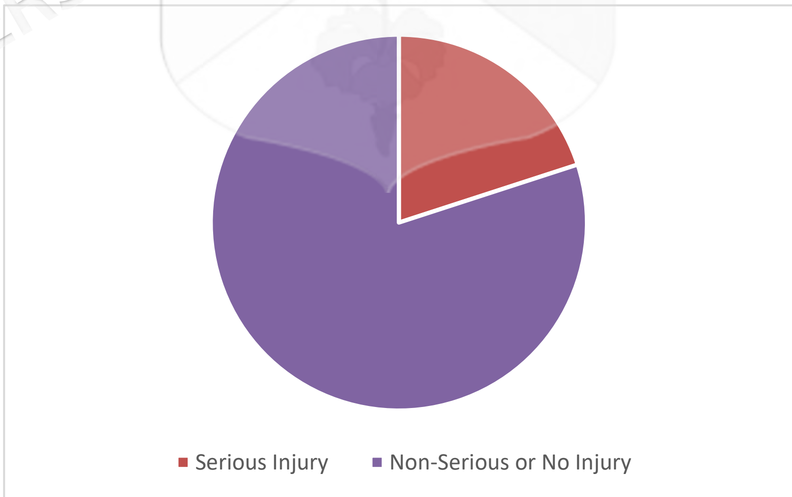

Figure 8 Outcomes of Falls Among Older Adults

The consequences of falls extend beyond the immediate physical trauma, imposing a staggering burden on public service systems and the psychological well-being of older adults. Economically, the cost is immense, with annual direct medical costs for falls in the United States alone exceeding $30 billion (Haddad et al. 2024; Reider et al. 2022). This substantial expenditure diverts critical resources and underscores the economic imperative of effective prevention. Perhaps even more insidious is the profound psychological impact (Haddad et al. 2024; Kwon et al. 2022). A single fall can trigger a debilitating "fear of falling," a condition that becomes a key psychological barrier to continued physical activity and community engagement. This fear often leads to a self-imposed restriction of activities, which ironically creates a vicious cycle of deconditioning, as illustrated in Figure 9: reduced mobility leads to muscle weakness, diminished balance, and social isolation, all of which paradoxically increase the risk of subsequent falls (Tamulaityte-Morozoviene et al. 2024).

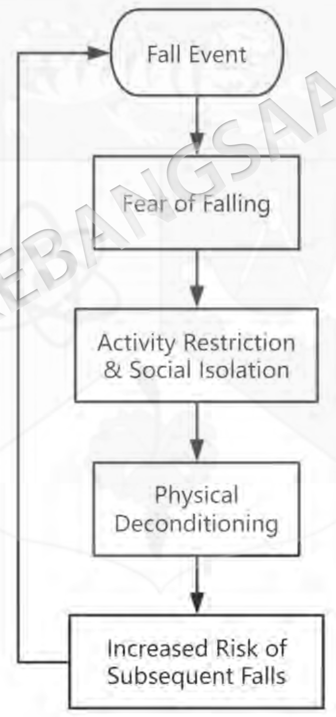

Figure 9 The Vicious Cycle of Deconditioning Following a Fall (Tamulaityte-Morozoviene et al. 2024)

Fortunately, falls are not an inevitable consequence of aging and are, in large part, preventable. An extensive body of evidence has robustly established that regular physical activity, particularly structured exercise programs that target multiple risk factors, is the single most effective strategy for reducing fall risk (Tomazin, Knific & Dolenc 2023). The most successful interventions typically involve multicomponent training that includes strength, aerobic, and flexibility exercises, with a special emphasis on balance training. Modalities such as Tai Chi have been extensively studied and are particularly celebrated for their efficacy in this domain. Research has consistently demonstrated that the practice of Tai Chi can significantly improve dynamic balance, reduce the incidence of falls, and concurrently alleviate the fear of falling, thereby addressing both the physical and psychological dimensions of the problem (Chen et al. 2023a; Li et al. 2024a; Zhang et al. 2023).

Although Tai Chi and multicomponent exercise are well supported, their effectiveness varies with delivery context, participant confidence, supervision, and the ability to maintain regular participation beyond structured sessions.

The scientific link between targeted exercise and fall prevention is therefore clear and unequivocal; the challenge lies not in what to do, but in how to get it done effectively and sustainably. The proven efficacy of an intervention like Tai Chi in a controlled clinical trial is of little public health value if older adults in the community do not participate in it, or fail to adhere to it over the long term (Chen et al. 2023a). This critical gap between the known efficacy of balance training and its real-world effectiveness highlights a central problem in gerontological health promotion (Ambrens et al. 2024). Therefore, the primary challenge shifts from a biomechanical or medical question to one of motivation, engagement, and adherence. The persistent difficulties in sustaining participation in traditional, often monotonous, exercise programs a problem this thesis terms the "adherence dilemma" will be the focus of the following section (Gavin et al. 2024). This logic informs the study plan of the thesis, which shifts the focus from whether Tai Chi-based balance training is effective to how older adults adopt, experience, and sustain engagement with a Tai Chi-based VR/MR exergame.

2.2.3 The Adherence Dilemma In Traditional Balance Training

While the previous section established the unequivocal efficacy of traditional balance training programs like Tai Chi in preventing falls, a significant chasm exists between their proven potential in controlled settings (*efficacy*) and their actual impact on public health (*effectiveness*). This gap is primarily caused by what can be termed the "adherence dilemma": the persistent challenge of ensuring older adults' long-term participation and compliance with these exercise regimens (Corniani et al. 2025). Research consistently shows that adherence to traditional exercise among community-dwelling older adults is generally low, with poor compliance and high dropout rates severely limiting the potential health benefits of these established programs (Chen et al. 2020). Consequently, the central problem in fall prevention is often not a lack of effective interventions, but rather the profound difficulty in motivating and sustaining the very behaviors required to make these interventions work in the real world (Corniani et al. 2025). The roots of this adherence dilemma are multifaceted, stemming from both intrinsic and extrinsic factors, as summarized in Figure 10 and detailed in Table 4.

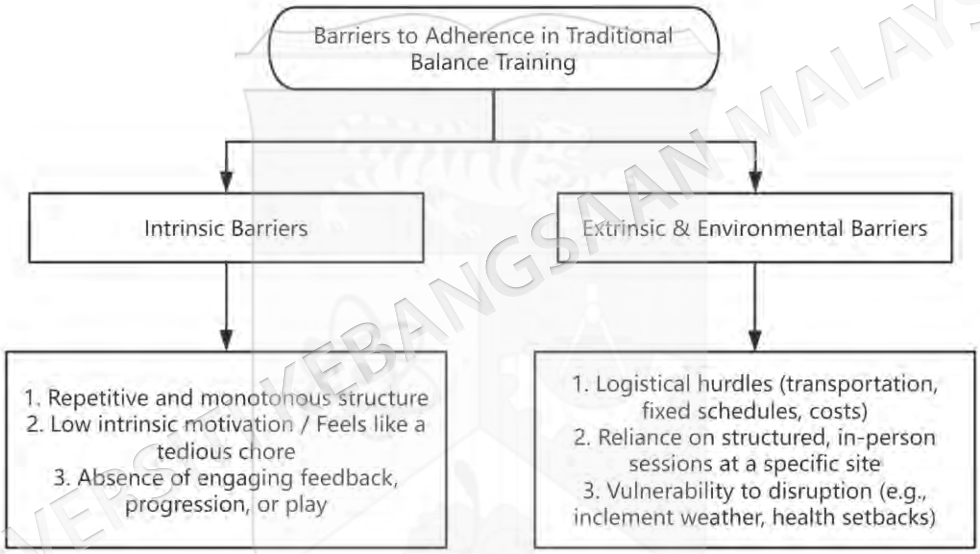

Figure 10 A Conceptual Map of Adherence Barriers in Traditional Balance Training

Table 4 Barriers to Adherence in Traditional Balance Training for Older Adults

Barrier Category	Specific Description	Impact on Older Adults
Intrinsic Barriers	Characterized by a repetitive and monotonous structure.	Diminishes participants' motivation over time. Makes the practice feel like a tedious chore.
Intrinsic Barriers	Absence of engaging feedback loops, a clear sense of progression, or elements of play.	Leads to low intrinsic motivation, making long-term, self-directed commitment difficult.
Extrinsic & Environmental Barriers	Relies on structured, in-person sessions at a specific site (e.g., community center or clinic).	Imposes considerable logistical hurdles, including transportation needs, adherence to a fixed schedule, and potential financial costs.

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Extrinsic & Environmental Barriers	Can be disrupted by factors like inclement weather or temporary health setbacks.	Makes it difficult to maintain the consistent training frequency and duration necessary for training benefits.

The roots of this adherence dilemma are multifaceted, stemming first from intrinsic factors related to the nature of the exercises themselves. Traditional balance training, while beneficial, is often characterized by a repetitive and monotonous structure that can diminish participants' motivation over time (Rodrigues et al. 2023). These conventional models frequently fail to address the specific emotional and experiential needs of the aging population, treating exercise as a clinical prescription rather than a fulfilling activity (Turner & Reed 2022). The absence of engaging feedback loops, a clear sense of progression, or elements of play can make the practice feel like a tedious chore (Ednie & Stibor 2017). This low intrinsic motivation is a primary psychological barrier, as the perceived effort of engaging in the activity outweighs the immediate psychological rewards, making long-term, self-directed commitment exceptionally difficult to maintain (Shin & Kim 2021).

Compounding these intrinsic challenges are significant extrinsic and environmental barriers that further complicate sustained participation. Traditional programs often rely on structured, in-person sessions that require a strict site, such as a community center or clinic, and the presence of a professional instructor or guide (Townsend, Chen & Wuthrich 2021). This model imposes considerable logistical hurdles for older adults, including the need for reliable transportation, adherence to a fixed schedule, and potential financial costs (dos Santos et al. 2021). Furthermore, factors like inclement weather or temporary health setbacks can easily disrupt the routine, making it difficult to maintain the consistent training frequency and duration necessary for training benefits (Coletta et al. 2025). These environmental and accessibility constraints severely limit the reach and sustainability of conventional programs, particularly for individuals with mobility issues or those living in remote areas (Roland et al. 2021).

Taken together, these psychological and environmental challenges reveal the inherent limitations of conventional exercise models and underscore the urgent need for a paradigm shift in intervention design (Labudek et al. 2023). It is clear that merely educating older adults about the benefits of balance training is an insufficient strategy to drive meaningful, long-term behavior change. The key challenge for researchers and practitioners is no longer simply to identify effective exercises, but to develop and deliver them through modalities that are accessible, engaging, and intrinsically motivating (Rodrigues et al. 2023). This necessitates a move towards solutions that can be seamlessly integrated into older adults' daily lives, providing them with the autonomy and enjoyment needed to transform exercise from a periodic, externally-driven task into a sustained, self-determined habit (Labudek et al. 2023).

This recognition has catalyzed a crucial shift in the research focus, moving from an exclusive emphasis on clinical efficacy to a more holistic consideration of the psychological dimensions of user experience, motivation, and sustained participation (Campo-Prieto, Cancela-Carral & Rodríguez-Fuentes 2022a). The critical question has become: how can we design interventions that older adults not only can do, but want to do, day after day? It is precisely this question the search for an innovative, engaging, enjoyable, and home-based solution to the adherence dilemma that has spurred the exploration of immersive technologies (Mehrabi et al. 2022; Rings et al. 2023). The following section will review the rise of virtual and mixed reality exergames as a powerful and promising approach to transforming balance training from a monotonous chore into a captivating and sustainable activity (Song et al. 2025).

2.3 Immersive Technologies And Exergames For Older Adults

Having established the profound challenge of the "adherence dilemma" in traditional exercise, this section now shifts its focus to the core technological solution investigated in this thesis (Mehrabi et al. 2022; Song et al. 2025). The limitations of conventional methods necessitate a search for innovative interventions that can transform physical activity from a monotonous duty into an intrinsically motivating experience. This discussion is therefore important because immersive exergames are not treated merely as novel technologies, but as potential design responses to the motivational, experiential, and adherence-related barriers identified in the preceding section. To this end, the confluence of immersive technologies specifically Virtual Reality (VR) and Mixed

Reality (MR) with the engaging principles of video games ("exergaming") has emerged as a highly promising frontier in gerontechnology (Stamm et al. 2022). The objective of this section is therefore twofold: first, to systematically introduce these core technologies and the motivational framework of exergaming, and second, to critically review the existing body of evidence regarding their efficacy in enhancing the physical, cognitive, and psychosocial well-being of older adults (Yen & Chiu 2021).

The evidence on immersive technologies is therefore treated as promising but mixed: VR/MR systems can increase engagement, but their benefits depend on comfort, usability, safety, and the extent to which the experience remains meaningful after novelty fades.

The exploration within this section is structured to build a comprehensive understanding from the ground up. The discussion will commence with a foundational overview of VR and MR, defining their distinct technical characteristics and, more importantly, their unique experiential implications for an older user base (Sebastian et al. 2024). Following this, it will delve into the concept of exergaming, analyzing how its inherent game-based mechanics are strategically designed to function as a powerful motivational tool to combat exercise monotony and promote engagement. Finally, this section will culminate in a thorough review of the scientific literature, synthesizing empirical findings to build a clear picture of what is currently known about the effectiveness of these novel interventions, thereby setting the stage for a more critical analysis of the adoption challenges that follow (Júnior et al. 2021).

2.3.1 An Overview Of Immersive Technologies: Virtual And Mixed Reality

Immersive technologies represent a paradigm shift in human-computer interaction (HCI), moving beyond the traditional two-dimensional interfaces of screens and monitors into three-dimensional, spatial, and embodied experiences (Wang 2024). At their core, these technologies aim to digitally simulate or augment reality, creating a compelling sense of presence that makes users feel as though they are physically part of the computer-generated world (Holt 2023). This is achieved by engaging the user's senses primarily sight and sound, but increasingly touch to a degree that the boundary between the physical and digital realms begins to blur (Desnoyers-Stewart et al. 2024).

Unlike conventional media, which are passively observed, immersive environments are actively experienced. Within the broad spectrum of immersive technologies, Virtual Reality (VR) and Mixed Reality (MR) stand out as the two most prominent and relevant modalities for the research presented in this thesis, each offering a distinct set of capabilities, experiences, and implications for the older adult user (Ahmmed et al. 2024).

Virtual Reality (VR) is the most established of these technologies and is defined as a fully computer-generated simulation of a three-dimensional environment that users can explore and interact with in a seemingly physical way (Loetscher et al. 2023). The quintessential apparatus for VR is the head-mounted display (HMD), a device worn over the eyes that completely occludes the user's view of their physical surroundings and replaces it with the virtual world (Loetscher et al. 2023). Modern VR systems achieve a high degree of immersion through a combination of key features: stereoscopic 3D visuals that create depth perception, high-resolution displays with a wide field of view, and integrated spatial audio (Kim et al. 2021). Crucially, they incorporate sophisticated tracking systems. Head tracking allows users to naturally look around the virtual scene as they would in real life, while six-degrees-of-freedom (6DoF) position and hand tracking enable them to physically walk within a defined space and use their hands to manipulate virtual objects (Jiang et al. 2022). The ultimate goal of VR is often to induce a strong sense of "presence" the profound psychological sensation of truly "being there" inside the virtual environment. This feeling of presence is believed to be the primary driver of VR's power to engage, entertain, and effectively train users (Loetscher et al. 2023).

In contrast to the fully synthetic worlds of VR, Mixed Reality (MR) operates on the principle of blending the real and the virtual (Riva 2023). MR is a technology that merges the physical and digital worlds to produce new environments and visualizations, where real-world and computer-generated objects can co-exist and interact in real time. In the context of contemporary consumer HMDs, such as the Meta Quest 3 used in this research, this is primarily achieved via high-fidelity, full-color "video passthrough" technology (Apochi et al. 2024; Riva 2023). The device's external cameras capture a live feed of the user's actual physical environment and display it inside the headset. The system then renders, or "overlays," interactive digital elements such as instructional prompts, virtual characters, or game interfaces onto this real-world view. This creates the illusion that the virtual objects are part of the user's physical space. MR can be seen as an advanced form of Augmented Reality (AR), moving beyond simply displaying information on top of reality (as with a smartphone app) to creating a more seamlessly integrated and interactive experience where the user and the virtual elements are mutually aware and responsive (Amaro & Sieck 2023).

The fundamental distinction between these two technologies can be best understood by placing them on a "virtuality continuum," which spans from the completely real environment at one end to the completely virtual environment at the other (Aguayo 2021). Mixed Reality occupies the space between these two poles, augmenting the real world with digital information (López-Ojeda & Hurley 2022). Virtual Reality sits at the far end of the continuum, completely replacing the real world with a digital one. This conceptual difference translates into a profound experiential one: VR transports the user to an entirely new place, whereas MR keeps the user grounded in their familiar surroundings while enhancing it with new possibilities (Shin, Sibuea & Lee 2024). In a VR experience, the user is a visitor in a simulated world; in an MR experience, the user remains the inhabitant of their own world, which now contains new, interactive digital properties (Shin, Sibuea & Lee 2024).

When contextualized for the specific needs and vulnerabilities of older adults, this technological distinction becomes a critical design consideration with significant trade-offs (Drazich et al. 2023). The high level of immersion in Virtual Reality is its greatest strength for exergaming; it can create deeply engaging and motivating experiences, providing a sense of escapism that can distract from the physical exertion of exercise (Li, Shiyanov & Muschalla 2025). However, this same reality-occluding nature presents considerable challenges for older users. The complete separation from the physical environment can lead to disorientation, a loss of spatial awareness regarding real-world obstacles like furniture, and an increased risk of inducing cybersickness, which manifests as dizziness, eye fatigue, and nausea. Conversely, the primary advantage of Mixed Reality for this demographic is the preservation of real-world perception. The ability to see one's own body, furniture, and floor provides a powerful psychological "safety net," which can substantially reduce the fear of falling and enhance feelings of comfort and security. The potential trade-off, however, is that this grounding in reality may result in a lower sense of presence and immersion, potentially diminishing the escapism and motivational pull of the experience (Séba et al. 2023). This fundamental tension between the captivating but potentially disorienting power of VR and the safe but potentially less engaging nature of MR forms a central investigative axis of this thesis and directly informs the research into user comfort, long-term preference, and the "immersion paradox", as visually summarized in Figure 11. The key trade-offs between these two immersive modalities for older adult users are summarized in Table 5.

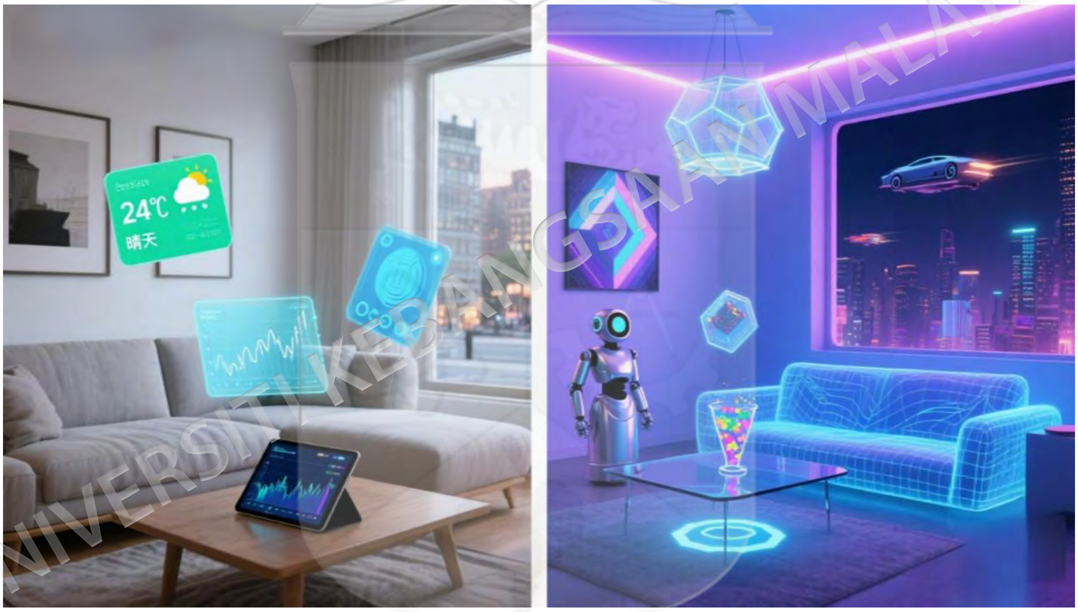

Figure 11 Experiential Trade-offs of Virtual Reality vs. Mixed Reality

Table 5 Comparison of Virtual Reality (VR) and Mixed Reality (MR) for Older Adult Users

Feature	**Virtual Reality (VR)**	**Mixed Reality (MR)**
Core Experience	A fully computer-generated simulation that completely replaces the user's view of their physical surroundings. The user is transported to a new place.	Blends the real and virtual worlds by overlaying digital elements onto the user's view of their actual environment. The user remains grounded in their familiar surroundings.
Main Advantage for Older Adults	The high level of immersion provides a sense of escapism that can distract from the physical exertion of exercise.	The ability to see one's own body and physical surroundings provides a psychological "safety net," reducing the fear of falling and enhancing feelings of security.

Main Challenge for Older Adults	Complete separation from the physical environment can lead to disorientation and an increased risk of cybersickness (dizziness, nausea).	The experience may have a lower sense of presence and immersion, potentially diminishing the motivational pull compared to VR.

2.3.2 The Rise Of Exergaming As A Motivational Tool

The rise of "exergaming" a portmanteau of "exercise" and "gaming" represents a direct and innovative response to the adherence dilemma detailed in the preceding section. At its core, an exergame is a video game that requires physical activity to play, effectively transforming the user's body into the controller (Stranick & Lopez 2021). The fundamental premise of this approach is to leverage the deeply engaging and motivational principles of game design to reframe the entire experience of physical exertion (Chan et al. 2025). Instead of being a monotonous, externally mandated chore pursued for a distant health benefit, exercise within an exergame becomes an intrinsically rewarding activity. The goal is no longer simply to complete a set of repetitions, but to achieve a high score, advance to the next level, or collaborate with a partner to overcome a challenge. This paradigm shift from compliance-driven exercise prescriptions to playful, user-centered experiences is the foundational reason why exergaming has emerged as a powerful motivational tool in health and rehabilitation (Chan et al. 2025; Júnior et al. 2021; Yansun, Kim & Wünsche 2022).

The psychological engine that drives the motivational power of exergaming is the principle of gamification, which involves the strategic application of game-design elements in non-game contexts to influence behavior (Xu et al. 2022). Well-designed exergames are rich with such elements, each targeting a specific aspect of human motivation. These include the provision of clear, immediate goals; real-time, multi-sensory feedback on performance; systems of points, badges, and leaderboards to signify achievement; and compelling narratives or virtual environments that provide context and purpose to the physical tasks (Xu et al. 2022). These mechanics work in concert to create a powerful positive feedback loop. Success is instantly recognized and rewarded, which in turn fosters a desire to continue playing and improving. This process taps into fundamental human psychological drivers for achievement, mastery, competition, and discovery, thereby fostering a state of intrinsic motivation, where the user engages in the activity for the inherent satisfaction and enjoyment it provides, rather than for some separable consequence (Harackiewicz & Elliot 1993; Kingsley & Grabner-Hagen 2023). The specific game-design elements that work in concert to create this motivational feedback loop are detailed in Table 6.

Table 6 Key Gamification Elements in Exergaming and Their Motivational Purpose

Gamification Element	**Motivational Purpose**
Clear, immediate goals	Provides context and purpose to the physical tasks.
Real-time, multi-sensory feedback on performance	Instantly recognizes success and fosters a desire to continue playing and improving.
Systems of points, badges, and leaderboards	Signifies achievement and taps into fundamental psychological drivers for mastery and competition.
Compelling narratives or virtual environments	Fosters intrinsic motivation by making the activity enjoyable for its own sake, rather than for some separable consequence.

The remarkable ability of exergames to foster such intrinsic motivation can be robustly explained through the lens of Self-Determination Theory (SDT) (Cotter et al. 2024), a leading theory of human motivation. Exergames are particularly adept at satisfying the three innate psychological needs proposed by SDT, as detailed in Table 7. SDT posits that all humans have three innate psychological needs: competence, autonomy, and relatedness. Exergames are particularly adept at satisfying these needs. The need for competence, or the feeling of mastery and effectiveness, is fulfilled through carefully calibrated challenges and immediate positive feedback. As this thesis's own research reveals, an optimal design can even create an "Empowerment Sweet Spot," a highly motivating state of low perceived challenge coupled with high perceived competence, which is particularly beneficial for older adults who may be anxious about failure (Cotter et al. 2024; Kirkland et al. 2011). The need for autonomy, or the sense of volition and control, is supported by providing players with choices, such as selecting difficulty levels, customizing avatars, or choosing different game modes, thereby making them the authors of their own exercise experience (Peng et al. 2012). Finally, the need for relatedness, or the feeling of social connection, can be met through multiplayer modes or social features that allow for collaboration or friendly competition, which is known to alleviate loneliness and enhance long-term engagement (Chan et al. 2025; Shah et al. 2023).

Table 7 Fulfillment of Self-Determination Theory (SDT) (Ryan & Deci 1985) Needs through Exergaming Design

SDT Core Psychological Need	**Definition**	**Fulfillment in Exergaming**
Competence	The feeling of mastery and effectiveness. The desire to feel effective, capable, and masterful in one's interactions with the environment.	Fulfilled through carefully calibrated challenges and immediate positive feedback. An optimal design can create an "Empowerment Sweet Spot" of low perceived challenge and high perceived competence.
Autonomy	The sense of volition and control. The desire to feel a sense of self-endorsement over one's own actions and decisions.	Supported by providing players with choices, such as selecting difficulty levels, customizing avatars, or choosing different game modes.
Relatedness	The feeling of social connection. The desire to feel socially connected, to care for and be cared for by others, and to have a sense of belonging.	Met through multiplayer modes or social features that allow for collaboration or friendly competition.

Furthermore, the deeply engaging nature of the most successful exergames can be understood through the concept of "Flow," a psychological state of complete absorption in an activity (Fong, Zaleski & Leach 2015). Described by psychologist Mihaly Csikszentmihalyi, flow is characterized by intense focus, a distortion of time perception, and the merging of action and awareness. The critical condition for achieving this optimal state is a dynamic and perceived balance between the level of challenge presented by the task and the user's own level of skill. If the challenge is too high relative to the skill, it leads to anxiety; if it is too low, it leads to boredom (Deterding & Cutting 2023). Effective exergames function as sophisticated "flow-generating engines," constantly adapting their difficulty to keep the player within this highly rewarding channel. This principle directly aligns with this thesis's findings, where a sense of both competence and appropriate challenge emerged as the most powerful independent predictors of a positive final user experience, underscoring the centrality of the challenge-skill balance in motivational design (Deterding & Cutting 2023; Fisher & Kulshreshth 2024).

When specifically applied to the context of older adults, the motivational framework of exergaming directly addresses the key barriers of traditional exercise. The novelty, variety, and goal-oriented structure of games provide a powerful antidote to the monotony and repetition of conventional drills (Bao et al. 2025). The capacity for many exergames to be used within the home environment effectively dismantles the significant logistical and environmental barriers of travel, scheduling, and reliance on external facilities or instructors, thereby greatly enhancing accessibility (Chu et al. 2021; Stanmore et al. 2024). Moreover, the virtual nature of the task can create a psychologically safe space for users to practice challenging balance movements. This allows them to push their limits and even "fail" without the immediate and severe real-world consequence of a physical fall, which can be instrumental in building the balance confidence required to overcome the debilitating fear of falling (E, C & S 2014).

While exergaming has been present for years on traditional two-dimensional platforms, the recent rise of consumer-grade immersive technologies, as described in the previous section, has amplified its motivational potential to an unprecedented degree (Born, Abramowski & Masuch 2019). The high sense of presence and embodiment afforded by VR and MR makes the gaming experience more visceral, believable, and all-encompassing, further blurring the line between exercise and play (Born, Abramowski & Masuch 2019). This heightened capacity of immersive exergaming to captivate and motivate users has fueled a surge of research interest into its specific applications and efficacy. The following section will now critically review the existing body of evidence on the impact of these advanced VR and MR exergames on the multi-faceted health and well-being of the older adult population (Buchem, Vorwerg & Stamm 2022).

2.3.3 Efficacy Of VR/MR Exergames For Older Adults: A Review Of Evidence

The motivational potential of immersive exergames, as discussed in the previous section, has catalyzed a substantial and growing body of research aimed at quantifying their tangible health benefits. Moving beyond theoretical promise, these empirical studies provide crucial evidence of the efficacy of VR and MR interventions across multiple domains (Kwan et al. 2024; Skjæret et al. 2016). This review will now systematically synthesize the findings from this body of literature, organizing the evidence into three key areas of impact that are central to the goals of Healthy Aging: (1) improvements in physical function, a direct countermeasure to frailty and fall risk; (2) enhancements in cognitive function, which is critical for maintaining independence and quality of life; and (3) positive impacts on social and psychological well-being, addressing the pervasive challenges of loneliness and mood decline.

a. Improvements in Physical Function

One of the most extensively researched and well-supported applications of immersive exergames for older adults lies in the enhancement of physical function, particularly balance, mobility, and overall motor control (Pacheco et al. 2020). These studies, with key examples summarized in Table 8, provide strong evidence that VR-based training can be at least as effective as, and often more engaging than, traditional exercise modalities. For instance, randomized controlled trials have demonstrated that structured VR balance training regimens can lead to significant improvements in participants' scores on standardized balance tests and, crucially, can also enhance their balance confidence while reducing their fear of falling (Pacheco et al. 2020; Percy et al. 2023). This highlights the technology's dual capacity to improve not only objective physical capabilities but also the subjective psychological factors that enable confident movement. Similarly, other research has validated the ecological relevance of VR training, finding that older adults exhibited comparable gait adaptability within an immersive virtual environment as they did in the real world, confirming that skills practiced in VR can be meaningfully transferred to everyday locomotor tasks (Ip et al. 2025).

The physical benefits documented in the literature extend beyond gross motor skills like balance and gait to encompass broader aspects of physical fitness and fine motor control. Studies have utilized exergames that encourage full-body movement, finding them to be a feasible and well-tolerated method for significantly enhancing lower limb strength and coordination in institutionalized older adults (Guede-Rojas et al. 2023; Peng et al. 2024). The physical demands of these games have also been quantified; studies comparing different modalities have found that while being more enjoyable, VR exergames can elicit a higher physiological workload compared to conventional 2D video exercises, affirming their legitimacy as a form of genuine physical exertion (Barbour et al. 2024). Even in the domain of fine motor skills, research has shown that despite VR-based tasks being more demanding initially, participants demonstrated significant learning effects over multiple trials, indicating the technology's potential for rehabilitating and maintaining hand-eye coordination (Lachowicz et al. 2024).

Table 8 Summary of Key Evidence on Physical Function Enhancement

Author(s)	Key Intervention	Key Finding on Physical Function
Pacheco et al., 2020; Percy et al., 2023	Structured VR balance training regimen	Led to significant improvements in standardized balance test scores and enhanced balance confidence while reducing fear of falling.
Ip et al., 2025	VR gait adaptability task	Confirmed that skills practiced in VR can be meaningfully transferred to everyday locomotor tasks, with older adults showing comparable gait adaptability as in the real world.
Guede-Rojas et al., 2023; Y. Peng et al., 2024	Full-body movement exergame	Proved to be a feasible and well-tolerated method for significantly enhancing lower limb strength and coordination in institutionalized older adults.

While this body of evidence robustly supports the efficacy of VR exergames in improving a range of physical functions, it also illuminates a more nuanced area for investigation that is central to this thesis (Ioannou et al. 2019). The majority of these studies focus on performance outcomes changes in test scores or task completion times but dedicate less attention to the *qualitative experience* of the training process itself, particularly the relationship between a user's objective performance and their subjective experience of competence during the task (Ioannou et al. 2019). This gap leads to critical design questions: Is perfect movement accuracy necessary for a positive experience? Can a user feel highly competent even if their objective performance is suboptimal? This line of inquiry directly sets the stage for this thesis's investigation into the "Accuracy-Competence Paradox". Understanding this paradox is crucial for designing exergames that can strike an optimal balance between maintaining user motivation and ensuring therapeutic effectiveness, a key challenge for unsupervised, home-based interventions (Huber et al. 2021).

b. Enhancements in Cognitive Function

A key advantage of exergaming over traditional physical exercise is its inherent capacity to simultaneously engage and challenge cognitive processes, offering a "dual-task" benefit that is highly relevant for older adults (Ogawa, You & Leveille 2016). The literature provides compelling evidence that immersive exergames can be an effective tool for enhancing a range of cognitive functions, with key examples summarized in Table 9. Longitudinal studies exemplify this potential, in which multitasking VR motion games required participants to perform both physical movements and cognitive tasks (Eggenberger et al. 2016). The results showed significant improvements not only in physical balance but also in working memory, reasoning abilities, and attention networks. This supports the "cognitive stimulation hypothesis," which posits that engaging in complex, mentally demanding activities can help build cognitive reserve and mitigate age-related decline (Eggenberger et al. 2016).

The immersive nature of VR is considered a key factor in its effectiveness as a cognitive training tool. By minimizing distractions from the physical world, VR environments can command a user's full attention, potentially leading to deeper cognitive engagement and learning (Corriveau Lecavalier et al. 2020). This is demonstrated in experiments using "virtual shop" tasks to assess episodic memory, which have validated that immersive VR can be a highly motivating and effective tool for this purpose, with performance correlating strongly with traditional neuropsychological tests. While this deep cognitive engagement is a clear benefit, it also raises questions about the role of immersion itself (Corriveau Lecavalier et al. 2020). The implicit assumption is often that higher immersion leads to better outcomes and a more positive experience. This thesis challenges that simple linear relationship, directly investigating the "Immersion Paradox" to explore whether the highest levels of sensory immersion always translate into the most positive long-term affective experience for older users.

Table 9 Summary of Key Evidence on Cognitive Function Enhancement

Author(s)	Key Intervention	Key Finding on Cognitive Function
Eggenberger et al., 2016	A multitasking VR motion game combining physical and cognitive tasks.	Resulted in significant improvements in working memory, reasoning abilities, and attention networks, supporting the "cognitive stimulation hypothesis" .
Corriveau Lecavalier et al., 2020	A "virtual shop" task designed to assess episodic memory in an immersive VR environment.	Validated that immersive VR can be a highly motivating and effective tool for memory assessment, with performance correlating strongly with traditional neuropsychological tests.

c. Positive Impacts on Social and Psychological Well-being

Beyond physical and cognitive benefits, as summarized in Table 10, immersive exergames have shown significant promise as interventions to improve the social and psychological well-being of older adults, addressing critical challenges such as social isolation, loneliness, and depression (Allegue et al. 2020). The engaging and enjoyable nature of these experiences can have a direct positive impact on mood. For example, large multicenter trials have found that exposing community-dwelling older adults to virtual reality experiences resulted in a significant immediate improvement in positive affect and a reduction in negative affect. This suggests that the novelty and escapism offered by virtual environments can serve as a potent tool for mood regulation (Chan et al. 2020).

Furthermore, the interactive capabilities of these technologies allow for the design of explicitly social experiences that can combat loneliness and foster a sense of community. Studies utilizing social and collaborative VR exergames have demonstrated that when participants worked together to complete tasks, the experience was perceived as significantly more motivating, enjoyable, and engaging than playing the same game alone (Shah et al. 2023). This finding underscores the importance of satisfying the fundamental human need for relatedness. While the existing literature clearly shows that positive affective and social outcomes are possible, this thesis seeks to delve deeper into the underlying mechanisms that enable them. It investigates not just the social features within a game, but the foundational social factors such as pre-existing community ties and interpersonal trust that act as a critical gateway to technology adoption in the first place (Shah et al. 2023). This exploration of the "Socio-psychological Barrier" aims to understand the prerequisite conditions that allow these positive well-being outcomes to be realized. A visual overview of the evidence coverage across domains is provided in Figure 12.

Table 10 Summary of Key Evidence on Psychosocial Well-being

Author(s)	Key Intervention	Key Finding on Psychosocial Well-being
Chan et al., 2020	Virtual reality tourism experiences for community-dwelling older adults.	Resulted in a significant immediate improvement in positive affect and a reduction in negative affect, serving as a potent tool for mood regulation.
Shah et al., 2023	A social and collaborative VR exergame requiring teamwork to complete tasks.	The collaborative experience was perceived as significantly more motivating, enjoyable, and engaging than playing the same game alone.

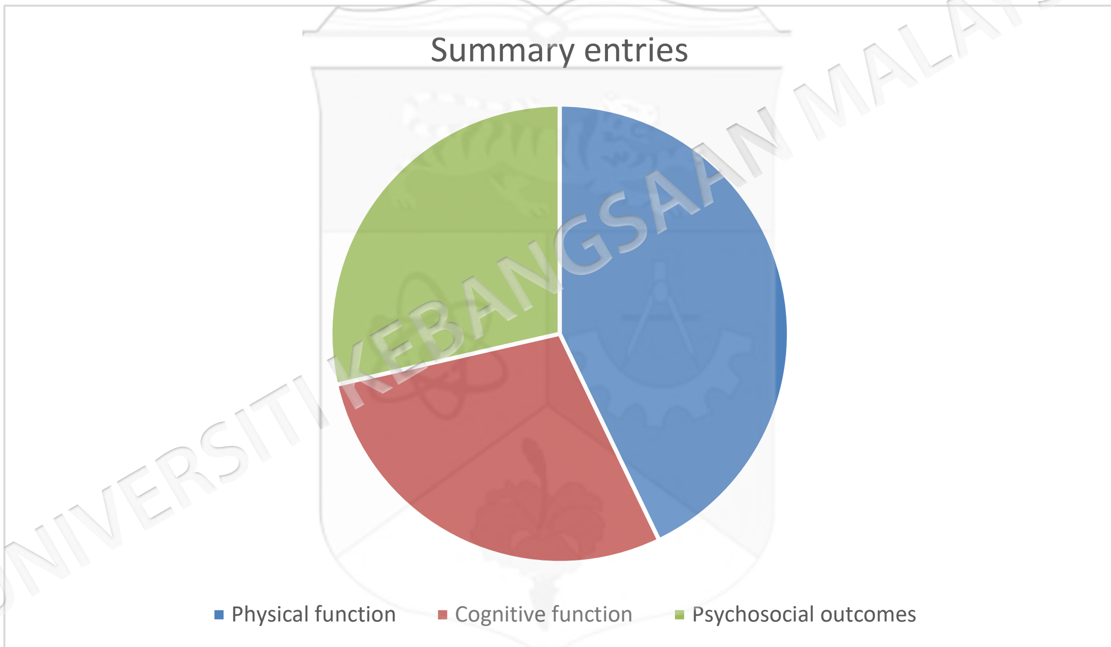

Figure 12 Coverage of evidence domains summarised in Chapter 2

2.4 Critical Factors In The Adoption And Sustained Engagement Of Immersive Technologies

While the preceding review has illuminated the significant promise and documented efficacy of immersive exergames, the path from a technologically potent solution to a successfully adopted and sustained health intervention is neither linear nor guaranteed. A substantial gap persists between what these technologies can achieve in controlled settings and what they do achieve in the complex, real-world contexts of older adults' daily lives (Mehrabi et al. 2022). This section, which forms the critical core of this literature review, therefore pivots from a discussion of potential to a deep and systematic exploration of the specific, multi-faceted barriers that hinder the successful application and long-term use of these technologies (Crane et al. 2023). Its purpose is to move beyond the question of "if" these tools can be effective, to the more pressing question of "why" they so often fail to be adopted, thereby building a solid and comprehensive literature foundation for the novel "Dynamic Barrier Framework" proposed in this thesis.

The forthcoming analysis is not an exhaustive catalogue of every possible issue, but rather a structured deconstruction of the most critical factors, organized to reflect the typical sequence of an older user's adoption journey (Al Khalifah et al. 2025; Schaumburg et al. 2025). The Dynamic Barrier Framework was developed through an iterative synthesis of the immersive-exergame literature, in which recurring barriers were grouped into a small set of conceptually distinct layers. The sequencing is rationale-driven and reflects the typical temporal progression of barriers during older adults' adoption, moving from basic interaction prerequisites (UX/usability) to modality-specific physiological constraints (cybersickness), and then to higher-level psychological (e.g., anxiety and trust) and motivational determinants that shape sustained engagement (Schaumburg et al. 2025; Song et al. 2025). This ordering is intended to capture how early, experience-limiting barriers can precipitate rapid dropout before later-stage barriers become salient.

These barriers form the basis of the Dynamic Barrier Framework proposed in this thesis, as conceptualized in Figure 13 and summarized in Table 11. The exploration will commence with the foundational challenges of general user experience (UX) and usability, which form the baseline for any successful human-computer interaction (Beraud-Peigne, Maillot & Perrot 2023). It will then delve into the powerful and often overriding physiological barrier of cybersickness, a phenomenon unique to immersive environments. Following this, the discussion will address the crucial psychological dimensions of technology anxiety and the mitigating role of interpersonal trust. Finally, it will examine the ultimate hurdle of sustaining motivation beyond the initial allure of novelty. By systematically reviewing the literature through this multi-layered lens, this section aims to construct a holistic understanding of the adoption process, revealing the complex interplay of factors that must be addressed to create truly effective and lasting solutions (Beraud-Peigne, Maillot & Perrot 2023).

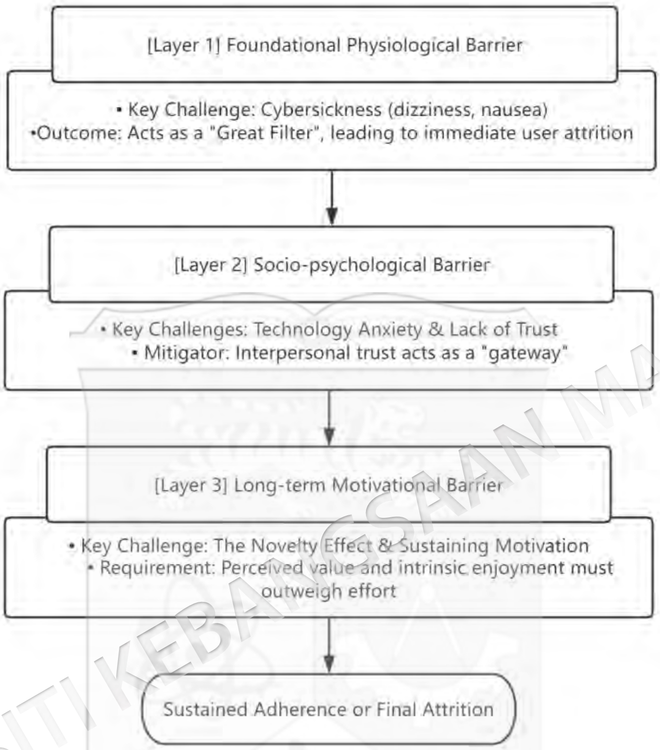

Figure 13 Proposed Dynamic Barrier Framework for Immersive Technology Adoption by Older Adults

Table 11 Key Barriers in the Proposed Dynamic Barrier Framework for Older Adults' Immersive Technology Adoption

Barrier Level	**Key Barrier**	**Brief Description**
Foundational Experience	UX & Usability	Encompasses pragmatic qualities like effectiveness and efficiency as well as the user's affective and emotional states. Challenges include hardware ergonomics and high cognitive load from software interfaces.
Physiological	Cybersickness	A variant of motion sickness arising from sensory conflict between the visual and vestibular systems. Symptoms include nausea, dizziness, vertigo, and headaches.
Psychological	Technology Anxiety & Trust	Apprehension or fear when confronted with technology , manifesting as a fear of damaging equipment or a fear of incompetence. Interpersonal trust can act as a mitigating factor.

... to be continued

... continuation

Long-term Motivation	The Novelty Effect	The tendency for initial interest to be artificially inflated due to newness. Sustained engagement depends on deeper drivers like perceived value and intrinsic enjoyment after novelty fades.

2.4.1 User Experience (UX) And Usability For Older Adults

Before delving into the unique challenges posed by immersive technologies, it is essential to first establish the foundational principles of User Experience (UX) and Usability, particularly as they apply to older adult populations (Contreras-Somoza et al. 2024). In the field of Human-Computer Interaction, Usability refers to the pragmatic qualities of a system that determine its ease of use. It is typically measured by its effectiveness (the accuracy and completeness with which users can achieve their goals), its efficiency (the resources expended in relation to the accuracy and completeness of goals achieved), and the satisfaction derived from its use (Rusu 2014). User Experience, in contrast, is a broader and more holistic concept. It encompasses the entirety of a user's perceptions and responses resulting from the use or anticipated use of a product, system, or service. UX includes not only the pragmatic aspects of usability but also the user's affective, emotional, and cognitive states, creating a comprehensive picture of the subjective quality of the interaction (Filippi & Barattin 2018).

For the older adult demographic, these principles of UX and Usability are not merely desirable qualities; they are fundamental prerequisites for technology adoption. While a poorly designed interface might be a minor frustration for a digitally native younger user, for an older adult it can be an insurmountable barrier that leads to immediate rejection of the technology (Katey & Chivers 2025). This heightened importance stems from several factors, including a potential lifetime of less exposure to complex digital ecosystems, which can result in lower baseline digital literacy. This difference in digital literacy is starkly reflected in demographic data on technology adoption, which reveals a significant "digital divide" for the 65+ age group, as illustrated in Figure 14 (Pew Research Center 2024). It should be noted that Figure 14 presents U.S. survey data as an illustrative example of age-related internet-use trends, and patterns may vary across countries and regions. Furthermore, normal age-related changes in sensory abilities (such as declining visual acuity or hearing), motor skills (such as reduced dexterity or hand stability), and cognitive functions (such as decreased working memory capacity or divided attention) can significantly amplify the negative impact of poor design (Wilson et al. 2022). An interface that is merely suboptimal for a younger person can become completely unusable for an older adult, quickly leading to feelings of frustration, incompetence, and the conclusion that "this technology is not for me."

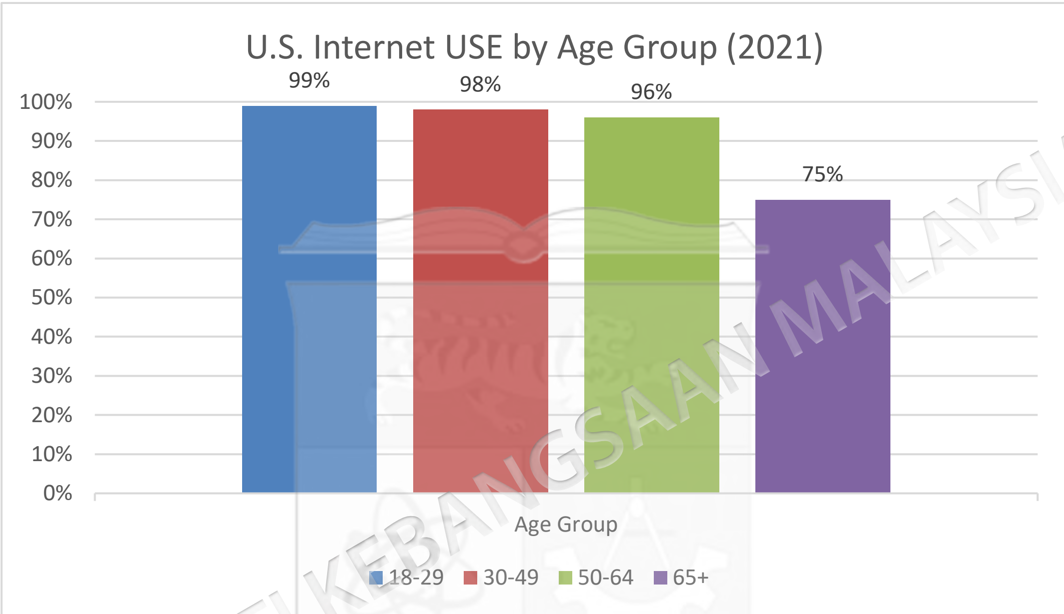

Figure 14 U.S. example of age-group differences in internet use (2021) (Pew Research Center 2024)

These challenges are particularly pronounced when considering the physical and ergonomic aspects of immersive hardware. The very first point of contact with a VR or MR system is the physical device itself, which can present a series of usability hurdles. The weight and front-heavy balance of many head-mounted displays (HMDs) can cause discomfort or neck strain over time (Bhargava & Baths 2024). The process of adjusting straps to achieve a fit that is both secure and comfortable, while also aligning the lenses for a clear image, can be a complex and physically demanding task, especially for individuals with conditions like arthritis. Beyond the headset, learning to use the accompanying hand controllers represents another significant barrier. These devices often feature an array of buttons, triggers, and joysticks with abstract functions that are not immediately intuitive, requiring a level of fine motor control and the ability to map physical actions to virtual outcomes that can be challenging to acquire (Gluck et al. 2022).

Moving from the physical hardware to the virtual software interface, a new set of cognitive and perceptual hurdles emerges. Many virtual environments and applications, often designed with a younger audience in mind, present a high cognitive load that can overwhelm older users (Huang & Zhang 2022). Common design flaws include the use of small, difficult-to-read fonts; low-contrast user interface elements that blend into the virtual background; and complex, multi-layered menu systems that are difficult to navigate. The very nature of perceiving and interacting within a three-dimensional virtual space can also be challenging. Depth perception can be distorted, making the act of reaching for and grasping virtual objects feel unnatural and imprecise. A steep learning curve, where the user constantly feels lost, confused, or unsure of how to proceed, is a primary driver of negative user experience, fostering feelings of inadequacy and reinforcing pre-existing technology anxiety (Benham et al. 2024).

Consequently, overcoming these multifaceted usability barriers requires a fundamental shift away from a one-size-fits-all design philosophy towards an approach that is deeply empathetic, inclusive, and participatory. It is not enough to make minor adjustments to interfaces designed for younger users; instead, technology for older adults must be built from the ground up with their specific needs and capabilities in mind (Wang et al. 2021). This necessitates a commitment to inclusive design practices, such as co-designing with older adults to ensure their perspectives are integrated throughout the development process. Practically, this translates into creating clear, simple, and forgiving interfaces that minimize the consequences of user error, providing comprehensive and patient onboarding processes and adaptation training, and incorporating personalization options that allow users to adjust settings like text size, movement speed, and task complexity to match their individual abilities (Wang et al. 2021). The key usability barriers at both the hardware and software levels are summarized in Table 12.

Table 12 Key Usability Challenges of Immersive Technology for Older Adults

Challenge Level	**Examples of Specific Issues**
Hardware & Ergonomics	- The weight and front-heavy balance of Head-Mounted Displays (HMDs) can cause discomfort or neck strain. - Adjusting straps and aligning lenses can be a complex and physically demanding task. - Hand controllers with non-intuitive buttons, triggers, and joysticks require a challenging level of fine motor control.
Software & Interface	- Many virtual environments present a high cognitive load that can overwhelm older users. - Common design flaws include small fonts, low-contrast UI elements, and complex menu systems . - Distorted depth perception can make grasping virtual objects feel unnatural and imprecise. - A steep learning curve often fosters feelings of inadequacy and reinforces pre-existing technology anxiety.

Ultimately, while addressing these general principles of UX and usability is a critical and non-negotiable first step in designing any technology for older adults, the unique nature of immersive technology introduces an even more profound and visceral challenge (Han et al. 2004). Even if an interface is perfectly intuitive and the hardware is ergonomically designed, these successes are rendered moot if the fundamental act of being immersed in a virtual world makes the user feel physically and debilitatingly ill. This powerful, physiological barrier, which operates on a level that precedes conscious cognitive evaluation, represents the next and most foundational hurdle in the adoption of immersive technologies. This challenge, known as cybersickness, will be the focus of the following section.

2.4.2 The Foundational Barrier: Cybersickness In Immersive Environments

While general usability presents a significant hurdle, the unique sensory experience of immersion introduces a far more visceral and often insurmountable obstacle: cybersickness. This phenomenon, a variant of traditional motion sickness, is arguably the single most critical barrier to the widespread adoption of immersive technologies, particularly among older adults. It is not a matter of user preference or technical skill, but a powerful, involuntary physiological response that can render an otherwise well-designed application completely unusable (Rebenitsch & Owen 2016). Cybersickness manifests as a constellation of debilitating symptoms, including nausea, dizziness, vertigo, headaches, eye strain, and a general feeling of disorientation and malaise. Its onset can be rapid and its effects can linger long after the headset has been removed, creating a strong and lasting negative association with the technology itself.

The most widely accepted scientific explanation for cybersickness is the Sensory Conflict Theory. This theory posits that the condition arises from a fundamental mismatch between the information being processed by the user's sensory systems. In a virtual environment, the visual system receives compelling, often high-fidelity, cues that the body is in motion for example, walking through a virtual landscape or turning to observe a dynamic scene (Hettinger & Riccio 1992). However, the vestibular system, located in the inner ear and responsible for the sense of balance and spatial orientation, simultaneously reports to the brain that the physical body is, in fact, stationary. This neural discord between what the eyes see and what the body feels creates a profound sensory conflict. The brain, unable to reconcile these contradictory inputs, is thought to interpret this state as a sign of neurological malfunction or poisoning, triggering the primitive defense mechanisms of nausea and dizziness (Hettinger & Riccio 1992).

While any user of any age can be susceptible to cybersickness, its implications are amplified for the older adult population. Age-related changes in both the visual and vestibular systems can potentially alter an individual's sensitivity and their ability to adapt to sensory conflicts. More critically, the consequences of the symptoms are far more severe for this demographic (Stanney et al. 2003). For a younger user, a momentary bout of dizziness may be merely uncomfortable; for an older adult who may already have compromised balance, the same sensation is not just unpleasant it is a direct threat to their physical safety. The feeling of disorientation inside a virtual world can instantly trigger a heightened fear of falling in the real world, transforming what is intended to be a beneficial exercise experience into one that feels fundamentally unsafe and anxiety-provoking (Li et al. 2024).

This potent combination of physiological discomfort and perceived risk establishes cybersickness as the foundational barrier in the technology adoption process. It often functions as a "great filter," unceremoniously eliminating a significant portion of the potential user base at the very first point of contact (Arns & Cerney 2005). This is not a theoretical concern but an empirical reality, powerfully demonstrated in recent research. In a 2025 study on older adults' use of immersive technology, approximately 11% of participants were unable to complete even a single introductory session due to the overwhelming onset of dizziness and other adverse physiological symptoms (Li, Shiyanov & Muschalla 2025). This finding starkly illustrates that a substantial segment of the target population may be physiologically precluded from using the technology, irrespective of its design, content, or potential benefits. This powerful, involuntary physiological veto must be acknowledged as the first and most formidable hurdle to overcome.

Furthermore, the impact of cybersickness is not a simple binary of immediate user attrition versus seamless adoption. Its influence is pervasive and continues to degrade the experience even for those users who persist through initial discomfort. Recent studies show that cybersickness significantly impairs psychomotor performance, reading ability, and working memory during VR immersion (Kourtesis, Papadopoulou & Roussos 2024). Moreover, these detrimental effects extend beyond immersion, with elevated physiological stress markers and sustained declines in working memory lasting up to 90 minutes post-exposure (Zielasko et al. 2025). Even after intense VR exposure, residual symptoms like nausea and vestibular discomfort persist, highlighting that physiological comfort is not merely a pass–fail gateway, but a continuous and critical factor mediating a user's ability to learn, perform, engage, and most importantly find enjoyment in the virtual experience (Papaefthymiou et al. 2024).

In conclusion, cybersickness stands apart from other usability challenges as the most immediate and foundational barrier to the adoption of immersive technologies by older adults. It acts as an initial filter for a substantial portion of the population and persistently undermines the quality of the experience for many who continue. A recent narrative review highlights that immersive VR usability in older populations is frequently hindered by sensory, motor, and cognitive limitations making physical comfort a prerequisite for safe and sustained engagement (Schaumburg et al. 2025). Although many studies report only mild cybersickness symptoms, the persistent presence of even minor adverse effects underscores the need to prioritize physiological well-being above interface design or motivational mechanics (Drazich et al. 2023).

Ergonomic design, sensory synchronization, and user training are consistently recommended in the literature as key strategies for minimizing cybersickness and maximizing usability for older users (Msweli & Phahlane 2025). Moreover, interventions like balance training have been shown to enhance users' tolerance to cybersickness, and adaptive system designs that respond in real-time to user discomfort can further support comfort and engagement (Kang et al. 2025).

This reality establishes a clear and non-negotiable hierarchy of design needs for this demographic: physiological comfort must be prioritized above all else since only when users feel physically safe and well within the virtual environment can they begin to meaningfully engage with higher-order psychological and motivational factors. The key symptoms that define cybersickness and the primary mitigation strategies proposed in the literature are summarized in Table 13.

Table 13 Cybersickness: Key Symptoms and Mitigation Strategies

Key Symptoms	Mitigation Strategies from Literature
- Nausea **- Dizziness** **- Vertigo** **- Headaches** **- Eye strain** **- Disorientation**	- Ergonomic design - Sensory synchronization - User training & adaptation - Balance training to enhance tolerance - Adaptive systems that respond to discomfort (Hettinger & Riccio 1992; Rebenitsch & Owen 2016; Stanney et al. 2003)

2.4.3 The Psychological Dimension: Technology Anxiety And Trust

For an older adult who successfully navigates the foundational physiological barrier of cybersickness, the adoption journey is far from complete. The next set of challenges they encounter is deeply psychological, involving a complex interplay of personal apprehension and social dynamics that profoundly influences their decision to continue engaging with a new technology. Narrative reviews have highlighted that age-related sensory and cognitive declines can contribute to anxiety, disorientation, and reduced engagement during immersive VR experiences (Schaumburg et al. 2025). This psychological dimension often determines whether an initial, physically comfortable experience can translate into a willingness to learn, explore, and ultimately commit to longer-term use. Empirical studies show that lower levels of technology anxiety and higher trust in the system are associated with stronger usage intentions among older adults (Al Khalifah et al. 2025). This section delves into two of the most critical and intertwined components of this dimension: the pervasive issue of technology anxiety and the powerful, mitigating role of interpersonal trust.

Technology anxiety can be defined as a state of apprehension, negative emotional arousal, or fear that an individual experiences when confronted with the use, or the potential use, of advanced technology. Within the context of older adults and immersive exergames, this anxiety is not a vague or abstract feeling; it manifests in several concrete and potent forms. One of the most common is a tangible fear of damaging the equipment. The perception of the head-mounted display and controllers as expensive, complex, and fragile can lead to hesitant and overly cautious interactions, preventing the user from engaging freely and naturally. A second, equally powerful, manifestation is the fear of incompetence a social and personal anxiety about appearing foolish, slow, or incapable in front of researchers or peers. This fear, often stemming from a lack of prior experience with gaming or virtual reality, can be a significant source of self-consciousness and pressure. Research has shown that poorly designed VR hardware increases discomfort and correlates with elevated technology anxiety among older users (Al Khalifah et al. 2025; Song et al. 2025), and that older adults commonly experience technology-related anxiety, resistance, fear of mistakes, and technophobia when using digital systems (Kim, Freddolino & Greenhow 2023). Finally, these anxieties culminate in a fear of failure, where the frustration of not immediately understanding the controls or navigating the interface can lead a user to prematurely conclude that the technology is simply too complicated for them to master.

This state of anxiety is not merely an internal feeling; it has direct and observable behavioral consequences that can sabotage the user experience ("(PDF) Immersive Virtual Reality for Older Adults" 2025). An anxious user is often a hesitant one. Their physical movements may be timid and restricted, and their interaction with the system is characterized by a reluctance to experiment or explore beyond the most basic instructions. This cautious approach can paradoxically lead to poorer in-game performance, as fluid and confident movements are often required to succeed (Te et al. 2023). This poor performance then serves to reinforce the user's initial feelings of incompetence, creating a debilitating negative feedback loop. The user's belief that they "can't do it" is confirmed by their struggle, strengthening their resolve to disengage. In this way, technology anxiety becomes a self-fulfilling prophecy, preventing the user from ever reaching a state of comfort and proficiency where they might begin to experience the positive, motivating aspects of the exergame.

Crucially, the most powerful antidote to this deep-seated anxiety is often not a better user manual or a simpler interface, but a foundation of human-to-human, interpersonal trust (Li, Shiyanov & Muschalla 2024). The social context in which a new and potentially intimidating technology is introduced can fundamentally alter an older adult's psychological framing of the entire experience (Hou, Li & Wang 2024). When an immersive system is presented by a known, trusted, and respected individual such as a family member, a close friend, or a familiar community liaison the technology is stripped of much of its alien and threatening character (Li, Shiyanov & Muschalla 2024). It is no longer just a piece of complex hardware; it becomes an activity associated with a positive and safe social relationship. This social validation provides a powerful psychological buffer, giving the older user the confidence and reassurance they need to approach the new experience with curiosity rather than apprehension.

The pivotal role of this social-psychological bridge was not just a theoretical assumption but was empirically demonstrated in the research conducted for this thesis. A key finding emerged when examining the determinants (or variables) that influenced to move from the initial, single-session trial to the more demanding, multi-day longitudinal study (Dohan et al. 2014). There was a statistically significant association between the strength of a participant's pre-existing social tie with the community recruiter and their willingness to commit to continued participation. Those who had a strong, familiar relationship with the person introducing the technology were far more likely to agree to continue than those who were recruited through weaker or more formal channels. This provides powerful evidence that interpersonal trust acts as a crucial "socio-psychological gateway," enabling users to overcome their initial anxiety and take the critical leap from a one-time trial to a longer-term engagement (Figure 15) (Emery, Silverman & Carey 2023; Ma et al. 2019).

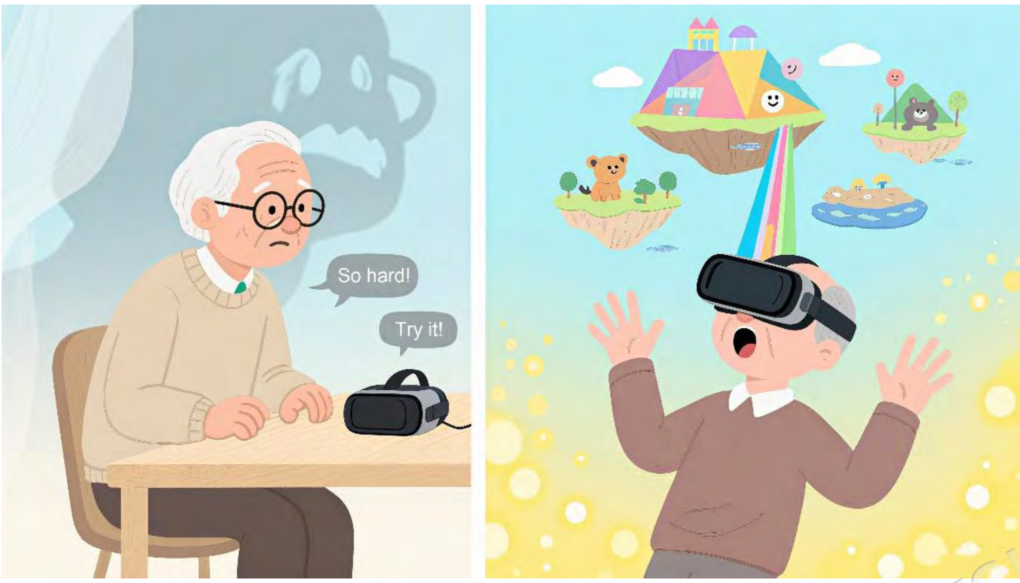

Figure 15 Overcoming the Psychological Barrier: From Apprehension to Engagement

The mechanism behind this phenomenon is twofold. Qualitatively, participants expressed that the endorsement from a trusted source provided immense reassurance, assuaging their fears about breaking the equipment or failing at the task. This trust also created a sense of benign social obligation and reciprocity, a feeling that they were participating not just for themselves, but also as a favor to a respected community member (Ferguson et al. 2023). In conclusion, successfully navigating this psychological dimension of anxiety and trust is a vital prerequisite for fostering a user's long-term interest. However, even with anxiety allayed and trust established, the final decision to persist with the technology day after day hinges on an even deeper, more personal evaluation of its intrinsic value and motivational pull. This ultimate challenge sustaining motivation once the initial barriers have been crossed will be the focus of the subsequent section (Zhang & Boot 2023).

2.4.4 Sustaining Motivation: The Challenge Of The Novelty Effect

Once an older adult has successfully navigated the initial physiological and psychological barriers to adopting an immersive technology, they enter the final and most decisive phase of the adoption journey. This is the transition from initial, often tentative, acceptance to long-term, habitual adherence. This phase is governed almost entirely by motivation a complex and dynamic force that must be robust enough to outlast the initial excitement of a new experience and compelling enough to integrate the technology into the fabric of a user's established daily life (Lu et al. 2025; Shaleha, Roque & Harrell 2024). This ultimate challenge of sustaining motivation is where many promising technological interventions falter. This section will explore this critical final barrier, beginning with a critique of the often misleading and transient nature of initial user enthusiasm, a phenomenon widely known as the novelty effect (Zhao & Fu 2024).

The novelty effect is a well-documented concept in technology adoption research, referring to the tendency for an individual's initial interest, engagement, and even performance with a new system to be artificially inflated simply because of its newness. The curiosity and sense of discovery associated with a first-time experience can create a powerful, but temporary, spike in motivation. This phenomenon presents a significant methodological challenge for the field of gerontechnology, as a vast number of studies reporting high user satisfaction and engagement are based on short-term, single-session evaluations (Modirshanechi et al. 2023; Shin et al. 2019). These studies are at high risk of capturing a snapshot of this peak of novelty rather than a realistic and predictive measure of a user's true, sustainable interest. The initial excitement of being transported to a virtual world is a potent but fleeting experience; it is not, in itself, a sufficient foundation for building a lasting health habit.

The attrition of novelty is an almost inevitable psychological process. As the user becomes more familiar with the technology, the sense of wonder and discovery naturally diminishes. The mechanics of putting on the headset, navigating the menus, and interacting with the virtual environment become routine. At this point, the user's focus shifts from the novelty of the medium to the substance of the core activity itself. If the underlying exercise routine within the exergame becomes repetitive, or if the game fails to offer a continuing sense of growth, challenge, and purpose, boredom inevitably sets in (Kojima et al. 2023; Vafeas 2024). The user begins to conduct a subconscious cost-benefit analysis, weighing the effort required to engage with the technology against the immediate enjoyment and perceived long-term benefits it provides. It is at this critical juncture that the technology must prove its lasting value, transitioning from a novelty to a meaningful tool.

Once the initial novelty wears off, continued engagement is determined by a set of deeper, more substantive motivational drivers. Research for this thesis has shown that the decision to persist or to abandon the technology at this stage is a highly personal evaluation of its long-term worth. One of the primary drivers is perceived value: the user must develop a genuine and continuing belief that the activity is providing a tangible benefit to their health and well-being. Without this belief, the activity can feel pointless (Luo et al. 2024). An equally, if not more, powerful driver is intrinsic enjoyment: the activity must be inherently pleasurable, satisfying, and fun in its own right. If the experience begins to feel like a monotonous chore or a mere task to be checked off a list, it will fail to compete for the user's valuable leisure time against other, more established sources of enjoyment.

Furthermore, sustaining motivation is also a deeply practical matter of habit formation and lifestyle integration. A new exergame, no matter how well-designed or enjoyable, must find a compatible niche within a user's established daily and weekly routines. It enters into direct competition for a finite amount of time and energy with pre-existing habits, cherished social engagements, and other preferred leisure activities. The failure of the technology to seamlessly integrate into a user's life can be a powerful, pragmatic reason for attrition, even if the user holds a generally positive view of the experience (Bree et al. 2017; Fleig et al. 2016). As this research qualitatively uncovered, users may abandon an exergame simply because it conflicts with a valued existing social habit, such as an evening walk with friends, ultimately judging the established activity to be more beneficial or rewarding.

In summary, sustaining motivation beyond the initial, often deceptive, allure of novelty is the ultimate challenge for achieving long-term adherence to immersive exergames. It requires a sophisticated design approach that delivers not just an initial "wow factor," but also lasting perceived value, deep intrinsic enjoyment, and a seamless, frictionless fit into the user's complex life. Understanding and designing for these profound motivational drivers requires moving beyond simple usability heuristics and descriptive studies of user satisfaction. It necessitates the application of robust psychological theories of human motivation that can systematically explain what makes an activity truly and enduringly worthwhile. This need for a deeper theoretical lens provides the impetus for the final section of this literature review, which will explore the foundational theories that can illuminate the path toward creating genuinely sustainable and motivating experiences. This conceptual pattern is summarised in Figure 16, which illustrates the decline in engagement as novelty wears off across adoption stages.

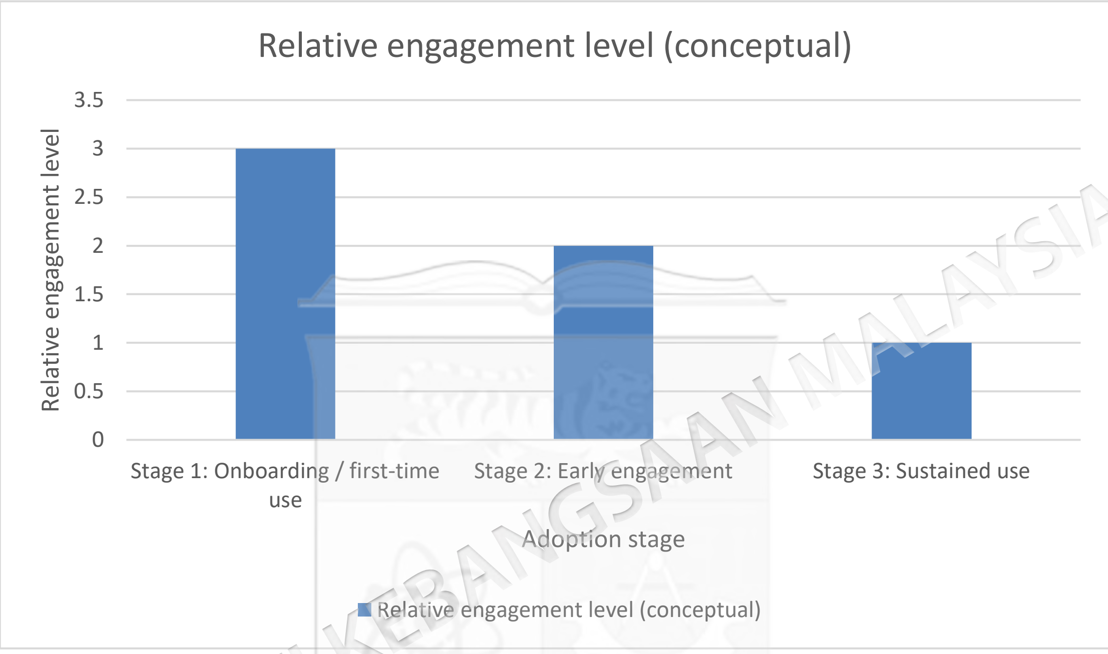

Figure 16 Conceptual novelty effect across adoption stages

2.5 Theoretical Foundations For Technology Adoption And Motivation

A comprehensive description of the multifaceted barriers to adoption, as detailed in the previous section, provides a crucial map of the challenges faced by older adults. However, a map alone is insufficient for a deep scholarly analysis; a theoretical compass is required to navigate this complex terrain and to explain why these barriers emerge and how they interact. Therefore, this section of the literature review transitions from a descriptive account of empirical phenomena to a critical engagement with the theoretical frameworks that seek to explain them (Lee & Coughlin 2015). The objective here is twofold: first, to situate the current research within the existing theoretical dialogues on technology adoption and user motivation, and second, to critically assess the explanatory power of these theories, thereby arguing for the necessity of introducing a new, more nuanced theoretical perspective to fully capture the complexities at hand.

To achieve this, the following discussion will unfold as a structured theoretical dialogue. It will begin by examining the dominant and highly influential Technology Acceptance Models (TAM and UTAUT), which have long served as the standard frameworks for predicting user adoption of new technologies (Ammenwerth 2019; Shachak, Kuziemsky & Petersen 2019). A critical analysis will be presented to highlight the inherent limitations of these traditional, cognition-focused models when applied to the unique context of older adults engaging with deeply embodied and physiologically demanding immersive technologies. Subsequently, this review will introduce and explore an alternative and more suitable set of theories centered on intrinsic motivation namely Self-Determination Theory (SDT) and Flow Theory. It will be argued that these frameworks offer a more powerful lens for understanding the crucial challenge of not just initial acceptance, but of sustained, long-term user engagement, thereby paving the way for the novel theoretical synthesis proposed in this thesis.

2.5.1 Technology Acceptance Models (TAM & UTAUT) And Their Limitations

To understand the factors that drive individuals to adopt or reject new technologies, researchers in information systems and human-computer interaction have long sought robust theoretical models. Among the most influential and pervasively cited of these is the Technology Acceptance Model (TAM) (Ammenwerth 2019; Davis & Davis 1989). Developed as a parsimonious yet powerful framework, the primary purpose of TAM is to explain the determinants of user acceptance, providing a causal chain that links system characteristics to user intentions and, ultimately, to actual use. The model's enduring appeal lies in its simplicity and its consistent empirical support across a wide range of technologies, primarily within organizational and workplace contexts.

The explanatory power of TAM is rooted in two primary perceptual constructs: Perceived Usefulness and Perceived Ease of Use. Perceived Usefulness is defined as the prospective user's subjective probability that using a specific application will increase their performance or enhance their life. It is a pragmatic, outcome-oriented judgment. Perceived Ease of Use, conversely, refers to the degree to which a person believes that using a particular system will be free of physical and mental effort (Davis & Davis 1989; Venkatesh & Davis 2000). The central logic of the model posits that

Perceived Ease of Use has a direct positive influence on Perceived Usefulness (a system that is easier to use is perceived as more useful) and also directly impacts a user's Attitude Toward Using the technology. These two factors Perceived Usefulness and Attitude then become the primary predictors of a user's Behavioral Intention to Use, which is considered the most immediate determinant of actual system usage.

In an effort to consolidate the findings from TAM and several other competing models, the Unified Theory of Acceptance and Use of Technology (UTAUT) was later proposed. UTAUT integrates constructs from eight prominent models into a more comprehensive framework, identifying four key direct determinants of usage intention and behavior. These are: Performance Expectancy, which is analogous to Perceived Usefulness; Effort Expectancy, which is analogous to Perceived Ease of Use; Social Influence, which captures the extent to which an individual perceives that important others believe they should use the new system; and Facilitating Conditions, which refers to the user's perception of the organizational and technical resources available to support use. A significant contribution of UTAUT was its inclusion of key moderating variables, such as age, gender, and experience, acknowledging that the influence of the core determinants can vary across different user populations and contexts (Magsamen-Conrad et al. 2015; Venkatesh et al. 2003).

However, despite their immense influence and predictive power in many domains, both TAM and UTAUT exhibit fundamental limitations when applied to the specific and complex context of older adults adopting immersive exergames. The first major limitation is their inherently static, cross-sectional nature. These models are designed to capture a snapshot of a user's attitudes and intentions at a single point in time, typically before or immediately following an initial interaction. Yet, the adoption of a health technology is not a singular event; it is a dynamic and evolving process that unfolds over days, weeks, and months. These frameworks are ill-equipped to explain the longitudinal journey of a user, which includes critical phenomena such as the gradual decay of the novelty effect, the development and reinforcement of habits, the overcoming of learning curves, or the eventual decision to abandon the technology due to emergent factors like boredom or a perceived lack of value (Lee & Xie 2018; Shachak, Kuziemsky & Petersen 2019).

The second, and arguably more critical, limitation is their profound cognition-centric bias. The logic of both models is predicated on a rational user who is capable of and primarily concerned with making cognitive judgments about a technology's utility and ease of operation. This assumes a "disembodied" user whose primary mode of interaction is intellectual. This assumption completely breaks down in the context of immersive technologies, where the user's first and often most dominant experience is not cognitive, but deeply physiological and embodied (Fares et al. 2024; Msweli & Phahlane 2025). A strong, involuntary physical reaction like cybersickness can act as a powerful and immediate "physical veto," completely short-circuiting the cognitive evaluation process (see Figure 17). These models have no conceptual mechanism to account for a scenario where the user's body viscerally rejects the technology long before their mind has the opportunity to rationally accept it.

Figure 17 Older adults who experience cybersickness after using a VR headset (HMD)

Consequently, due to their static nature and their failure to account for the primacy of embodied experience, TAM and UTAUT are far more adept at explaining initial acceptance intentions among a user group that has already been implicitly pre-screened for physiological tolerance. They are, however, profoundly inadequate for explaining the central problem of this thesis: the dynamic, multi-stage process of user attrition. They fail to capture the pre-cognitive physiological filters, the evolving psychological states of anxiety and trust, and the complex motivational calculations that lead many older adults to abandon immersive technologies over time. Therefore, to truly understand and address the adherence dilemma, it is necessary to move beyond these traditional acceptance models and turn to theoretical frameworks that can provide a richer understanding of human motivation and the qualitative nature of the user experience itself (Lee, Ramasamy & Subbarao 2025; Shachak, Kuziemsky & Petersen 2019). These core limitations of traditional models are summarized in Figure 18.

This embodied limitation is central to the need for the DBF, because older adults' adoption of immersive exergames depends not only on cognitive acceptance but also on bodily tolerance, sensory comfort, confidence, and repeated motivational appraisal.

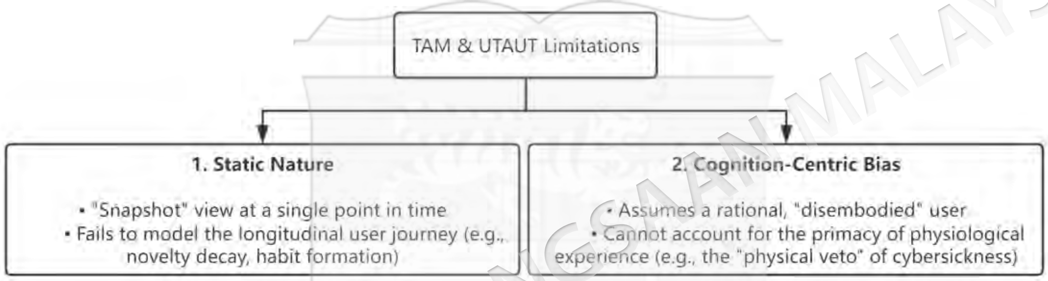

Figure 18 Core Limitations of TAM/UTAUT (Davis 1989; Venkatesh et al. 2003) in the Context of Immersive Exergames for Older Adults

2.5.2 Theories Of Intrinsic Motivation: Self-Determination Theory (SDT) And Flow

The limitations of traditional technology acceptance models necessitate a fundamental shift in the theoretical focus. To understand the complex challenge of long-term adherence, particularly for a voluntary health behavior, the inquiry must move beyond predicting an initial, one-time decision to accept a technology and instead focus on explaining the mechanisms of sustained, voluntary motivation (Chan et al. 2019; TB, Tece Bayrak & C., BW, Wünsche 2021). This requires a turn towards psychological theories that address the core question of what makes an activity deeply and enduringly rewarding. Among the most prominent of these are Self-Determination Theory (SDT) and Flow Theory, two complementary frameworks that, together, provide a useful lens for analyzing the drivers of intrinsic motivation that support long-term engagement with immersive exergames.

At the same time, these theories are not intended to explain all stages of technology uptake. In particular, SDT and Flow do not directly account for structural and modality-specific constraints that can prevent initial use (e.g., cybersickness, hardware ergonomics, safety concerns, and access). Accordingly, in this thesis, SDT and Flow are used primarily to interpret sustained engagement and motivational processes, while earlier-stage barriers are addressed through the proposed Dynamic Barrier Framework.

For this reason, SDT and Flow are used here to explain later-stage competence, autonomy, challenge fit, and enjoyment, while the DBF links these motivational mechanisms to earlier physiological and socio-psychological filters.

Self-Determination Theory (SDT) is a broad, organismic theory of human motivation, personality development, and well-being. Its central premise is that human beings have an innate and natural propensity toward growth, integration, and psychological wellness, but that these tendencies require a supportive social environment to flourish (Deci 2017). A key distinction within SDT is between extrinsic motivation, which involves engaging in an activity to attain some separable outcome such as a reward or the avoidance of punishment, and intrinsic motivation, which refers to engaging in an activity for the inherent satisfaction, curiosity, and enjoyment it provides. For a health habit like regular exercise to become truly self-sustaining without the need for constant external prompts or oversight, it must transition from being extrinsically motivated to being intrinsically motivated. The activity must become its own reward.

According to SDT, the cultivation of this vital intrinsic motivation is contingent upon the satisfaction of three universal and innate psychological needs. The first is the need for Competence, which is the desire to feel effective, capable, and masterful in one's interactions with the environment. It involves seeking out challenges that are optimal for one's capacities and persistently trying to maintain and enhance those skills (d'Ailly & Blokhuis 2018; Kusurkar, Croiset & Ten Cate 2011). This theoretical tenet is consistent with this thesis's empirical findings, such as the discovery of an "Empowerment Sweet Spot" and the identification of competence as a primary predictor of positive user experience. The second need is for Autonomy, which is the desire to feel a sense of volition, control, and self-endorsement over one's own actions and decisions. It is the feeling that one's behavior is an expression of the self, rather than the result of external coercion or pressure. The third need is for Relatedness, which is the desire to feel socially connected, to care for and be cared for by others, and to have a sense of belonging within a community.

Complementing the broad motivational framework of SDT, Flow Theory provides a detailed phenomenological account of what constitutes an optimal, intrinsically motivating experience. Flow is described as a state of complete absorption in an activity, a condition of "being in the zone" where one is so fully immersed with energized focus that the sense of time becomes distorted and the concerns of the self seem to disappear (Rheinberg 2008). The experience of flow is often described as an optimal form of intrinsically motivating experience; the activity is so enjoyable that it becomes autotelic, or worth doing for its own sake, regardless of any external goals. This concept is particularly relevant to exergaming, as the goal of a well-designed game is precisely to induce this state of deep engagement, making the physical exertion feel effortless and enjoyable.

The central mechanism for achieving a flow state, according to the theory, is the establishment of a dynamic and perceived balance between the challenges presented by a task and the skills of the individual. This challenge-skill balance is the architectural blueprint for optimal experience. If the challenges far exceed the user's current skill level, the resulting experience is one of anxiety, stress, and frustration. Conversely, if the user's skills far exceed the challenges, the experience becomes one of boredom and disinterest, leading to disengagement. The flow channel exists in the delicate equilibrium between these two negative states. This theoretical principle helps interpret the empirical pattern observed in this thesis that a sense of "challenge" was the other key independent predictor of a positive user experience. An ideal exergame, therefore, should function as a system that can adapt its difficulty over time to keep the player within this highly rewarding and motivating flow state (Deterding & Cutting 2023; Hendrix et al. 2019).

In synthesis, as summarized in Table 14, these two theories provide a complementary foundation for understanding sustained engagement with immersive exergames compared with traditional acceptance models. While TAM and UTAUT are concerned with the rational decision to begin using a technology, SDT and Flow Theory illuminate the affective and psychological reasons why a user would choose to continue using it voluntarily over the long term. SDT explains the fundamental psychological "nutrients" competence, autonomy, and relatedness that the experience must provide to be fulfilling, while Flow Theory offers a specific design blueprint the challenge-skill balance for structuring the moment-to-moment interaction to be optimally engaging. These motivational theories therefore provide a conceptual basis for the analysis of user experience in this thesis and inform the development of a more holistic framework for understanding technology adoption (Chan et al. 2019; Huang et al. 2019). The synthesis of these theories, which forms the motivational foundation for this thesis, is illustrated in Figure 19.

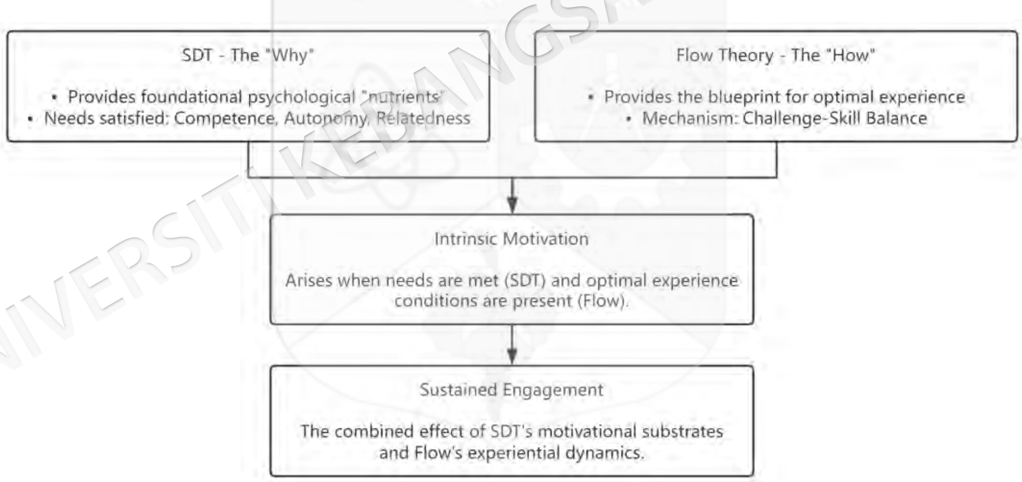

Figure 19 A Synthesis of SDT (Deci & Ryan 1985) and Flow Theory for Sustained Engagement (Csikszentmihalyi 1990)

As illustrated in Figure 19, SDT explains the motivational “why” of sustained engagement, whereas Flow Theory explains the experiential “how”; together, they complement rather than replace technology acceptance models by addressing embodied and motivational dimensions that are less visible in TAM/UTAUT.

Table 14 Comparison of Technology Adoption and User Motivation Theories

Theoretical Framework	**Technology Acceptance Models (TAM & UTAUT) (Davis & Davis 1989; Venkatesh et al. 2003)**	**Theories of Intrinsic Motivation (SDT & Flow) (Csikszentmihalyi 1990; Ryan & Deci 1985)**
Core Constructs	Perceived Usefulness, Perceived Ease of Use, Performance Expectancy, Social Influence.	Competence, Autonomy, Relatedness, Challenge-Skill Balance.
Primary Focus	Predicting the initial, rational decision to	accept a technology.
Assumed User	A "disembodied," cognition-centric user making rational judgments about utility and effort.	An embodied user with innate psychological needs for growth, fulfillment, and enjoyment.
Key Limitation (in this study's context)	Static nature; fails to account for embodied experiences (e.g., cybersickness) and the dynamic, longitudinal user journey.	/

2.6 Research Gaps

2.6.1 Synthesis Of The Literature

This final section of the literature review serves a critical synthetic and transitional function. Having navigated the diverse bodies of literature pertaining to healthy aging, immersive technologies, and the complex dynamics of user adoption, the purpose here is to distill the preceding discussions into a concise and powerful conclusion. The objective is to move beyond the detailed analysis of individual topics to a holistic synthesis of the entire chapter, crystallizing the key insights into a set of clearly articulated research gaps. In doing so, this section provides a direct and compelling justification for the specific research questions and the methodological approach that will be detailed in the subsequent chapter of this thesis.

The argument will unfold in three logical steps. First, a synthesis of the literature will be presented, drawing together the key themes to create a cohesive summary of the current state of knowledge one that acknowledges both the significant potential of immersive exergames and the formidable barriers that impede their success. Building upon this synthesis, the discussion will then formally articulate the key research gaps that have been identified, transforming the implicit critiques from earlier in the chapter into explicit statements of what remains unknown or unresolved in the field. Finally, this section will conclude by positioning the current thesis as a direct and targeted response to these gaps, explaining how its specific research objectives are designed to address them and thereby contribute new and valuable knowledge.

This comprehensive review of the literature has painted a compelling yet complex picture of the role of immersive exergames in the landscape of healthy aging. The first and most prominent conclusion is one of significant promise. Faced with the pressing public health challenge of promoting sustained physical activity to prevent falls and maintain independence in a rapidly aging global population, the literature presents immersive technologies as a uniquely powerful solution (Peng et al. 2024). A convergence of evidence suggests that the motivational affordances of exergaming its ability to transform exercise into an engaging, goal-oriented, and intrinsically rewarding activity directly address the adherence dilemma that plagues traditional exercise modalities. A growing body of empirical research confirms this potential, providing tangible evidence that well-designed VR and MR exergames can produce measurable improvements in the physical, cognitive, and psychosocial health of older adults.

However, juxtaposed with this optimistic narrative of potential, the literature reveals a far more sobering reality. The path from a promising technological concept to a successfully adopted and widely used health intervention is fraught with significant and often underestimated barriers. The literature strongly indicates that the adoption of immersive technology by older adults is not a simple, binary decision but a multi-layered gauntlet that filters out a large number of potential users at various, distinct stages of their journey. A synthesis of the reviewed evidence suggests that these barriers are not random or monolithic, but can be understood as a sequential and interconnected series of challenges that must be successfully navigated for long-term adherence to be achieved (Bertolazzi, Quaglia & Bongelli 2024; Lin 2023).

These barriers do not operate independently; physiological discomfort can increase anxiety, anxiety can weaken trust, and weak trust can reduce the motivation needed for continued engagement.

The first and most foundational of these challenges, as the literature makes clear, is the physiological barrier. The primacy of the body in the immersive experience cannot be overstated. Unlike traditional screen-based technologies where the interaction is primarily cognitive, the experience of VR is deeply embodied (Boot & Dilanchian 2022; Ramaseri-Chandra & Reza 2024). The literature, supported by this thesis's preliminary findings, demonstrates that cybersickness the constellation of disorienting and nauseating symptoms arising from sensory conflict is not merely an inconvenient side effect but a primary and powerful barrier to adoption. It often functions as a "physical veto," terminating the user's journey before any cognitive assessment of the technology's usefulness or ease of use can even begin. This suggests that any successful design approach for this demographic must adopt a "body-first" philosophy, prioritizing physiological comfort and a sense of physical safety as the non-negotiable foundation of the entire user experience.

For those users who are physiologically tolerant enough to pass through this initial gateway, the literature indicates that the next set of critical challenges is psychological. A significant body of research highlights the prevalence of technology anxiety among older populations, which can manifest as a fear of incompetence, a fear of damaging expensive equipment, or a general frustration with unfamiliar interaction paradigms. Critically, the literature suggests that the most potent antidote to this anxiety is not technical simplicity alone, but the establishment of interpersonal trust. The social context of the introduction to the technology plays a pivotal role, with support from trusted community members or family acting as a crucial "psychological bridge" that provides the reassurance and social validation necessary for an older adult to overcome their apprehension and commit to a new and potentially intimidating experience (Chen et al. 2024; Song, Yang & Cheng 2022).

Finally, for the resilient user who has crossed both the physiological and psychological bridges, the literature points to a final and most enduring challenge: the test of sustained motivation over time (Nguyen, Murphy & Andrews 2025; Rings et al. 2023). The initial excitement and engagement driven by the novelty of the technology are, as the literature consistently warns, transient and a poor predictor of long-term adherence. Once this novelty fades, the decision to continue is based on a deeper and more personal evaluation. The synthesis of the reviewed evidence shows that this long-term motivation is fueled by two primary drivers: a genuine belief in the activity's long-term health value and, perhaps more importantly, a profound sense of intrinsic enjoyment. The experience must be fun, rewarding, and capable of integrating seamlessly into the user's established lifestyle to successfully compete for their time and energy against other preferred activities.

This comprehensive review of the empirical landscape culminates in a final synthesis of the theoretical state of the field. The literature shows that the dominant Technology Acceptance Models, TAM and UTAUT, with their static and cognition-focused frameworks, are fundamentally ill-equipped to capture the dynamic, embodied, and multi-stage process of adoption and attrition observed in this context (Lee, Ramasamy & Subbarao 2025; Ma & Luo 2022). In stark contrast, theories of intrinsic motivation, such as Self-Determination Theory (SDT) and Flow Theory, provide a much richer and more suitable vocabulary for understanding what makes an experience lastingly engaging, by focusing on concepts like competence, autonomy, and the challenge-skill balance. The literature, in its totality, therefore points not only to a series of practical and empirical challenges but also to a significant theoretical stalemate, highlighting a clear and pressing need for a new, integrated framework that can provide a more holistic view of the older adult's complex adoption journey.

2.6.2 Articulation Of Key Research Gaps

This comprehensive synthesis of the literature, which highlights the field's promises, its profound barriers, and its theoretical limitations, culminates in the identification of three critical and interconnected research gaps. These gaps are not minor omissions in the existing body of knowledge; rather, they represent fundamental unresolved questions that significantly hinder the progress of gerontechnology. Addressing these gaps is therefore essential for advancing the design and successful real-world implementation of effective immersive VR/MR exergame technologies for the older adult population. The following subsections will articulate each of these gaps in detail, providing a clear and evidence-based rationale for the research undertaken in this thesis.

Among several gaps identified across the literature, this thesis focuses on three key gaps that most directly support the research objectives and the construction of the DBF.

a. Gap 1: The Empirical Gap: Lack Of Long-Term, Process-Oriented Evidence

The first and most significant empirical gap identified in the literature is the overwhelming dominance of short-term, often single-session, evaluations of immersive technologies for older adults. The existing body of research is saturated with feasibility and usability studies that, while valuable for initial validation, are methodologically incapable of looking beyond the user's first contact with a system. This presents a major validity problem, as these short-term studies are highly susceptible to the influence of the novelty effect. The initial excitement, curiosity, and heightened engagement that a user experiences when trying a novel technology for the first time can artificially inflate measures of satisfaction and perceived enjoyment, creating a distorted and overly optimistic picture of user acceptance. This initial "honeymoon phase" is almost always transient and is a poor predictor of a user's willingness to integrate the technology into their life as a sustained habit (Suchy, Kraybill & Franchow 2011; Tsabary et al. 2022).

The consequence of this reliance on short-term data is a significant void in our understanding of the longitudinal user journey. Critical questions about sustained use remain largely unanswered (Song et al. 2025). For instance, the comparative long-term effects and user preferences for different immersive modalities such as the fully occluding Virtual Reality versus the reality-grounded Mixed Reality have not been adequately explored over a multi-day or multi-week period. Furthermore, the core psychological drivers that truly sustain motivation once the initial novelty has faded have not been sufficiently identified and validated within this specific demographic. The literature, therefore, lacks a deep, process-oriented understanding of how an older user's perceptions, motivations, and behaviors evolve as they move from initial curiosity to familiar, routine use, which is the most critical phase for determining long-term adherence.

b. Gap 2: The Practical Gap: Insufficient Focus On Foundational Embodied Barriers

The second major gap lies in the literature's frequent underestimation and improper positioning of fundamental, embodied barriers, most notably cybersickness. While many studies acknowledge cybersickness as a potential negative side effect or a usability issue, they often fail to frame it correctly as a foundational, pre-cognitive barrier that can act as a primary and powerful filter in the adoption process. It is often treated as one of several factors to be considered in a user's overall evaluation of a system, rather than as a powerful physiological veto that can entirely prevent such an evaluation from ever taking place. This perspective overlooks the sheer force of an involuntary physiological reaction and its capacity to override all other design considerations (Boot & Dilanchian 2022).

This practical gap in the literature the need for a more embodied, "body-first" perspective means that the true scale of the physiological barrier in real-world settings is likely underestimated (Boot & Dilanchian 2022; Séba et al. 2023). There is a lack of detailed empirical data documenting the initial attrition rates specifically caused by physiological discomfort when this technology is introduced to a naive older adult population. Furthermore, there is insufficient research exploring the persistent, negative impact of even mild, sub-threshold cybersickness symptoms on the ongoing user experience of those who do not immediately drop out. The literature, therefore, needs a more nuanced understanding of the role of physical comfort not merely as a component of user satisfaction, but as the non-negotiable prerequisite for any meaningful and positive interaction to begin and to be sustained.

c. Gap 3: The Theoretical Gap: The Need For A Dynamic, Integrated Framework

The final and most profound gap identified is theoretical. The dominant models used to explain and predict technology adoption, particularly the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT), are conceptually inadequate for explaining the complex phenomenon of older adults adopting immersive exergames (Ammenwerth 2019; Lee & Xie 2018). The critique presented in this review highlights that these models are fundamentally static, designed to capture a single snapshot of user intention, which makes them incapable of modeling the dynamic, longitudinal process of adoption, habituation, and potential attrition. Moreover, their cognition-centric focus on rational evaluations of "usefulness" and "ease of use" renders them unable to account for the primacy of the embodied, physiological experience that is central to immersion.

While more suitable psychological theories of motivation, such as Self-Determination Theory and Flow Theory, provide a powerful vocabulary for understanding what makes an experience intrinsically rewarding, the literature lacks a comprehensive, integrated framework that bridges these different theoretical worlds. There is no single, widely accepted model that can holistically account for the entire user journey. Such a model would need to integrate the sequential and interactive effects of foundational physiological barriers, subsequent psychological factors like technology anxiety and interpersonal trust, and the ultimate drivers of long-term motivation. This theoretical vacuum hinders the development of a systematic, evidence-based approach to designing for sustained engagement. The field requires a new, process-oriented framework that can capture the true complexity of the older adult's adoption journey (Oppl et al. 2024).

2.6.3 Positioning The Current Thesis

The research presented in this thesis is not a general exploration of immersive technologies but a targeted and systematic endeavor, specifically designed to address the critical empirical, practical, and theoretical gaps identified in the preceding review. It is positioned as a direct response to the call for a more nuanced, dynamic, and embodied understanding of how older adults engage with and adopt immersive exergame technologies (Charness 2022). The following paragraphs will articulate precisely how the multi-phase research agenda of this thesis is structured to fill these identified voids, thereby contributing new, valuable, and actionable knowledge to the fields of gerontechnology and human-computer interaction, with the direct mapping between these gaps and the thesis's objectives summarized in Table 15.

To address the practical gap concerning the insufficient focus on foundational embodied barriers, this thesis undertakes its first research objective. This objective is realized through a foundational usability and feasibility study involving a large cohort of community-dwelling older adults (Bacha et al. 2023; Benham et al. 2024). Unlike studies that might overlook or minimize initial user attrition, this research is designed to move beyond anecdotal reports and systematically document the very first moments of the user journey. Its primary contribution in this regard is to empirically quantify the powerful filtering effect of physiological discomfort, providing concrete data on initial attrition rates specifically attributable to this barrier. Furthermore, this initial study aims to identify and deconstruct the qualitative nature of the early user experience, uncovering key phenomena such as the "Empowerment Sweet Spot" and the "Accuracy-Competence Paradox" that shape an older user's immediate perceptions of a new technology.

In direct response to the empirical gap created by the dominance of short-term, novelty-bound research, this thesis pursues its second research objective through a longitudinal, multi-day comparative study (Lee, Chen & Basu 2025; Szczepocka et al. 2024). By tracking users' experiences over a six-session repeated-exposure period, this research is explicitly designed to look beyond the transient allure of the novelty effect and investigate the factors that contribute to a more stable and sustained positive experience. This longitudinal approach provides crucial, and currently lacking, data on the comparative long-term user experience of different immersive modalities, specifically the fully immersive Virtual Reality versus the reality-grounded Mixed Reality. Most importantly, it employs advanced statistical analysis to move beyond simple satisfaction ratings and identify the core psychological drivers namely, the user's sense of competence and the perception of an appropriate challenge that robustly predict a sustained positive experience, thereby uncovering the potential secrets to long-term engagement rather than just initial curiosity.

Finally, and most significantly, to fill the critical theoretical gap left by the inadequacy of existing static and cognition-focused models, this thesis embarks on its third and most ambitious research objective. This objective is achieved through the synthesis of all empirical findings from the preceding studies into a new, cohesive theoretical framework. Instead of merely applying or testing an existing model, this research takes a bottom-up, evidence-based approach to theory building. By systematically analyzing the entire user journey paying close attention not just to the "survivors" but also to the reasons for user attrition at each distinct stage it aims to construct and propose a novel "Dynamic Barrier Framework." This framework is specifically designed to be process-oriented, multi-faceted, and to give due primacy to the user's embodied experience, providing a more holistic and powerful explanatory model for the complex adoption and attrition process (Costello & Bloesch 2017; Malinverni & Schaper 2018).

These three research objectives are interdependent and form a logically sequenced research agenda (Gaugler et al. 2018; Huang et al. 2021). The initial investigation establishes an empirical foundation by identifying the key real-world barriers associated with attrition. The subsequent longitudinal component examines how these barriers persist, shift, or interact over time across stages of use. Finally, the thesis integrates evidence from early dropouts and long-term users to consolidate the Dynamic Barrier Framework and support its validation, thereby strengthening the coherence and interpretability of the overall research program.

Table 15 Mapping of Identified Research Gaps to Thesis Research Objectives

Identified Research Gap	**Corresponding Thesis Objective**
Gap 1: Practical Gap Insufficient focus on foundational embodied barriers, such as cybersickness, as a primary filter in the adoption process.	RO1: To identify key barriers that lead to attrition during interaction with immersive exergames.
Gap 2: Empirical Gap Lack of long-term, process-oriented evidence that looks beyond the initial novelty effect.	RO2: To construct a Dynamic Barrier Framework of attrition of immersive technology exergames among older adults.
Gap 3: Theoretical Gap The need for a dynamic, integrated framework that can holistically model the entire user journey, overcoming the limitations of static, cognition-centric models .	RO3: To validate the Dynamic Barrier Framework across stages of adoption, engagement, and attrition.

In summary, by systematically addressing these well-defined and significant gaps in the literature through a carefully sequenced, multi-phase research design, this thesis is positioned to make a substantial and original contribution to our understanding of how older adults engage with the technologies of the future. It promises to deliver not only practical design insights but also a novel theoretical lens through which to view the complex human process of technology adoption. The specific, rigorous methodology designed to execute this ambitious research agenda and achieve these objectives will now be detailed in the chapter that follows.

2.7 Summary

This chapter has provided a comprehensive thematic review of the literature on immersive exergames and their relevance to healthy aging. The synthesis indicates that both Virtual Reality (VR) and Mixed Reality (MR) have demonstrated potential to support older adults' physical and cognitive functioning; however, the literature also converges on a persistent and under-resolved challenge: long-term adherence. While many studies report promising short-term outcomes, there remains a notable lack of process-oriented evidence explaining how initial engagement translates into sustained participation once the novelty effect diminishes. This gap suggests that adoption cannot be adequately understood as a one-time decision based solely on perceived usefulness or ease of use.

A key conclusion from this review is that older adults' engagement with immersive exergames is better characterized as a sequential adoption journey shaped by evolving constraints. First, physiological barriers, particularly cybersickness, can operate as a foundational "physical veto," terminating use before meaningful cognitive evaluation occurs. Second, psychological barriers, especially technology anxiety, may further impede continued engagement, yet the literature also suggests these can be mitigated through supportive onboarding and the development of interpersonal trust as a gateway to persistence. Third, once early-stage barriers are navigated, sustained engagement is unlikely to be maintained by novelty alone; rather, it depends on more stable motivational conditions, including the satisfaction of intrinsic motivation as articulated by Self-Determination Theory (competence, autonomy, relatedness) and Flow Theory (challenge–skill balance). Together, these findings reinforce that immersive exergame adoption is a dynamic, embodied, and longitudinal process.

Understanding these multifaceted challenges clarifies the scope and necessity of this thesis. Rather than merely assessing the feasibility of immersive devices, the research is positioned to address the identified empirical (limited longitudinal and process-based evidence), practical (under-emphasis of embodied barriers as primary filters), and theoretical (insufficient dynamic explanations beyond static acceptance models) gaps by focusing on the "why" and "how" of attrition over time. Accordingly, this chapter establishes the rationale for an integrated explanatory lens, the Dynamic Barrier Framework, to holistically model older adults’ experiences from initial contact through continued use and potential habit formation. These conclusions provide the evidence-based foundation for the research objectives and directly motivate the multi-stage methodological approach detailed in the following chapter.

CHAPTER III

METHODOLOGY

3.1 Introduction

This synthesis clarified how affective and motivational mechanisms, usability factors, and contextual constraints jointly influence adoption, sustained engagement, and attrition in older adults' immersive VR experiences, and it revealed gaps in prior work regarding an integrated, practice-oriented model for this population. These insights informed the refinement of our research questions and objectives, including the planned validation of the framework through expert review and semi-structured expert interviews.

3.2 Research Paradigm And Overall Design

3.2.1 Research Paradigm – A User-Centered Approach

This research is grounded in a User-Centered Design (UCD) paradigm, which positions users specifically older adults at the heart of the design and development process (Hallewell Haslwanter, Neureiter & Garschall 2018; Sujan Samuel Roy, Neumann & Fels 2016). The approach was chosen to address the gap between technological potential and real-world user attrition, recognizing that creating effective and acceptable technology requires active user involvement. Rather than imposing a top-down solution, the UCD paradigm emphasizes co-creation, ensuring that the outcomes align with users' real abilities, preferences, and lived experiences (Gaspar et al. 2022; Mansson et al. 2020). This principle guided the entire study, from the iterative development of the research instrument to the implementation of user experiments.

3.2.2 Overall Design – A Multi-Phase Sequential Framework

This study adopts a multi-phase sequential exploratory design to better understand how older adults engage with new technology over time (Dermody et al. 2026; Huang et al. 2021; Timon et al. 2024). This approach allows the research to capture both the initial user experience and the factors that influence continued use, recognizing that first impressions and long-term engagement may differ significantly. The two phases build on each other: insights from the first, broader exploration (Experiment A) directly guide the second, more focused study (Experiment B), forming a coherent and logically connected research process illustrated in Figure 20.

Experiment A was therefore used as the first filter for identifying immediate contact barriers, whereas Experiment B examined whether barriers among continuing users shifted under repeated exposure rather than simply repeating the initial usability judgment.

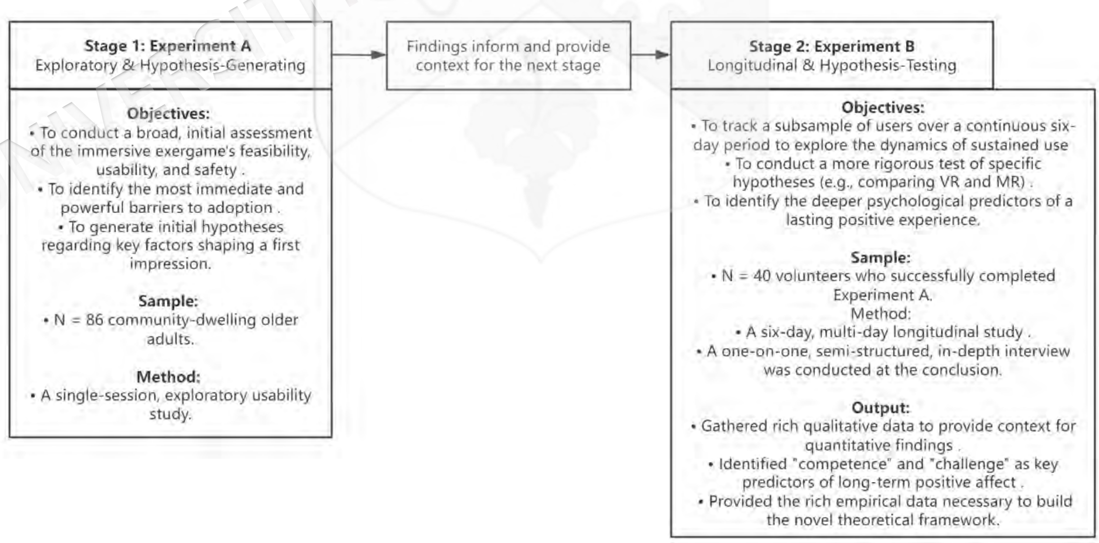

Figure 20 The Two-Stage Sequential Exploratory Research Design Framework

This two-stage design provides the empirical basis for addressing the three research objectives (Dermody et al. 2026; Pidgeon & Dawood 2022). Stage 1

(Experiment A) captures barriers during initial contact, and Stage 2 (Experiment B) examines how barriers persist or shift during repeated exposure; together, these two stages operationalize RO1. The integrated findings from Stages 1 and 2 then inform the development of the conceptual framework (RO2). The framework is validated through expert review (RO3). A summary of how each phase corresponds to the research objectives and methods is presented in Table 16.

Table 16 Overview of Chapter III (Methodology)

Section & Title	**Main Focus / Content Summary**	**Output**
3.1 Introduction	Introduces the overall purpose of Chapter 3, explaining how the three research objectives (RO1–RO3) are implemented through a sequential, multi-phase methodology.	Chapter roadmap linking ROs to methodological design and analytical flow.
3.2 Research Paradigm and Overall Design	Defines the user-centered, pragmatic paradigm and outlines a multi-phase sequential framework (identification → construction → validation) guiding the study.	Finalized research protocol including study phases, sampling plan, and data-collection structure.
3.3 Research Instrument: The Tai Chi Exergame	Describes the VR Tai Chi Exergame as the main experimental instrument, detailing its structure, gameplay, and built-in data-tracking functions.	Measurement toolkit: GEQ, VRSQ, usability and acceptability ratings, and game performance logs (accuracy, duration, completion rate).
3.4 Study Design for RO1: Identifying Initial Barriers	Details RO1 across Experiment A (Initial contact) and Experiment B (Repeated Exposure), including participants, procedures, and variables designed to detect physiological, socio-psychological, and motivational barriers across initial and repeated sessions.	Quantitative outputs for RO1 derived from GEQ, VRSQ, and performance data: (Experiment A) reliability results, baseline metrics, and initial attrition rate (18.6%); (Experiment B) repeated-session indicators of barrier persistence/change and adherence/attrition patterns, supporting RO1's identification of barriers across stages.
3.5 Study Design for RO2: Constructing the Framework	Describes how cross-experiment findings are synthesized to model the evolution of barriers and construct the Dynamic Barrier Framework.	Integrated evidence matrix, coding schema, and preliminary structure of the Dynamic Barrier Framework for validation.

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... continuation		
3.6 Study Design for RO3: Validating the Framework	Presents the RO3 expert-validation procedure using a purposive panel of 13 domain experts. The validation integrates a structured quantitative rating instrument and qualitative semi-structured interviews to assess the DBF's clarity/coherence, representativeness, content validity, and practical relevance (usefulness).	Validation dataset: block-/dimension-level descriptive statistics (M, SD, median, min–max), S-CVI indices, Cronbach's α, and qualitative themes/comments used to refine the DBF.
3.7 Hypothesis	Presents the phase-linked hypotheses derived from the DBF, specifying expected relationships among physiological burden, socio-psychological readiness, motivational maintenance, and cross-phase linkages.	Phase-linked hypotheses guiding the empirical interpretation and tests reported in Chapter 4.
3.8 Summary	Summarizes all methodological phases, aligning each with RO1–RO3, and previews the organization of Chapter 4 (Results and Discussion).	Integrated methodological overview linking design to subsequent empirical findings.

3.3 Research Instrument: The Tai Chi Exergame

3.3.1 User-Centered Design Philosophy

The development of the Tai Chi Exergame followed a UCD philosophy, ensuring that older adults were involved throughout the process as active co-creators rather than passive users. This approach addressed a common limitation in gerontechnology, where older users' feedback is often overlooked (Czaja et al. 2024; Fakhimi, Hughes & Gustavson 2025). The design focused on two core principles: (1) improving accessibility and usability to make the experience smooth and achievable, and (2) enhancing enjoyment and intrinsic motivation to encourage long-term engagement.

3.3.2 The Iterative Refinement Process

Following the UCD approach, the exergame was developed through an iterative process that involved continuous co-creation with older adults (Berglund et al. 2023; Chu et al. 2021). Each cycle included four steps: (1) developing a new prototype, (2) testing it with a small group from the target community, (3) collecting qualitative feedback through informal discussions and observation, and (4) analyzing the feedback to refine the design before the next iteration. This user-centered development cycle is shown in Figure 21.

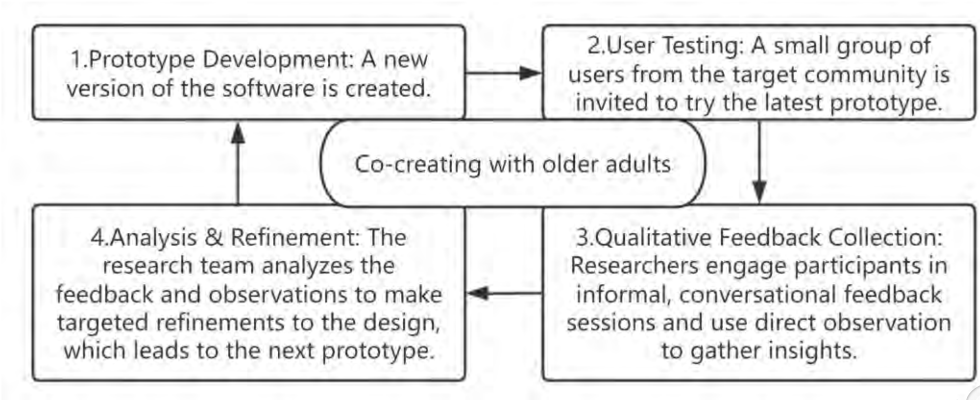

Figure 21 The User-Centered Iterative Design Cycle for the Tai Chi Exergame

User feedback played a key role in shaping the final version of the Tai Chi Exergame (Chu et al. 2021; Manser, Adcock-Omlin & De Bruin 2023). It led to important design changes that improved both usability and enjoyment. For example, to make the experience smoother and more accessible, the original 24-form Tai Chi routine was simplified to a 16-form version by removing physically demanding postures. To make the game more engaging, participants' favorite and culturally familiar music tracks were added as optional background music. These examples of how user input directly informed design decisions are summarized in Table 17.

Table 17 Key Design Changes Based on User Feedback

User Feedback	**Design Change**	**Design Goal**	**Result on User Experience**
Some Tai Chi moves were too difficult and caused frustration.	Simplified the routine from 24 to 16 forms by removing highly demanding postures.	Improve accessibility and make movements smoother.	Reduced difficulty and created a more comfortable, confidence-building experience.
Participants preferred familiar community songs instead of generic background music.	Added two user-requested tracks: *Erquan Yingyue* and a popular "War Horse" square dance song.	Enhance enjoyment and increase intrinsic motivation.	Made the experience more familiar, engaging, and culturally meaningful.

3.3.3 The Final Intervention Material

The final outcome of this iterative process was a refined version of the Tai Chi Exergame, which was used in both Experiment A and Experiment B. Its main features and core mechanics are summarized below. The Tai Chi exergame was self-developed by the research team using Unity.

Rather than treating Tai Chi as the only possible activity, it was selected because its slow, balance-oriented, low-impact movements match common fall-prevention goals and can be adapted for older adults with different movement confidence levels.

(1) Core Gameplay: The game is built around sixteen classic Tai Chi movements. A life-sized virtual coach demonstrates each posture, while the system tracks the user's head and hand positions through three on-screen "hot-spots" (see Figure 22). The success rule was intentionally lenient, users only needed to align with one of the three hot-spots to progress. This design reduced frustration, built a sense of competence, and supported the "Empowerment Sweet Spot" effect identified in this study (Hsieh et al. 2018; Kim et al. 2024).

Figure 22 Game UI Concept Design Diagram

(2) Selectable Modes: The game included two sets of user-selectable modes. The Display Mode let users choose between a fully immersive Virtual Reality (VR) view and a more grounded Mixed Reality (MR) view (see Figure 23). The VR and MR conditions were implemented as two selectable display modes within the same Unity-based Tai Chi exergame, rather than as two separate applications. The Feedback Intensity could be adjusted to a *Soothing Mode* with calm music and gentle cues, or an *Intense Mode* with more energetic music and stronger audiovisual feedback.

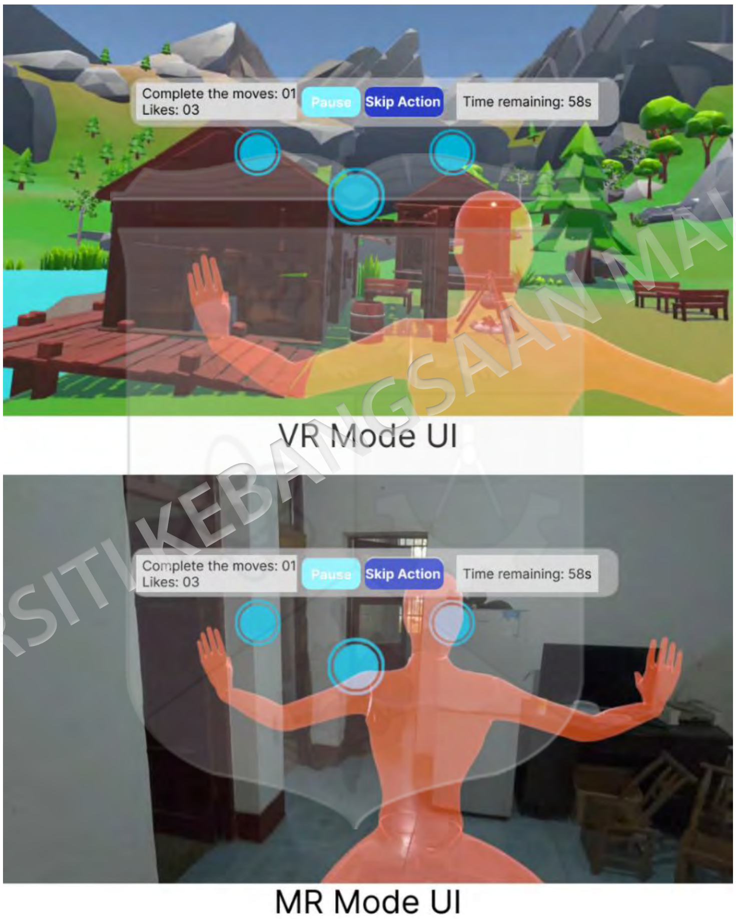

Figure 23 Game screenshots

(3) User Agency and Control: The design included features that encouraged user control and reduced technology anxiety (Chu et al. 2021; Park et al. 2022; Wu et al. 2025). Players could pause, resume, or stop the game at any time, and skip any movement they found too difficult. These control options were presented through a simple and accessible interface, as shown in Figure 24 and Figure 25.

Figure 24 UI design for game settings

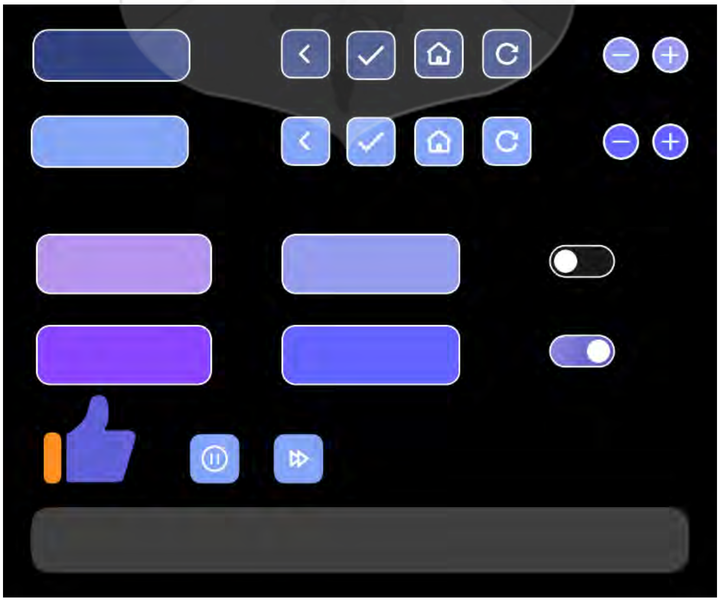

Figure 25 Game Theme and Control Design

3.3.4 Experimental Apparatus

The study used the Meta Quest 3, a standalone head-mounted display (HMD) selected for its strong performance and user-friendly design (Godden, Steedman & Pan 2025). It supported both Virtual Reality (VR) and Mixed Reality (MR) modes, which were essential to the research setup. All interactions were operated using the Meta Quest Touch Plus controllers. The equipment used in the study is shown in Figure 26.

The apparatus therefore allowed the same Tai Chi exergame task to be experienced under VR and MR display conditions while keeping the headset platform and controller input consistent across conditions. Tracking, controller handling, and headset fit were treated as part of the intervention context because these technical features could themselves become adoption barriers for older adults.

Figure 26 VR experimental equipment

3.4 Methodology For Ro1: Identifying Stage-Specific Barriers

This section describes the methods used to identify and track the barriers older adults faced when adopting and continuing to use the immersive exergame, addressing the first research objective (RO1) across both initial contact (Experiment A) and repeated exposure (Experiment B).

3.4.1 Method: User Experiment (Experiment A: Initial Contact)

To address the first research objective (RO1) of identifying initial adoption barriers, a single-session user experiment (Experiment A) was conducted. This method allowed observation and measurement of participants' immediate physiological and psychological responses in a controlled yet realistic setting (Hansa & Hansen 2025; Kisker, Gruber & Schöne 2019; Terfurth, Gramann & Gehrke 2024).

The experiment used a 2×2 between-subjects design with two independent variables: Display Mode (Virtual Reality [VR] vs. Mixed Reality [MR]) and Feedback Intensity (Soothing vs. Intense) (Gayathri & Nam 2024; Hinricher, Schröer & Backhaus 2023; Palmieri & Deutsch 2024). A total of 86 participants were randomly assigned to one of four conditions: VR with Soothing feedback, VR with Intense feedback, MR with Soothing feedback, or MR with Intense feedback. This design allowed a systematic comparison of how display type and feedback strength influenced users' initial experience and potential adoption barriers.

Table 18 2×2 Experimental Conditions Matrix for Experiment A: Initial Contact

	Virtual Reality (VR) Display	**Mixed Reality (MR) Display**
Soothing Feedback Mode	Condition 1: VR with Soothing feedback	Condition 2: MR with Soothing feedback
Intense Feedback Mode	Condition 3: VR with Intense feedback	Condition 4: MR with Intense feedback

3.4.2 Participants, Procedure, And Data Analysis

a. Participant Sampling And Screening

To recruit participants for Experiment A, a community-based approach was used, combining purposive and snowball sampling. Collaboration was established with local community liaisons in an older adult residential area (Felix & Kitcharoen 2026; Kimpel et al. 2025). Recruitment took place through community centers and local advertisements, targeting older adults living independently. This approach ensured that participants were drawn from real social and environmental contexts relevant to future health technology use. The recruitment site is shown in Figure 27.

Prior VR experience, health status, and physical readiness were considered as screening and contextual factors rather than experimental outcomes, because these characteristics could influence comfort, confidence, and willingness to continue.

Figure 27 Participants are in the waiting area

Participants were required to be 60 years or older, with normal or corrected-to-normal vision, adequate hearing, and normal cognitive function to follow instructions (Benham, Pennell & Wynarczuk 2022; Makmee & Wongupparaj 2022). Individuals were excluded if they had medical conditions incompatible with VR use, such as epilepsy, severe cardiovascular or musculoskeletal disorders, or experienced strong discomfort (e.g., nausea or dizziness) during familiarization. These criteria ensured both safety and data validity, resulting in an initial cohort of 86 participants for Experiment A, as summarized in Table 19.

Table 19 Participant Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
1. Aged 60 years or older.	1. A known personal history of conditions incompatible with the use of virtual reality devices (e.g., epilepsy, severe chronic vertigo).
2. Possess normal or corrected-to-normal vision, with the ability to see the virtual interface clearly.	2. The presence of severe cardiovascular or musculoskeletal diseases that would make engagement in even light physical activity unsafe.
3. Have normal hearing, sufficient to understand verbal instructions.	3. Severe, uncorrected vision loss that would prevent clear perception of the virtual environment.
4. Demonstrate normal cognitive function, enabling comprehension of the study's requirements.	4. The experience of extreme and insurmountable discomfort (e.g., severe nausea or disorientation) during the initial device familiarization session.

b. Procedure And Initial Attrition

The procedure was standardized for all 86 participants in the single-session study (Xu et al. 2025; Zhai et al. 2021). After completing the informed consent and a short demographic survey, each participant received brief adaptation training to reduce technology anxiety (Al Khalifah et al. 2025; Cieślik et al. 2023). A researcher provided one-on-one guidance on using the hand controllers and wearing the headset, with step-by-step instruction (see Figure 28). Participants were then given time to adjust to the virtual environment, sometimes while seated, to ensure comfort before the session began (Figure 29).

Figure 28 Researchers helped participants put on and adjust their VR equipment

Figure 29 A participant undergoing the initial adaptation and familiarization session with the VR equipment

After the familiarization phase, each participant was randomly assigned to one of the four experimental conditions in the 2×2 design (see Table 18). They then completed a single exergame session lasting about 15–30 minutes (Figure 30). During the session, a researcher supervised the process to ensure physical safety, monitoring participants' actions in real time, especially for those with weaker physical conditions (Figure 31). After the session, participants filled out the Virtual Reality Sickness Questionnaire (VRSQ) and the Game Experience Questionnaire (GEQ) to record their immediate responses (Campo-Prieto, Cancela-Carral & Rodríguez-Fuentes 2022b; Costa et al. 2024; Qiu et al. 2022).

Figure 30 Experimental Setup

Figure 31 Researchers stayed by the side of participants with weaker physical conditions

During this stage, a noticeable dropout pattern was observed (Figure 32). Of the 86 participants who started, 16 (18.6%) withdrew before finishing the session. Most of these cases (14 participants) were due to physiological discomfort, mainly cybersickness. As a result, 70 participants completed all procedures for Experiment A, and their data were used for the initial usability analysis.

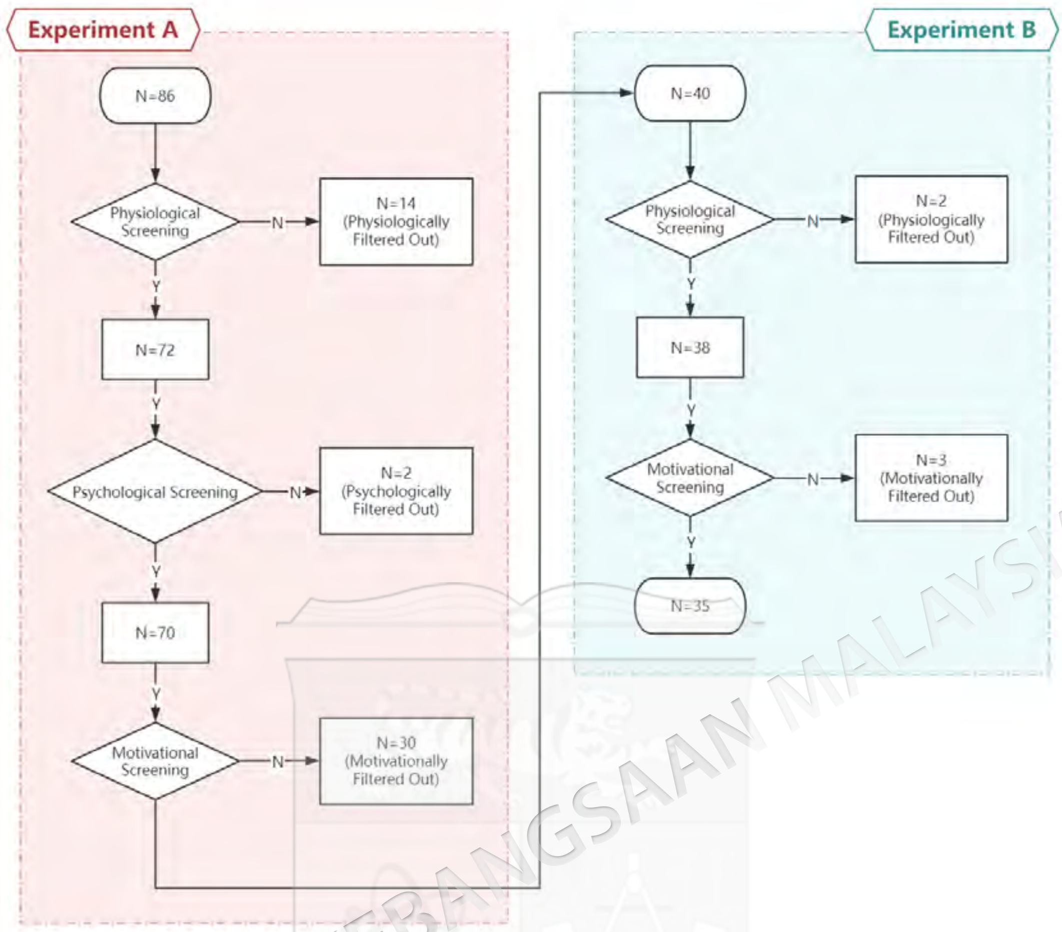

Figure 32 Participant Attrition Funnel Illustrating the "Three Barriers" Filtering Model

c. Data Collection And Analysis

Participants were recruited using a purposive convenience sampling strategy from community-dwelling older adults who met the study's age, health, and safety eligibility criteria. To address RO1, Experiment A used a multi-source data strategy (Somrak, Pogačnik & Guna 2021; Wang et al. 2023). We recorded attrition data (counts and stated reasons for withdrawal), administered the Virtual Reality Sickness Questionnaire (VRSQ) immediately after the session to capture physiological comfort, collected participants' self-reported experience using the Game Experience Questionnaire (GEQ) (Competence, Challenge, Positive Affect), and logged objective performance from game logs (e.g., movement accuracy, time per round).

Data analysis focused on the Experiment A cohort (N = 86). We used descriptive statistics to summarize participant characteristics and session completion patterns. To examine the physiological barrier, Mann–Whitney U tests compared VRSQ scores between participants who discontinued due to discomfort and those who completed the session (Kitapcioglu et al. 2024; Rubio-López et al. 2025). Among participants who completed the session, Spearman's correlations were used to explore associations between GEQ dimensions and game-log performance indicators.

3.4.3 Method: Longitudinal User Experiment (Experiment B: Repeated Exposure)

To extend the initial-exposure findings from Experiment A and to track barrier dynamics under repeated exposure, a six-session repeated-exposure follow-up study (Experiment B) was conducted with eligible participants from Experiment A. Experiment B retained participants' original condition assignments and tracked gameplay experience, perceived exertion, and performance indicators across sessions to support RO1's stage-based barrier identification. Physiological comfort was represented by the VRSQ measured after Experiment A and was not treated as a continuously repeated symptom measure during Experiment B.

a. Procedure of Experiment B: Repeated Exposure (Longitudinal Study)

The six-session design is therefore interpreted as a short repeated-exposure protocol rather than evidence of long-term adherence, and its purpose was to observe early barrier transitions after novelty and first-contact effects began to stabilize.

Although the framework synthesizes evidence from the entire study, the longitudinal data capturing sustained use came from Experiment B, a six-session follow-up with participants from Experiment A (Kim et al. 2024). The procedure had three phases: Phase 1 (Day 0), recruitment, renewed consent, confirmation of eligibility, retention of original VR/MR assignments, and baseline measures (demographics and BBS); Phase 2 (Sessions 1–6), six repeated-exposure Tai Chi exergame sessions, with no more than one session conducted per day and with game log recording of performance and post-session Borg-RPE ratings of exertion (participant activity shown in Figure 33); and Phase 3, GEQ assessment after the final Experiment B session, followed by debriefing.

The complete procedure is summarized in Table 20. The VRSQ was administered after Experiment A and used as an initial physiological response indicator for participants entering Experiment B; it was not administered repeatedly across the six Experiment B sessions. GEQ captured key gameplay experience dimensions (competence, challenge, and affect) relevant to sustained engagement after repeated exposure. Borg-RPE ratings were collected after each session to monitor perceived exertion and safety across the repeated-exposure period, and BBS was used as a baseline balance screening measure. Each session was conducted individually, with one participant tested at a time, thereby minimizing direct group or peer influence during gameplay.

Table 20 Experimental procedure

Phase	Time / Period	Key Activities & Content	Data Collected / Measures Used
Phase 1: Recruitment & Baseline Assessment	Before the Intervention (Day 0 - Pre-test)	1. Recruit eligible participants from the community. 2. Sign the informed consent form. 3. Retain participants' original 2×2 condition assignment from Experiment A (Display Mode × Feedback Intensity); no re-randomization was performed. 4. Conduct comprehensive baseline data collection.	• Demographic Information • E-Device Usage Questionnaire • BBS[a] (1st assessment)
Phase 2: Longitudinal Exergame Intervention	Over a period of 6 days (Day 1 - Day 6)	1. Participants complete 6 sessions of Tai Chi exergame training according to their assigned group. 2. Each training session consists of 3 rounds of gameplay. 3. Record subjective exertion after each training session.	• Game Logs: Continuously record metrics such as Accuracy, Track, and Time Spent for every round. • Borg RPE[b]: Measured after each training session.
Phase 3: Final Assessment & Debriefing	After the 6th intervention session (Post-test)	1. Conduct the final subjective experience assessment after the last training session. 2. Debriefing: Thank participants and answer any questions.	• GEQ[c] • VRSQ[d]

[a]BBS : Berg Balance Scale. [b]Borg-RPE : Borg Rating of Perceived Exertion. [c]GEQ : Game Experience Questionnaire. [d]VRSQ : Virtual Reality Sickness Questionnaire.

Figure 33 Participants in the game

b. Participant Journey And Attrition Analysis

The participant journey was documented using a stage-based funnel model to track retention and attrition across Experiment A, the transition phase, and Experiment B (Bevens et al. 2022). At each stage, withdrawals were recorded and the stated reasons were coded using the predefined barrier categories (physiological, socio-psychological, and motivational). Stage-specific retention, conversion, and overall completion rates were then calculated and are reported in Chapter 4.

Figure 34 shows the main physiological, psychological, and motivational reasons for participant withdrawal, highlighting how each barrier changed during adoption. The study began with 86 participants in Experiment A; 70 completed Experiment A. Of these, 40 consented to participate in Experiment B, and 35 completed Experiment B and were included in the analysis.

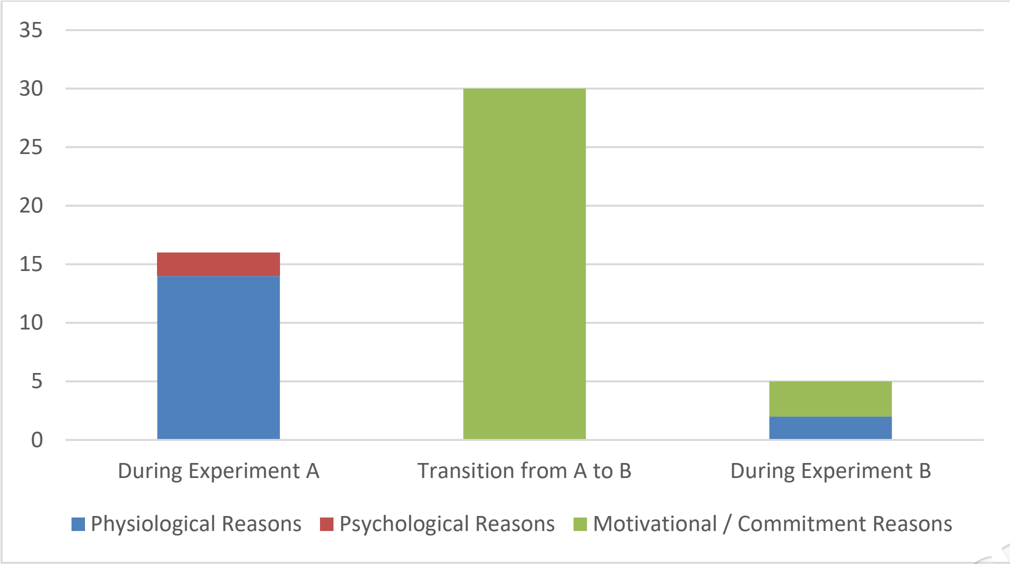

Figure 34 Data Table for Participant Attrition Analysis

c. Core Data Sample And Baseline Equivalence

The transition to Experiment B involved an invitation process that could introduce self-selection bias. To confirm the validity of this core sample, baseline comparisons between the VR group (N=18) and the MR group (N=17) were conducted using Mann–Whitney U tests. As shown in Table 21, no significant differences were found in key baseline characteristics, confirming group equivalence before the longitudinal study. The modal gender category in both groups was female, reflecting the gender composition of the retained Experiment B sample. This female dominance should be considered when interpreting the repeated-exposure findings and their generalisability.

Table 21 Baseline characteristics comparison between VR and MR groups

Demographic				
	VR[a] (n=18)	MR[b] (n=17)	*Z*	*P*
Gender Group	female	female	-1.37	.171
Age Group	65-70	60-65	-0.424	.672
Height Group	150-160	150-160	-0.844	.399
Education	High / Technical Secondary School	Junior High	-1.669	.095

... to be continued

... continuation

Exercise Intensity	Severe	Severe	-0.686	.493
Health	With cardiovascular and pulmonary diseases	With cardiovascular and pulmonary diseases	-0.136	.892
BBS[c] (balance ability)	56(54.75~56)	56(55~56)	-0.918	.358
Electronic Device Usage	3-5 hours	3-5 hours	-0.551	.582

[a]VR: virtual reality. [b]MR: mixed reality. [c]BBS: Berg Balance Scale.

The detailed demographic characteristics of the final resilient cohort (N=35) that provided the richest longitudinal data for framework construction are presented in Table 22 and further illustrated in Figure 35 and Figure 36.

Because Experiment B was based on participants who had already completed Experiment A and agreed to continue, the final cohort should be interpreted as a resilient subgroup rather than as a fully representative sample of all initially recruited older adults.

Table 22 Demographic information of participants (n=35)

(n=35)		Number	Percentage(%)
Gender	male	10	28.6
	female	25	71.4
VR[a] & MR[b]	VR	18	51.4
	MR	17	48.6
Age Group	60-65	17	48.6
	66-70	4	11.4
	71-75	6	17.1
	76-80	6	17.1
	81+	2	5.7
Height Group (cm)	140-150	7	20
	151-160	18	51.4
	161-170	8	22.9
	171+	2	5.7
Education	Primary school and below	4	11.4
	Junior high	14	40
	Senior high / Technical secondary	13	37.1
	Junior college and above	4	11.4
Avg. daily smartphone use (hours)	Less than 1 hour	4	11.4
	1 - 3	9	25.7
	3 - 5	12	34.3
	5+	10	28.6
Exercise intensity	Low	6	17.1
	Mild	9	25.7
	Severe	20	57.1
Health	No illness	14	40
	With cardiovascular and pulmonary diseases	21	60
BBS[c] (balance ability)	Low Fall Risk	34	97.1
	Medium Fall Risk	1	2.9
	High Fall Risk	0	0

[a]VR: virtual reality. [b]MR: mixed reality. [c]BBS: Berg Balance Scale.

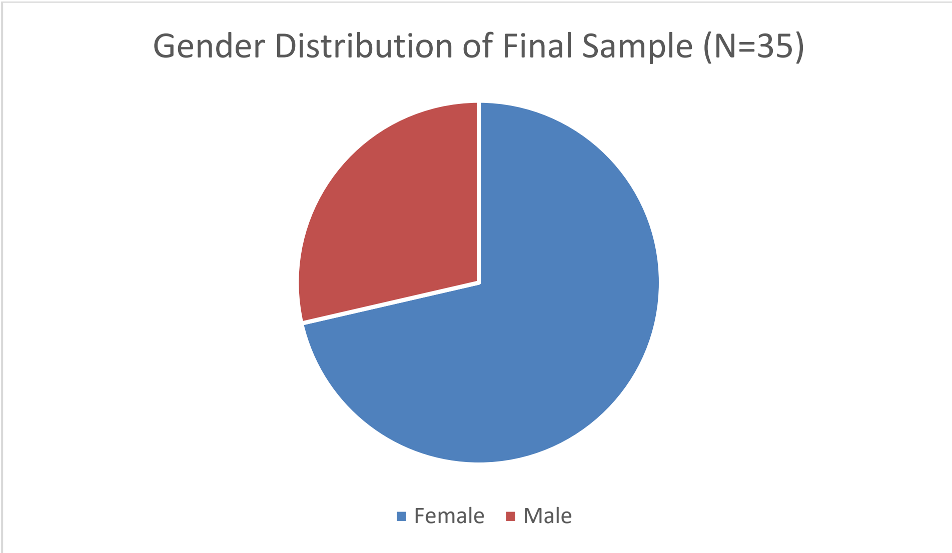

Figure 35 Gender Distribution of Final Sample (n=35)

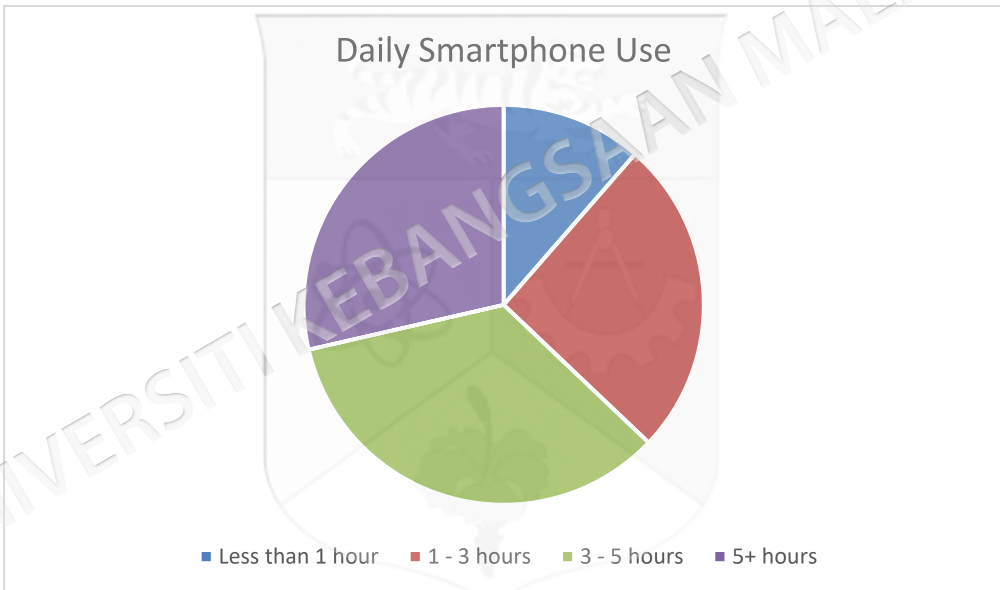

Figure 36 Daily Smartphone Use Distribution of Final Sample (n=35)

d. Data Sources For Framework Construction

The framework was built using multiple data sources to ensure a solid foundation. These included longitudinal quantitative data from Experiment B (e.g., GEQ, Borg-RPE, and game logs) and qualitative data from semi-structured interviews (Schumacher et al. 2021). Questionnaires were administered with researcher guidance, and a summary of all data collection instruments is provided in Table 23.

Table 23 Summary of Data Collection Instruments and Measures

Construct Measured	Instrument / Measure	Description	Time of Measurement
Subjective Experience	Game Experience Questionnaire (GEQ)	A revised 32-item core version measuring seven dimensions of the in-game experience, including Competence, Flow, and Positive Affect.	Post-Experiment A; Post-Experiment B (Day 6).
Physiological Comfort	Virtual Reality Sickness Questionnaire (VRSQ)	A standardized 9-item questionnaire used to quantify cybersickness symptoms (e.g., dizziness, eye fatigue, blurred vision, and vertigo) and produce a total score.	Post-Experiment A only; used as an initial physiological response indicator for Experiment B.
Objective Performance	Game Logs	Automatically recorded backend data from the exergame, including metrics such as movement accuracy, time spent per round, and total movement amount.	Continuously during all sessions of Experiment A and Experiment B.
Participant Background	Self-developed Questionnaire & Physical Activity Scale for the Elderly (PASE)	Collects demographic information, self-reported health history, prior technology experience, and standardized data on regular exercise habits.	Before Experiment A (demographics); Before Experiment B (detailed background and PASE).
Baseline Balance Ability	Berg Balance Scale (BBS)	A standardized and validated 14-item scale used to objectively assess a participant's functional balance ability and categorize their risk of falling.	Before the start of the Experiment B intervention.
Subjective Exertion	Borg Rating of Perceived Exertion (Borg-RPE)	A scale used to measure a participant's subjective perception of their level of physical effort immediately following an exercise session.	After each daily session during the six-day Experiment B.

3.5 Methodology For Ro2: Constructing The Framework

3.5.1 Methodological Strategy: Mixed-Methods Synthesis

To accomplish Research Objective 2 (RO2), the construction of the Dynamic Barrier Framework (DBF), this study adopted a bottom-up mixed-methods synthesis in which the multi-phase experimental dataset was treated as a coherent body of convergent evidence about a single adoption process (Galea, Mainey & Chugh 2025). The analytic logic followed triangulation: quantitative evidence was used to establish *what* occurred and *when* key transitions and discontinuities emerged across phases (e.g., patterned shifts in physiological responses, experiential appraisals, and behavioral indicators), whereas qualitative evidence was used to clarify *why* those shifts occurred and *how* they translated into withdrawal or commitment decisions (e.g., participants' stated reasons for discontinuation, brief interview clarifications, and researcher observation notes). Rather than imposing a priori model structure, the framework was progressively abstracted from empirically observed inflection points along the study timeline and from the mechanisms implied by participants' accounts. This design provides a transparent methodological basis for the results chapter's identification of the three core barriers, the phase-wise mapping of barrier salience, and the specification of cross-phase mechanisms (A/B/C) within the DBF.

3.5.2 Data Inputs And Preparation

This framework synthesis integrates evidence across three sequential phases aligned with the study design. Phase 1 (Initial Contact; Experiment A) provided initial physiological and experiential measures together with early withdrawal records. Phase 2 (Decision Transition) captured the post–Experiment A commitment decision, including trust- and safety-related feedback that shaped willingness to proceed. Phase 3 (Long-term Use; Experiment B) tracked repeated engagement and late-stage attrition to inform motivational and value-based mechanisms of sustained use. To maintain stage-specific inference, participants who entered the longitudinal phase (N = 40) were distinguished from those who completed the full protocol and constituted the sustained-use analytic sample (N = 35). Data preparation included standardized scoring of questionnaire and log-derived indicators, principled handling of missingness and outliers, and distributional screening to guide the selection of robust analytic procedures.

3.5.3 Establishing Barrier Categories: Coding Protocol And Evidence Matrix

RO2 translated participants' discontinuation experiences into barrier constructs using an iterative coding protocol guided by grounded-theory principles. Coding drew on stated withdrawal reasons, brief interview clarifications when available, and researcher field notes recorded during and immediately after sessions. Open coding first generated descriptive labels for proximal withdrawal mechanisms, which were then consolidated via constant comparison across cases and phases into three domains: Physiological, Socio-psychological, and Motivational. When multiple reasons were reported, a prespecified adjudication rule assigned the primary barrier based on the dominant failure point at withdrawal, with secondary reasons retained as context and ambiguities resolved using contemporaneous field notes. An evidence matrix (barrier × phase) was then constructed to align quantitative signals with qualitative themes at each phase, supporting phase-wise judgments of barrier salience. Operational definitions for classifying attrition reasons into the three barrier domains are provided in Table 24.

The coding was conducted manually by the researcher, without qualitative coding software or an independent second coder. This coding procedure was conducted as an audit-oriented interpretive process using documented withdrawal reasons, field notes, and phase-specific quantitative signals; therefore, the emphasis was on transparent evidence linkage rather than on claiming inter-rater reliability that was not independently established.

Table 24 Operational Definitions for Participant Attrition Barriers

Barrier Type	Operational Definition
Physiological Barrier	A withdrawal was classified as due to this barrier if the stated reason was primarily related to adverse physical symptoms (e.g., dizziness, nausea).
Socio-psychological Barrier	A withdrawal was classified as due to this barrier if the stated reason was rooted in fear or anxiety about the technology or its use (e.g., "I was afraid I would break it").
Motivational Barrier	A withdrawal was classified as due to this barrier if it was a value-based decision to discontinue after the user had already demonstrated the capability to use the system (e.g., "it felt boring," "I don't see the point").

3.5.4 Phase Mapping And Relationship Inference

Following barrier categorization, the DBF's dynamic logic was derived by mapping the three domains onto the empirically observed adoption trajectory. Phase boundaries were anchored in the study's sequential inflection points: Phase 1 (Initial Contact; early filtering), Phase 2 (Decision Transition; commitment juncture), and Phase 3 (Long-term Use; motivational maintenance). Within this structure, barrier salience was determined using an evidence-convergence criterion: a barrier was designated as dominant when it best accounted for the primary discontinuity at that phase and was supported by aligned quantitative and qualitative evidence; co-occurring factors were classified as latent/supporting when present but not explanatory of the phase's main transition. Cross-phase relationships were then inferred from consistent co-patterning in the evidence matrix: Relationship A linked physiological discomfort to heightened anxiety/concern indicators, Relationship B associated sustained physiological strain with motivational erosion and reduced positive experience, and Relationship C connected social trust/support with commitment decisions and sustained engagement. This procedure preserves a transparent link between empirical evidence and the resulting phase-structured framework.

3.6 Methodology For Ro3: Validating The Framework

This section outlines the methodology for the third research objective (RO3), which focuses on the validation of the newly constructed DBF v1. A systematic expert validation process was designed to assess the framework's scientific merit and practical utility.

3.6.1 Purpose And Design Overview

Purpose: To validate the Dynamic Barrier Framework (DBF) developed from RO1 and RO2 through expert evaluation across four key dimensions: (1) Content Validity (comprehensiveness and accuracy of the framework components), (2) Clarity and Coherence (logical structure and interpretability), (3) Representativeness (alignment with real-world older adults' engagement and attrition patterns), and (4) Practical Relevance (usefulness for research and design practice).

Design: A multi-method validation design was adopted, centered on qualitative semi-structured interviews with domain experts, supplemented by a quantitative rating instrument to systematically assess the framework's components (Fernández-Gómez et al. 2020; Kaufman & Kueppers 2026).

3.6.2 Expert Selection And Recruitment

Selection Criteria: A purposive sampling approach was used to recruit a panel of 13 experts to evaluate the DBF. Eligibility was defined broadly to ensure both academic rigor and practical relevance, including (a) researchers with formal training and publication/research experience in relevant fields (e.g., aging/gerontology, HCI/UX, VR/MR, serious games, digital health), and/or (b) senior practitioners with substantial professional experience (e.g., clinical, rehabilitation, sport science, VR development, interaction/UX design) related to older adults' technology use or immersive exercise applications. To ensure adequate expertise and credibility, all experts had a minimum of 5 years of relevant experience, with the final panel intentionally covering multidisciplinary perspectives across academia, clinical practice, and industry.

The sample size of 13 experts was considered appropriate for content validation because it provided multidisciplinary coverage across aging, rehabilitation, VR/MR, HCI/UX, digital health, and serious-game expertise while remaining manageable for structured rating and qualitative feedback.

Recruitment Strategy: Experts were identified and invited through professional networks, relevant academic and practitioner communities, and targeted invitations to ensure disciplinary diversity. Invitations included a brief study overview, consent information, and the validation materials. Recruitment continued until the intended multidisciplinary coverage was achieved, resulting in a final panel of 13 experts representing both academic and applied domains (Ahmad & Wilkins 2024; Corrigan & Onwuegbuzie 2020).

3.6.3 Validation Procedure

Step 1: Preparation of the Validation Package: Each expert received a standardized digital validation package prior to data collection, including: (a) a brief overview of the research context and RO3 objectives; (b) the DBF diagram; (c) concise textual definitions of the three stages, dominant barriers, and cross-stage mechanisms; (d) a structured rating form (4-point scale) for content validity assessment; and (e) a semi-structured interview guide and consent information.

Pilot refinement of the materials. Prior to the formal RO3 validation, the structured rating form and interview guide were refined through two iterative rounds of expert feedback: an initial round with one expert to identify ambiguous wording and missing options, followed by a second round with two additional experts to confirm clarity and completeness. During this refinement, overly open-ended prompts were minimised and, where appropriate, converted into single-choice or multiple-choice items to ensure feasibility and consistency of expert responses. The finalized version was then distributed to the full expert panel for the formal rating-and-interview procedure.

Step 2: Structured Rating Collection (Content Validity): Experts first completed the structured rating form to evaluate the DBF components using a 4-point scale (1 = not relevant/clear/useful; 4 = highly relevant/clear/useful). Each evaluation block was rated across four criteria, Relevance, Clarity, Representativeness, and Usefulness, covering stage definitions, stage-specific mechanisms, cross-stage links, attrition-phase mapping, overall logical flow, and figure readability. In addition to the block-level ratings, the rating form included three global items to contextualize experts' overall judgments of the DBF: (a) perceived theoretical contribution (Q46; categorical selection), (b) overall practice fit (Q50; four-level fit rating), and (c) experience-based confirmation of key DBF assumptions (Q49; multiple-response). These global items were analysed descriptively and are reported in Section 4.7.3 (Table 44), alongside the CVI- and reliability-based indices reported in Section 4.7.2 (Table 43).

Step 3: Semi-Structured Interviews: After completing the rating form, each expert participated in a semi-structured interview conducted online to elaborate on their ratings and provide deeper feedback. The interview lasted approximately 20–30 minutes (overall participation typically 30–40 minutes including ratings) and followed a standardized guide focusing on perceived theoretical contribution, real-world fit, missing elements, and revision priorities. With consent, interviews were audio-recorded to ensure accuracy (Guro, Rombraan & Guimba 2025; Mujlli et al. 2023; Ventura-Silva et al. 2023).

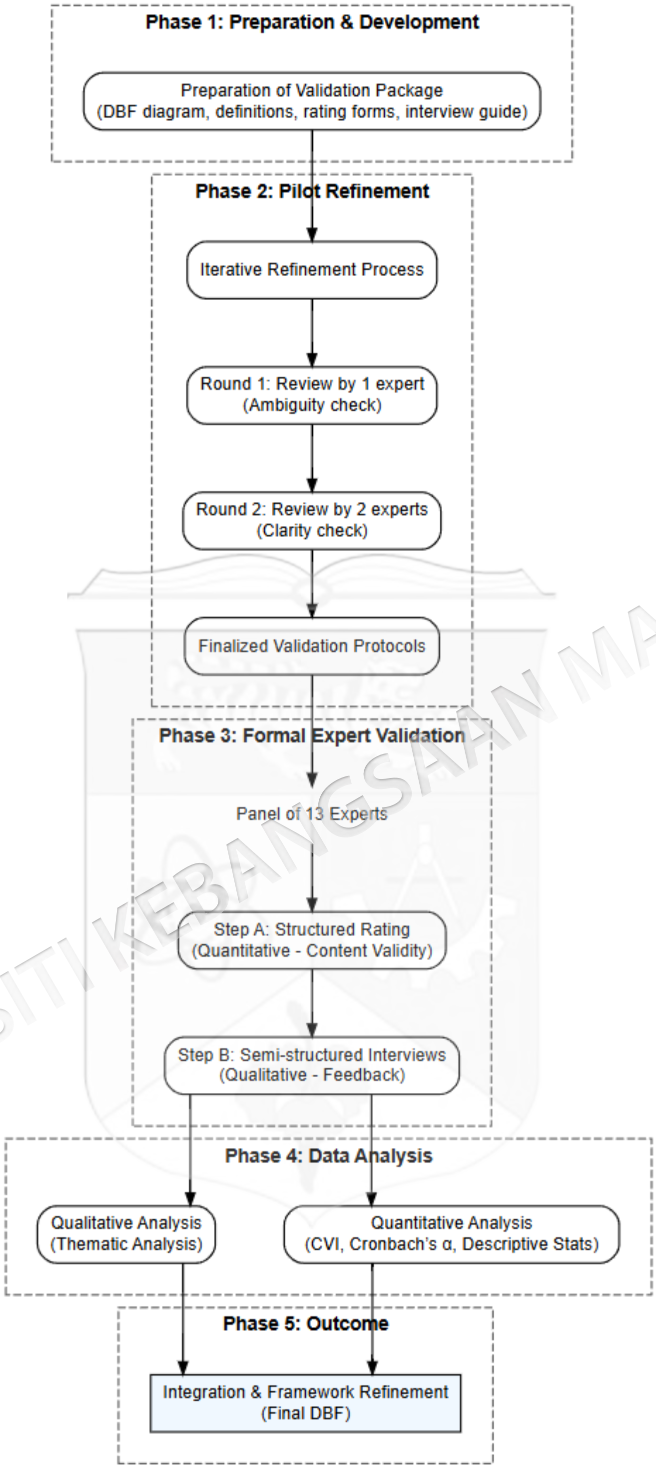

Figure 37 Flowchart of the expert validation procedure for the Dynamic Barrier Framework.

3.6.4 Data Analysis

Qualitative Analysis: The interview recordings were transcribed verbatim. A thematic analysis was conducted to identify recurrent themes, refinement suggestions, and points of consensus or disagreement across experts, which were used to interpret quantitative patterns and guide framework revisions.(Danaei et al. 2022; Hoseini-Esfidarjani et al. 2021).

Quantitative analysis. Experts' ratings (1–4 scale) were summarized at the evaluation-block level (e.g., the three sequential stage blocks and cross-cutting components). For each block, mean ratings (M) and dispersion statistics (SD, median, min–max) were computed by first averaging item ratings within the block for each expert and then averaging across the expert panel (N = 13). Scale-level content validity (S-CVI) was computed for each block as the proportion of all ratings that were ≥ 3 (endorsed as acceptable) across items and experts. Internal consistency within each block was examined using Cronbach's α, calculated across the items within the block.

The S-CVI values were interpreted using the conventional logic that higher proportions of ratings at or above the acceptable threshold indicate stronger expert agreement on clarity, relevance, and representativeness.

The qualitative themes and quantitative CVI results were integrated to form a comprehensive evaluation of the DBF. Components showing relatively lower CVI/mean ratings and those repeatedly highlighted in interviews were prioritized for refinement. The finalized DBF presented in the Results chapter was produced by iteratively revising definitions, stage boundaries, cross-stage mechanisms, and the framework visualization based on the integrated evidence.

All participants provided written informed consent prior to participation and were informed of the study procedures, potential risks (including cybersickness), and their right to withdraw at any time without penalty. Participant data were anonymised using coded identifiers and stored securely on a password-protected server accessible only to the research team. Participation was voluntary, and small gifts were provided as tokens of appreciation.

3.7 Hypothesis

Guided by the Dynamic Barrier Framework (DBF) developed from Experiments A and B, this dissertation specifies the following phase-linked hypotheses to be examined in Chapter 4.

Although the hypotheses are phase-linked rather than purely variable-driven, each hypothesis specifies the expected direction between a dominant barrier domain and the relevant engagement or attrition outcome.

H1 (Initial contact: Physiological burden). Greater physiological discomfort (VRSQ) is associated with less favorable immediate experience during initial contact (e.g., lower positive affect and/or higher withdrawal risk).

H2 (Long-term Use: Motivational maintenance). More favorable motivational appraisals during repeated use (e.g., higher competence and challenge fit) are associated with stronger sustained positive experience and continued participation.

H3 (Decision Transition: Socio-psychological readiness). Greater social trust/support (e.g., stronger social ties) is associated with a higher likelihood of committing to the longitudinal phase (Experiment B).

H4 (Cross-phase linkages). Physiological burden is positively associated with anxiety/concern indicators (Relationship A) and is negatively associated with motivational maintenance over time (Relationship B), whereas socio-psychological trust/support facilitates commitment and persistence (Relationship C).

Collectively, these hypotheses reflect the DBF’s phase-structured logic: physiological barriers dominate early filtering, socio-psychological factors condition the commitment transition, and motivational factors govern long-term engagement. The empirical tests reported in Chapter 4 draw on convergent quantitative and qualitative evidence aligned with these phase-specific predictions. This conceptual logic and the hypothesized relationships across the three phases are visualized in Figure 38.

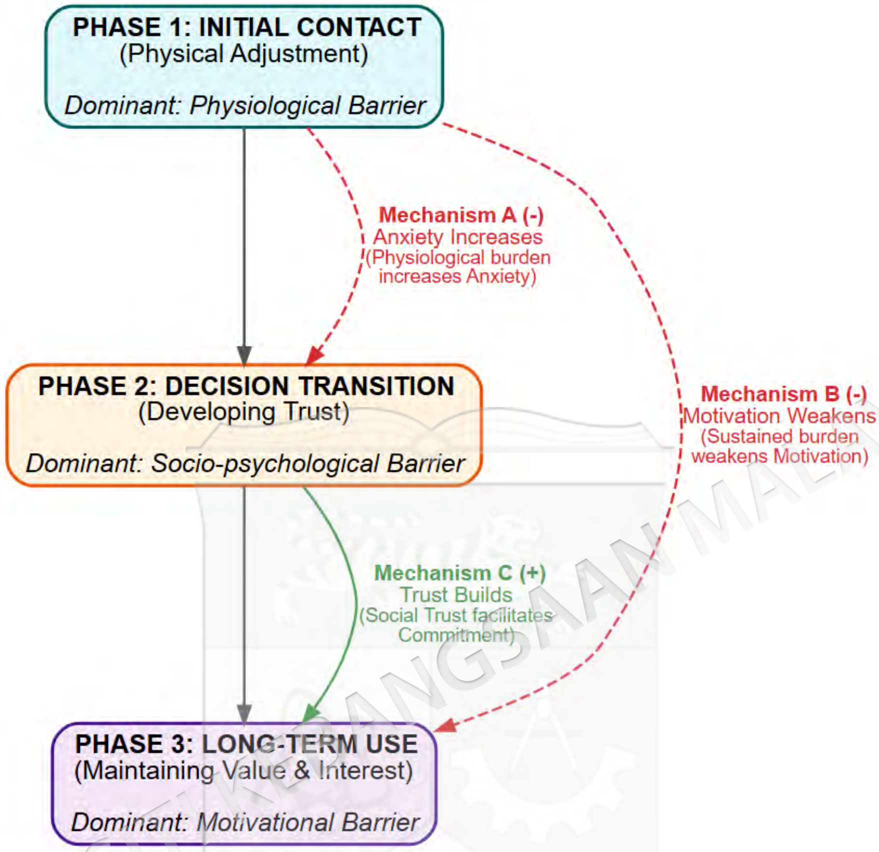

Figure 38 Dynamic Barrier Framework (DBF): phase-structured mechanisms linking initial discomfort, trust formation, and long-term engagement in immersive exergaming.

Note. Solid arrows indicate the sequential adoption phases (Phase 1 → Phase 2 → Phase 3). Dashed arrows represent cross-phase mechanisms inferred from convergent evidence: Mechanism A (–), physiological burden increases anxiety during the decision transition; Mechanism B (–), sustained physiological burden weakens motivation over time; Mechanism C (+), social trust facilitates commitment and supports long-term use. “Dominant” denotes the barrier domain most salient at each phase.

3.8 Summary

This chapter described the methodology adopted to examine older adults’ engagement and attrition in immersive exergames delivered through Virtual Reality (VR) and Mixed Reality (MR), and to develop and validate the Dynamic Barrier Framework (DBF). Aligned with the three research objectives, the study employed a multistage approach that combined two user experiments with systematic framework development and expert evaluation. Across all stages, the methodology was designed to capture both observable participation patterns and the process-level reasons that shaped discontinuation over time.

To address RO1, the chapter detailed the procedures and data sources used in Experiment A (Initial Contact) and Experiment B (Repeated Exposure) to document dropout timing and withdrawal reasons across VR and MR conditions. Data collection integrated participants' stated withdrawal reasons, brief interview clarifications when available, and researcher field notes, supporting consistent documentation of discontinuation experiences. Ethical approval and informed consent procedures were also specified, together with confidentiality measures and secure data handling.

To address RO2 and RO3, the chapter explained how discontinuation experiences were translated into barrier constructs through an iterative coding protocol supported by operational definitions, and how a barrier by phase evidence matrix was constructed to support phase-wise synthesis. On the basis of this integrated evidence, the DBF articulated three phases of attrition, Phase 1 Physical Adjustment, Phase 2 Developing Trust, and Phase 3 Maintaining Value and Interest, and organised withdrawal mechanisms into physiological, socio-psychological, and motivational barriers. The chapter concluded by outlining the expert evaluation procedure used to assess the framework's clarity and relevance, providing the methodological foundation for the results presented in Chapter 4.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Introduction

Chapter 4 presents the empirical results and integrative analysis of this study, following the logic of exploration, construction, and validation (see Table 25). It first reports the findings of Experiment A (Initial contact) and Experiment B (Repeated Exposure), which together address RO1 by identifying and tracking the barriers influencing user adoption across different phases. The results reveal a progressive shift in dominant barriers from Physiological to Socio-psychological to Motivational providing the empirical foundation for RO2. Building on these findings, the chapter constructs the Dynamic Barrier Framework, a process-oriented model that explains how barrier salience and interrelations evolve through the phases of Initial contact, Decision Transition, and Long-term Use. Finally, the chapter reports the validation of RO3, assessing the framework's clarity, coherence, and practical relevance through expert evaluation. Overall, Chapter 4 links empirical evidence to theoretical development, establishing a coherent foundation for the subsequent validation and discussion.

Table 25 Overview of Chapter IV (Results and Discussion)

Section & Title	Content Summary	Output
4.1 Introduction	Outlines the "explore–construct–validate" logic of the chapter, showing how empirical results (RO1) inform the framework (RO2) and set up validation (RO3). Provides a roadmap for the chapter.	Chapter structure and reading guide.
4.2 Experiment A – Initial contact (RO1)	Reports Experiment A (single-session, N=86 → N=70). Covers scale properties, subjective experience, physiological comfort (VRSQ), and performance. Identifies the Physiological Barrier as the primary early-stage filter (18.6% attrition).	Key finding: physiological intolerance filters initial adoption; establishes the role of physiological adaptation at first contact.
4.3 Discussion (Experiment A: Initial Contact)	Interprets Experiment A findings, emphasizing first-contact usability, physiological comfort, early attrition, and the role of physiological intolerance as an initial adoption filter.	Discussion of Experiment A findings and design implications for first-contact adoption.
4.4 Experiment B – Repeated Exposure (RO1)	Reports Experiment B (multi-session, N=35), including participant characteristics, final experience and comfort outcomes, intergroup comparisons, correlations, regression, and learning trajectories.	Key finding: repeated exposure clarifies sustained-use experience, motivational predictors, and VR/MR learning trajectories.
4.5 Discussion (Experiment B: Repeated Exposure)	Interprets Experiment B findings, including the immersion paradox, comparable VR/MR comfort outcomes, and the importance of competence and challenge for sustained positive affect.	Discussion of repeated-exposure findings and bridge to framework construction.
4.6 Framework Construction (RO2)	Integrates Experiment A and Experiment B findings to construct the Dynamic Barrier Framework, with three phases and cross-phase interrelations.	Formal proposal of the Dynamic Barrier Framework, addressing RO2.
4.7 Framework Validation (RO3)	Reports the RO3 expert-validation results (N = 13), integrating quantitative ratings (M, S-CVI, Cronbach's α) and qualitative feedback.	Validation evidence supporting the DBF's clarity, coherence, content validity, and practical relevance.
4.8 Conclusion	Synthesizes Chapter 4 findings and links RO1–RO3 to the broader conclusions in Chapter 5.	Chapter conclusion and transition to Chapter 5.

To clarify the analytic samples used throughout Chapter 4, Table 26 summarizes participant flow and attrition across Experiment A, the transition to Experiment B, and the repeated-exposure phase. This overview provides the denominator for the Ns reported in Sections 4.2–4.5 and shows where withdrawals occurred at each stage. The staged pattern of attrition is consistent with the study's focus on how barrier salience can shift from initial contact to longer-term use.

The steep reduction from Experiment A completion to Experiment B participation is therefore interpreted as evidence of a continuation-decision barrier, not merely as ordinary sample loss.

Table 26 Participant Funnel Analysis for the "Three Barriers" Filtering Model

Stage	Description	Count	Details / Conversion Rate
Start	Total participants entering Experiment A	86	100% of initial participants
Experiment A	Did not complete Experiment A	16	Details: 14 for Physiological reasons, 2 for Socio-psychological
	Completed Experiment A	70	Completion Rate: 81.4% (70 / 86)
Transition	Did not proceed to Exp. B after completing A (Attrition)	30	42.9% attrition from Exp. A completers (30 / 70)
	Proceeded to Experiment B (Conversion)	40	57.1% conversion rate from Exp. A to B (40 / 70)
Experiment B	Did not complete Experiment B	5	Details: 2 for Physiological reasons, 3 for Motivational reasons
Final Outcome	Successfully completed all experiments	35	Final overall completion rate is 40.7% (35 / 86)

4.2 Experiment A: Initial Contact

4.2.1 Psychometric Properties Of Outcome Scales

Internal consistency was evaluated on the present sample using Cronbach's α and Spearman–Brown split-half coefficients. Because several components (Tension/Annoyance, Challenge, Negative Affect) exhibited pronounced floor effects with near-zero variance, internal consistency coefficients for these scales were not estimable; for these, we report distributional summaries only. Reliability results for all measures are shown in Table 27. Per the GEQ guideline, we dropped the story-related Immersion item (#3), leaving five items for this component; reliability values in Table

27 reflect this adapted set. These reliability results guided the interpretation of the subsequent findings: reliable subscales were used as more stable indicators, whereas floor-effect subscales were interpreted descriptively and not over-emphasized.

Table 27 Internal Consistency of GEQ and VRSQ Subscales

Measure	**k (items)**	**Cronbach's α**	**Split-half (Spearman–Brown)**
Competence	5	0.667	0.750
Sensory & Imaginative Immersion	5	0.657	0.583
Flow	5	0.546	0.539
Tension/Annoyance	3	NA (floor effect)	NA (floor effect)
Challenge	5	NA (floor effect)	NA (floor effect)
Negative Affect	4	NA (floor effect)	NA (floor effect)
Positive Affect	5	0.860	0.850
VRSQ total	9	0.782	0.689

Note. k = number of items in the subscale. Cronbach's α and split-half reliability (Spearman–Brown coefficient) indicate internal consistency, with higher values reflecting better reliability. NA indicates that the reliability estimate could not be computed due to a floor effect (i.e., responses clustered at the lowest score, resulting in insufficient variance). Superscripts (e.g., b) follow the original scale specification/footnote in the thesis.

In total, 86 older adults were recruited; 16 (18.6%) discontinued during acclimation due to intolerance, and data from 70 participants were analyzed. Per-condition medians (IQRs) for the four cells are available in Table 29.

Scale reliability. Internal consistency was good for Positive Affect (α = .860; split-half = .850) and acceptable for the VRSQ total (α = .782; split-half = .689). Competence (α = .667; split-half = .750) and Sensory/Imaginative Immersion (α = .657; split-half = .583) were in the moderate range, whereas Flow was borderline (α = .546; split-half = .539). Coefficients for Tension/Annoyance, Challenge, and Negative Affect were not estimable due to floor effects (near-zero variance). See Table 27.

These coefficients indicate that the strongest scales supported direct interpretation, whereas moderate or borderline coefficients were interpreted cautiously and in conjunction with distributional patterns and behavioral indicators.

Prior to the main analysis, the assumption of normality for the key dependent variables was assessed using the Shapiro–Wilk test. The results are detailed in Table 28. While a few indicators did not significantly deviate from normality (e.g., Challenge $p = .156$; game log Score $p = .062$; Posture $p = .060$; Movement Distance (m) $p = .286$), the majority of variables substantially deviated (e.g., Accuracy $p = .032$; most GEQ/VRSQ dimensions $p < .001$). Therefore, to maintain consistency and ensure robust inference across all analyses, nonparametric procedures were uniformly adopted.

Table 28 Shapiro–Wilk Test of Normality for GEQ Dimensions, VRSQ Symptoms, and Game Performance Indicators

	W	***n***	***p***
Overall GEQ Dimension Score			
Competence	0.798	70	<.001
Sensory and Imaginative Immersion	0.777	70	<.001
Flow	0.719	70	<.001
Tension/Annoyance	0.275	70	<.001
Challenge	0.974	70	.156
Negative Affect	0.573	70	<.001
Positive Affect	0.551	70	<.001
VRSQ Main Symptom			
General discomfort	0.205	70	<.001
Fatigue	0.28	70	<.001
Headache	0.158	70	<.001
Eye fatigue	0.431	70	<.001
Difficulty concentrating	0.153	70	<.001
Head fullness	0.346	70	<.001
Blurred vision	0.349	70	<.001
Dizziness when closing eyes	0.512	70	<.001
Dizziness/Vertigo	0.494	70	<.001
Key Game Performance			
Score	0.967	70	.062

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Posture	0.967	70	.06
Accuracy	0.962	70	.032
Average Time Spent	0.796	70	<.001
Movement Distance (m)	0.979	70	.286

Note. W = Shapiro–Wilk test statistic; n = sample size; p = p-value. A smaller W generally indicates greater deviation from normality. For the Shapiro–Wilk test, $p < .05$ suggests a departure from normality.

4.2.2 Descriptive Statistics

We report per-condition descriptive statistics for key outcomes across the 2×2 design (VR/MR × feedback intensity). As planned, no between-condition inferential tests were conducted; values are summarized as median [IQR] for interpretability with non-normal distributions. See Table 29 for the four cells.

Table 29 Per-condition descriptive statistics (Median (IQR))

Outcome	Group A:VR-Soothing (n=17)	Group C: VR-Intense (n=19)	Group B: MR-Soothing (n=17)	Group D: MR-Intense (n=17)
Positive Affect	4(3.8–4)	4(3.8–4)	4(3.4–4)	4(3.8–4)
Flow	4(3.2–4)	3.8(3.6–4)	4(3.2–4)	4(3.2–4)
Competence	3.6(3.1–4)	3.8(3.2–4)	3.6(3.4–4)	4(3.3–4)
Challenge	1.4(1.2–1.6)	1.4(1–1.8)	1.6(1.1–1.7)	1.6(0.8–1.7)
VRSQ Total	0(0–1)	0(0–2)	0(0–1.5)	0(0–2)
Accuracy (%)	75(56–84)	65(54–81)	65(54–77)	79(54–94)

Note. Values are median [IQR]. Per-condition n shown in column headers. No inferential tests were planned; descriptive summaries only.

4.2.3 Overall Usability And Acceptability Of The VR Tai Chi Game

To evaluate the overall usability and acceptability of the VR Tai Chi game for older users, this study collected and analyzed survey data from GEQ, VRSQ, and objective game performance log data.

4.2.4 Subjective Game Experience (GEQ)

As reflected in Table 30, subjective gaming experience picked up by the GEQ was highly positive. Median levels on positive aspects like "Positive Affect" (*Mdn* = 4.0), "Flow" (*Mdn* = 4.0), "Competence" (*Mdn* = 3.8), and "Sensory/Imaginative Immersion" (*Mdn* = 3.8) all far surpassed the theoretical midpoint of the scale ($p < .001$ in all). Medians on negative aspects like "Tension/Annoyance" (*Mdn* = 0) and "Negative Affect" (*Mdn* = 0) were below midpoint to a statistically significant degree ($p < .001$ in both). Median level on "Challenge" was low to a statistically significant degree as well (*Mdn* = 1.4, $p < .001$).

Table 30 Descriptive Statistics and One-Sample Wilcoxon Signed-Rank Test for GEQ Dimensions

Dimension	**Median (IQR)**	***p***
Competence	3.8(3.2–4)	<.001
Sensory/Imaginative Immersion	3.8(3.2–4)	<.001
Flow	4(3.2–4)	<.001
Tension/Annoyance	0(0–0)	<.001
Challenge	1.4(1–1.6)	<.001
Negative Affect	0(0–0.25)	<.001
Positive Affect	4(3.8–4)	<.001

Note. GEQ scores were rated on a 0–4 scale. p-values reflect a one-sample Wilcoxon signed-rank test comparing the median score against the theoretical midpoint of 2.0. IQR = Interquartile Range.

4.2.5 Physiological Comfort (VRSQ)

The physiological comfort of the screened participants was assessed using the VRSQ. Overall, the incidence and severity of reported symptoms were low. Detailed item-level medians, statistical test results, incidence rates, and severity scores for reporters are presented in Table 31. The *p*-values in the table should be interpreted as exploratory signals of which symptoms were most frequently endorsed, rather than as confirmatory hypothesis tests.

Table 31 Overall VRSQ Main Symptom Statistical Analysis

Symptom Item	**Median**	***p***	**Incidence Rate**	**Mean Severity for reporters**
General discomfort	0(0–0)	.083	4.3%	1
Fatigue	0(0–0)	.038	7.1%	1.4
Headache	0(0–0)	.157	2.9%	1
Eye fatigue	0(0–0)	.002	15.7%	1.273
Difficulty concentrating	0(0–0)	.18	2.9%	1.5
Head fullness	0(0–0)	.014	10.0%	1.286
Blurred vision	0(0–0)	.011	10.0%	1.143
Dizziness when closing eyes	0(0–0)	<.001	20.0%	1.214
Dizziness/Vertigo	0(0–0)	<.001	18.6%	1

Note. Median values are presented as median (IQR), where IQR is the interquartile range. Incidence rate indicates the percentage of participants who reported the symptom (i.e., symptom score > 0). Mean severity for reporters is the mean symptom severity calculated only among participants who reported the symptom (score > 0). p values are reported for the comparison test of symptom severity (two-tailed), with $p < .05$ indicating statistical significance.

4.2.6 Game Performance

A look at the in-game objective performance data listed in Table 32 reveals wide individual variations among older adult participants. Participants demonstrated a fluid rhythm of interaction with a median time spent per action of 6.4 s. However, large variations across major indicators were apparent due to wide interquartile ranges seen across Score and Accuracy measurements. Median movement accuracy was 68.5% (IQR 54.2–82.3%). Scores higher than 48 indicate participants completed more than a single loop (or accrued numerous hot-spot holds within movement) within a 5-min time period.

Table 32 Key Game Performance Indicators

Indicator	**Median**
Score	96(70.25–133.5)
Posture (count; no fixed cap, 48 = one loop)	47(39.75–55)
Accuracy (%)	68.5(54.2–82.3)
Average Time Spent (s)	6.4(5.5–7.5)
Movement Distance (m)	273.5(231.5–317.25)

Note. Values are presented as median (IQR), where IQR denotes the interquartile range. Accuracy is expressed as percentage (%). Average Time Spent is measured in seconds (s). Movement Distance is measured in meters (m). Posture represents the total count of correct posture detections; one loop corresponds to 48 posture events, with no fixed upper limit.

4.2.7 Correlation Analysis Of Key Usability Factors

Correlation between major usability factors was examined using Spearman's rank correlation analysis, and results were presented in Table 33. Flow was positively significantly correlated with Accuracy (ρ = .342, *P* = .004) and Competence was positively significantly correlated with Accuracy (ρ = .322, *P* = .007). VRSQ total score was significantly inversely correlated to Positive Affect (ρ = -.334, *P* = .005). Competence was not significantly correlated with Age (ρ = -0.179, *P* = .14).

Table 33 Spearman Rho Correlation Analysis (n=70)

Hypothesis	Variable 1	Variable 2	Correlation Coefficient	*P* Value
H1	Flow	Accuracy	.342**	.004
H2	VRSQ Total Score	Positive Affect	-.334**	.005
H3	Accuracy	Competence	.322**	.007
H4	Age	Competence	-0.179	.14

Note. Correlation coefficients represent Spearman's rho (ρ). n = sample size. p values are two-tailed. ** indicates statistical significance at $p < .01$.

4.3 Discussion (Experiment A: Initial Contact)

Experiment A provides a clear "first-contact" usability profile for the VR/MR Tai Chi exergame among community-dwelling older adults who successfully completed acclimation. Across the screened sample, subjective experience was strongly positive, with high perceived competence and positive affect alongside notably low challenge, suggesting that the interaction demands were accessible during initial contact and that the design successfully avoided early frustration. At the same time, this "high competence–low challenge" pattern should be interpreted as a deliberate early-stage engagement signature rather than evidence of optimized training intensity, because overly low challenge can limit skill progression if it persists across later sessions. The absence of a significant association between age and perceived competence within the studied range is encouraging for inclusivity, implying that older age in itself did not systematically erode self-efficacy during first use.

Theoretically, this pattern can be interpreted through Self-Determination Theory and Flow Theory. The high perceived competence observed during initial contact suggests that the exergame successfully supported older adults' sense of capability, which is central to intrinsic motivation in SDT. However, the simultaneously low level of perceived challenge indicates that the system was more effective as an onboarding and confidence-building tool than as a fully optimized training environment. From a Flow Theory perspective, sustained engagement would require a progressive balance between users' growing skill and the difficulty of the task. Therefore, the early "high competence–low challenge" profile should be understood as beneficial for first-contact trust and confidence formation, but it also highlights the need for adaptive challenge calibration in later sessions.

Physiological comfort, however, emerged as the most consequential gatekeeper in the earliest phase of adoption. Although the analyzed sample reported low cybersickness overall, the initial attrition during acclimation (16/86; 18.6%) indicates a substantial "tolerance filter," meaning the post-screening comfort estimates likely overstate what would be observed in an unselected older adult population. Even among those retained, a non-trivial minority still reported mild symptoms (e.g., dizziness/vertigo and eye fatigue), which matters in the intended home-based scenario where users may lack immediate supervision. Practically, these results argue that successful deployment depends less on marginal gains in enjoyment and more on systematic mitigation strategies, screening guidance, short ramp-up sessions, stable headset fit and performance, and easily accessible comfort settings, so that early discomfort does not become an avoidable cause of dropout.

A further design tension emerged between objective movement accuracy and perceived competence. Median movement accuracy (68.5%) fell below the exploratory internal benchmark (80%), yet perceived competence remained high, consistent with a permissive scoring rule that rewards partial hotspot matches. This trade-off can be advantageous for first-time engagement, supporting confidence and reducing anxiety, yet it also raises a validity question for skill-oriented training if perceived competence drifts too far from verifiable performance. Importantly, the correlational pattern suggests that accuracy still matters psychologically: higher accuracy was associated with stronger flow and competence, while greater physiological discomfort was linked to reduced positive affect. Together, these findings motivate a refinement strategy that preserves motivational "safety nets" while progressively tightening performance feedback (e.g., adaptive multi-point matching, clearer corrective cues, and optional guidance tiers), thereby aligning enjoyment, comfort, and measurable movement quality for sustainable independent use.

The competence finding should not be interpreted as reduced effort; rather, it likely reflects supportive onboarding and lenient scoring that helped first-time users maintain confidence despite imperfect movement accuracy.

4.4 EXPERIMENT B: REPEATED EXPOSURE

4.4.1 Preliminary Analysis: Participant Characteristics And Data Distribution

Data from 35 participants (n = 18 in the VR group; n = 17 in the MR group) were included in the final analysis. No baseline characteristics (gender, education, exercise intensity, health status, age group, smartphone-use, height group, or initial BBS) differed significantly between the two groups. Categorical variables were tested with Pearson's χ^2 (or Fisher's exact test when expected cell counts were < 5), and the continuous variable (BBS) with the Mann–Whitney U test.

The Shapiro-Wilk test for normality of the key dependent variables showed that the data for most variables, including scores from the GEQ and the VRSQ, were not normally distributed ($p < .05$); therefore, nonparametric tests were used for the subsequent analyses (see Table 34). Notably, Tension–Annoyance exhibits a pronounced floor effect (median = 0, IQR = 0–0; see Table 35), which explains its very low Shapiro–Wilk statistic ($W = 0.161$).

Table 34 Normality test of key dependent variables (Shapiro–Wilk test)

	W	**N**	***p***
Game Score Variables			
Average Accuracy Rate	0.874	35	<.001
Activity Volume	0.96	35	0.234
Average Time Spent (s)	0.705	35	<. 001
GEQ Variables			
Competence	0.84	35	<. 001
Sensory and Imaginative Immersion	0.9	35	0.004
Flow	0.85	35	<. 001
Tension–Annoyance	0.161	35	<. 001
Challenge	0.946	35	0.086
Negative Affect	0.846	35	<. 001
Positive Affect	0.7	35	<. 001
VRSQ Total Score	0.812	35	<. 001

Note. W = Shapiro–Wilk test statistic; N = sample size; p = p-value. A smaller W and $p < .05$ indicate departure from normality.

Descriptive statistics for the full sample (N = 35) on the final measures are presented in Table 35. e.g., the median score for Positive Affect was 4.0, while the median score for the VRSQ total score (Physical Discomfort) was 1.0.

Table 35 Descriptive statistics of final measurement indicators (N = 35)

GEQa	
	Median
Competence	3.6(2.8–4)
Sensory and Imaginative Immersion	3.2(2.6–3.8)
Flow	3.2(2.6–4)
Tension–Annoyance	0(0–0)
Challenge	1.2(0.8–1.6)
Negative Affect	0.25(0–0.75)
Positive Affect	4(3.4–4)
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VRSQb	
	Median
VRSQ total score	1(0–4)
Game Scores	
	Median
Average Accuracy Rate	89%(80.67%–94.67%)
Activity Volume	899(786–990)
Average Time Spent (s)	4.90 (4.60–5.57)

Note. Values are presented as median (IQR), where IQR denotes the interquartile range. $N = 35$. Accuracy is expressed as percentage (%), and Average Time Spent is measured in seconds (s).

4.4.2 Intergroup Comparison: User Experience And Cybersickness Symptoms (VRSQ)

After applying Holm–Bonferroni correction, we found that the VR group reported substantially higher scores than the MR group for both Flow (U = 293.5, adjusted p < .001, $r_{rb} = -0.918$, 95% CI [–0.962, –0.831]) and Sensory and Imaginative Immersion (U = 291.0, adjusted p < .001, $r_{rb} = -0.902$, 95% CI [–0.954, –0.799]). In contrast, we observed no statistically significant differences between modes for positive affect (U = 200.0, adjusted p = .440, $r_{rb} = -0.307$, 95% CI [–0.608, 0.071]) or cybersickness symptoms (VRSQ: U = 165.5, adjusted p = 1.000, $r_{rb} = -0.082$, 95% CI [–0.438, 0.297]) showed no statistically significant between-mode differences (see Table 36). These between-mode effects are visualized in Table 36, which highlights the markedly higher Flow and Sensory–Imaginative Immersion scores in the VR group, whereas Positive Affect and VRSQ scores did not differ significantly.

Table 36 Comparison of final measurement indicators between VR and MR groups (Mann-Whitney U test)

GEQ Variables	**VR (*n* =18)**	**MR (*n* =17)**	**U**	**Effect Size (r_{rb})**	**95% CI**	**Adjusted *p***
Competence	3.8 (3–4)	3.6 (2.5–3.8)	191	-0.248	[-0.595, 0.134]	1
Sensory and Imaginative Immersion	3.8 (3.6–4)	2.6 (2.2–2.9)	291	-0.892	[−0.954, −0.799]	<. 001*
Flow	4 (3.8–4)	2.6 (1.8–3)	293.5	-0.918	[−0.962, −0.831]	<. 001*
Tension–Annoyance	0 (0–0)	0 (0–0)	-	-	-	-
Challenge	1.2 (1–1.65)	1.4 (0.7–1.6)	166	-0.085	[-0.441, 0.294]	1
Negative Affect	0.5 (0–0.75)	0.25 (0–0.5)	162	-0.098	[-0.419, 0.319]	1
Positive Affect	4 (3.7–4)	3.8 (3–4)	200	-0.307	[-0.608, 0.071]	0.44
VRSQ Variable	VR[c] (*n* = 18)	MR[d] (*n* = 17)	U	Effect Size (r_{rb})	95% CI	Adjusted p
VRSQ total score	1.5 (0–4)	1 (0–2.5)	165.5	-0.082	[-0.438, 0.297]	1

Note. Values are median (IQR). U = Mann–Whitney U statistic. Effect size ($r_{(rb)}$) represents the rank-biserial correlation. 95% CI = 95% confidence interval. Adjusted p values are two-tailed and corrected for multiple comparisons. VR (n = 18); MR (n = 17).

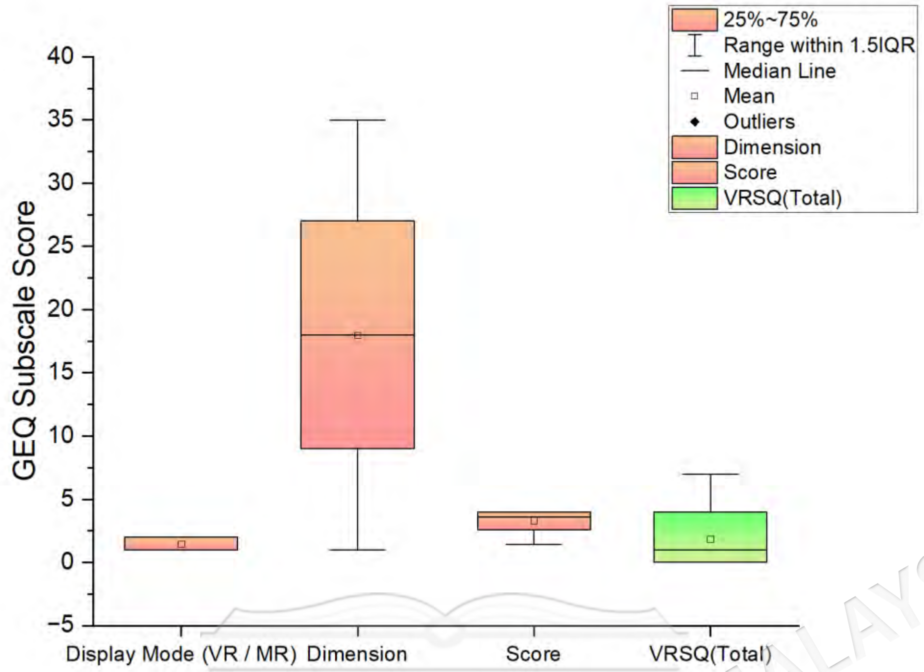

Figure 39 Comparison of GEQ and VRSQ scores between VR and MR groups.

4.4.3 Correlation Analysis

To explore the relationships between variables, this study performed a Spearman rank correlation analysis on all final measurement indicators (see Table 37 and Figure 40). The analysis showed that positive affect was significantly and positively correlated with competence (r_s = *.407, p* = *.015*), sensory and imaginative immersion (r_s = *.573, p* < *.001*), and flow (r_s = *.424, p* = *.011*). As visualized in Figure 40, the heatmap provides an intuitive overview of the interrelationships among all indicators, where warmer colors represent stronger positive correlations and cooler colors indicate negative ones.

As one of the core experience dimensions, competence was significantly associated with better objective performance (Average Accuracy Rate: r_s = *.408, p* = *.015*), less time spent in the game (Average Time Spent: r_s = −*.477, p* = *.004*), and lower cybersickness symptoms (VRSQ total score: r_s = −*.512, p* = *.002*). These relationships, especially the negative associations with VRSQ and Average Time Spent, are visually evident in the blue-shaded regions of Figure 40. A smaller negative correlation was also observed with Challenge (see Table 37 and Figure 40).

In the end, competence (β = .785, $p < .001$) and challenge (β = .633, $p < .001$) remained the strongest predictors, indicating that subjective experiential dimensions, rather than objective performance indicators, were more strongly associated with final positive affect. The substantial explanatory power of Model 1 (Adjusted $R^2 = .459$) suggests that motivational experience accounted for a meaningful proportion of older adults' positive feelings, whereas adding objective performance variables contributed little additional explanation ($\Delta R^2 = .038$, $p = .515$).

Table 37 Spearman correlation analysis among final measurement indicators

Variable	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Competence	–										
Sensory and Imaginative Immersion	.523*	–									
Flow	.479*	.834*	–								
Tension–Annoyance	-.078	.077	.052	–							
Challenge	-.386*	.023	-.044	-.111	–						
Negative Affect	.013	.119	-.069	.070	-.196	–					
Positive Affect	.407*	.573*	.424*	-.075	.245	-.033	–				
VRSQ Total Score	-.512*	-.214	-.216	.179	.361*	-.191	-.047	–			
Average Accuracy Rate	.408*	.010	-.014	-.068	-.528*	.191	.033	-.370*	–		
Activity Volume	.027	-.280	-.128	-.153	-.516*	.324	-.340*	-.409*	.315	–	
Average Time Spent (s)	-.477*	.035	-.008	.272	.370*	-.147	-.056	.433*	-.621*	-.397*	–

Note. Values represent Spearman's rank correlation coefficients (ρ). $N = 35$. All p values are two-tailed. $p < .05$ indicates statistical significance.

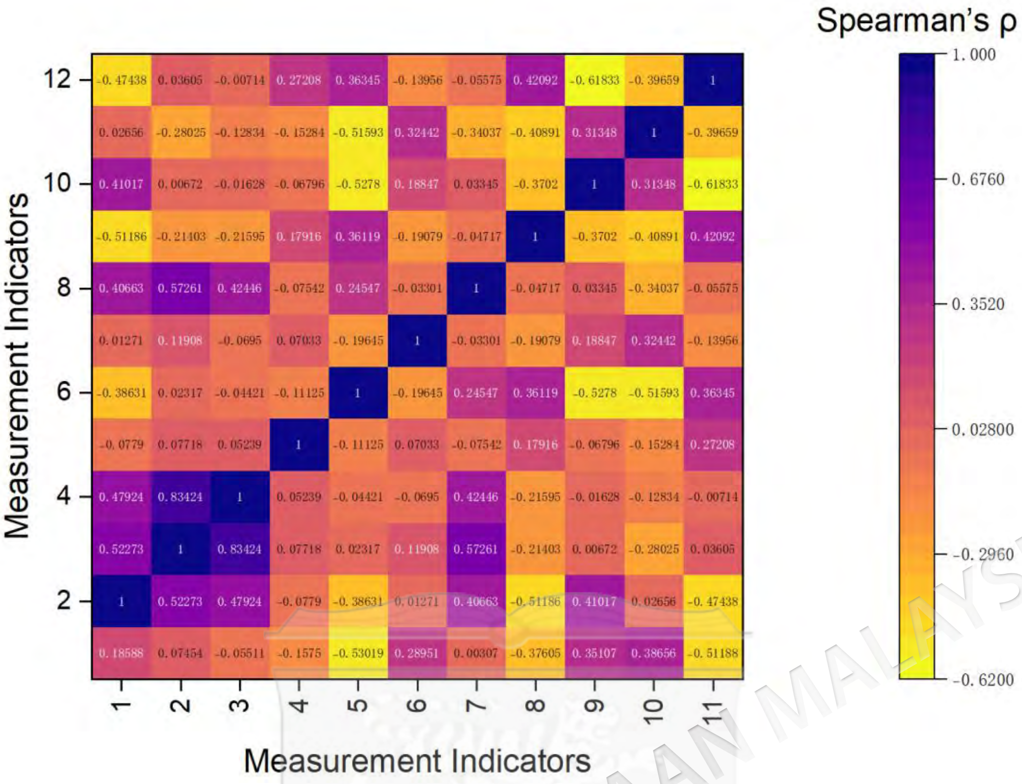

Figure 40 Spearman correlation heatmap among final measurement indicators (*N* = 35)

To identify predictors of positive feelings, a stepwise (hierarchical) multiple regression analysis was conducted (see Table 38 for details). The first model, incorporating both competence and challenge, strongly predicted positive feelings (Adjusted $R^2 = 0.459$, $p < 0.001$). To test a different idea, basic performance scores were included in a second step; however, these additions did not significantly improve the model ($\Delta R^2 = 0.038$, $p = 0.515$). In the end, competence ($\beta = .785$, $p < .001$) and challenge ($\beta = .633$, $p < .001$) remained the strongest predictors, indicating that subjective experiential dimensions, rather than objective performance indicators, were more strongly associated with final positive affect.

Table 38 Multiple regression analysis predicting positive affect (exploratory)

Predictor	**Model 1**	**Model 2**
	β	*β*
Block 1: Core Predictors		
Tech Mode (VR vs. MR)	-0.122	-0.159
Competence	.709*	.785*
Challenge	.646*	.633*
Block 2: Objective Performance		
Average Accuracy Rate		0.139
Average Time Spent (s)		0.16
Activity Volume		0.148
Model Summary		
R^2	0.507	0.545
Adjusted R^2	0.459	0.448
ΔR^2		0.038
F for ΔR^2		0.701
p for ΔR^2		0.515

Note. β represents standardized regression coefficients. Model 1 includes core predictors (tech mode, competence, and challenge). Model 2 additionally includes objective performance variables. R^2 = coefficient of determination; ΔR^2 = change in explained variance between models. F for ΔR^2 tests the significance of the incremental variance explained. All tests are two-tailed. * indicates $p < .05$.

As shown in Table 39, linear mixed-effects models revealed significant practice effects across sessions, with Accuracy improving ($F(2, 39.95) = 4.291$, $p = .021$) and a marginal decrease in Average Time Spent ($F(2, 29.63) = 3.213$, $p = .055$). Activity Volume remained stable ($p = .978$). No significant main effects or interactions involving Mode were observed (all $p > .13$), indicating that both VR and MR groups exhibited comparable learning trajectories over the six-session intervention.

Table 39 Summary of linear mixed-effects models for the three performance indices

Dependent variable	Effect	*df*	*F*	*p*
Average Time	Mode	1, 87.84	2.145	0.147
	Day	2, 29.63	3.213	0.055
	Mode * Day	2, 74.60	0.067	0.935
Accuracy	Mode	1, 75.68	0.048	0.827
	Day	2, 39.95	4.291	0.021*
	Mode * Day	2, 72.04	0.193	0.825
Activity Volume	Mode	1, 95.66	2.319	0.131
	Day	2, 64.36	0.022	0.978
	Mode * Day	2, 77.69	0.284	0.754

Note. Results are from linear mixed-effects models. *df* = degrees of freedom (estimated using the Satterthwaite approximation). *F* = F statistic; *p* = two-tailed p-value. Mode refers to technology condition (VR vs. MR); Day refers to measurement day; Mode × Day indicates the interaction effect. * indicates $p < .05$.

4.5 Discussion (Experiment B: Repeated Exposure)

Experiment B examined whether repeated exposure would amplify the advantages often attributed to mixed reality (MR) in older adults' sustained use. The expectation of MR superiority was based on the assumption that partial visibility of the physical environment could reduce isolation and cybersickness concerns while preserving a sense of presence. However, the results did not support the hypothesized superiority of MR on end-of-intervention affective outcomes or comfort. Although the VR mode produced substantially higher flow and sensory–imaginative immersion, these experiential gains did not translate into higher final positive affect, and cybersickness symptoms (VRSQ) were comparable between modes. Importantly, both groups demonstrated similar learning trajectories across the six-session intervention: accuracy improved over sessions, average time spent showed a marginal decline, and activity volume remained stable, with no meaningful mode-related main effects or interactions. Taken together, these findings provide empirical support for an "immersion paradox" in a multi-session context, greater technological immersion can be achieved, yet it does not necessarily yield better sustained affective experience for older users once novelty is no longer the dominant driver.

This pattern suggests that display immersion alone was insufficient to improve sustained positive affect when competence, challenge fit, and perceived value became more important determinants of continued experience.

The predictive models further clarify why these between-mode differences did not emerge at the level of sustained positive affect. Psychological appraisals, particularly perceived competence and perceived challenge, were the only robust predictors of final positive affect, whereas display mode was not a significant predictor. Moreover, adding objective performance indices did not improve model fit, suggesting that what ultimately sustains positive affect is not simply how well users perform, nor how immersive the display appears, but whether repeated interaction continues to support mastery and an appropriate challenge–skill balance. This interpretation aligns with motivational accounts in which sustained engagement depends on users' ongoing sense of capability and meaningful challenge, especially after initial orientation has passed and experience becomes routinized. In practical terms, repeated exposure appears to "move the goalposts": once users can operate the system reliably, the determinants of continued enjoyment shift toward motivation-relevant design qualities rather than hardware modality alone.

These results carry direct implications for designing immersive exergames intended for sustained use. First, optimizing immersion should not be treated as a standalone pathway to long-term engagement; instead, systems should prioritize mechanisms that protect perceived competence while dynamically calibrating challenge over time (e.g., adaptive difficulty, layered goals, and feedback that becomes progressively more informative as skill improves). Second, comfort remains a necessary baseline condition rather than a differentiator in this dataset; when discomfort is present, even mildly, it may undermine users' willingness to invest effort and persist. Finally, the pattern observed here provides a clear bridge to RO2 and the DBF framework: the absence of mode-based advantages in sustained affect, alongside the central role of competence and challenge, indicates that late-phase attrition risk is more plausibly governed by motivational dynamics than by display technology per se. This motivates the subsequent framework construction step, which formalizes how dominant barriers can shift across phases of the adoption journey from initial contact to repeated use.

4.6 Framework Construction

4.6.1 Identifying Core Barriers And Their Interrelationships From Empirical Data

This section synthesizes the empirical findings from Experiment A (Initial contact, Section 4.2) and Experiment B (Repeated Exposure, Section 4.4) to identify the core barriers influencing older adults' adoption and attrition journey with the immersive exergame, and to explore the interrelationships between these barriers. The analysis reveals three distinct yet interconnected barriers. The first, termed the Physiological Barrier, emerges prominently during the Initial contact phase. Evidence from Experiment A (Section 4.2.1) showed a substantial initial attrition rate of 18.6% (16 out of 86 participants), with the vast majority (14 out of 16) withdrawing due to acute physical discomfort, primarily symptoms consistent with cybersickness. Statistical comparison confirmed this, as the withdrawn group exhibited significantly higher VRSQ scores compared to those who completed the session ($p < .001$), establishing this bodily response as the primary and most immediate filter.

The barrier-to-phase assignment was based on convergent evidence from dropout timing, stated withdrawal reasons, VRSQ and GEQ patterns, performance logs, and later expert validation, rather than on a single data source.

Table 40 Summary of Core Barriers, Evidence, and Phase Roles

Barrier Type	Operational Definition	Empirical Evidence (source & stats)	Dominant Phase & Main Manifestations
Physiological Barrier	Body-based discomfort and sensory intolerance (e.g., cybersickness) that can force early discontinuation.	Exp A: Attrition 18.6% (16/86); withdrawn group shows markedly higher VRSQ (e.g., $Z = -6.059$, $p < .001$).	Phase: Initial contact (early filter). Manifestations: dizziness, nausea, head/eye strain; physical intolerance.

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Socio-psychological Barrier	Concerns about privacy, safety, risk and interpersonal trust that condition mid-phase commitment.	Exp B: attention to trust/safety increases over sessions; residual physical discomfort correlates with technology anxiety (e.g., $\rho \approx .36, p < .01$).	Phase: Decision transition. Manifestations: hesitation to commit, fear of damaging equipment, reliance on trusted recommendation.
Motivational Barrier	Intrinsic affective-cognitive calculus sustaining long-term use (enjoyment, perceived usefulness, competence/challenge fit).	Exp B: final Positive Affect was predicted by Competence ($\beta = .785$, $p < .001$) and Challenge ($\beta = .633$, $p < .001$), whereas adding objective performance variables did not significantly improve the model ($\Delta R^2 = .038$, $p = .515$).	Phase: Long-term use. Manifestations: decreased interest, perceived lack of value, conflict with routines if motivation not supported.

Once the initial physiological hurdle is navigated, the Socio-psychological Barrier becomes critical, particularly during the transition phase where users decide whether to commit to longer-term engagement. Data from the transition between Experiment A and B (N = 70 to N = 40) revealed that the strength of pre-existing social ties significantly predicted willingness to continue participation (χ^2, $p = .01$). Qualitative data further illuminated this association, contrasting participants' fear of damaging equipment or appearing incompetent against the reassurance provided by trusted recruiters. Thus, this barrier encapsulates the balance between technology anxiety and interpersonal trust, acting as a crucial bridge to user commitment. Finally, for users who commit, the Motivational Barrier dictates long-term adherence. Evidence from Experiment B indicated that late-phase attrition (N = 40 to N = 35) was not linked to demographic variables but to subjective evaluations like boredom or conflict with existing habits. Crucially, regression analysis identified perceived Competence and Challenge as the sole significant predictors of sustained positive affect ($p < .001$), defining this final barrier as an ongoing calculus of intrinsic enjoyment, perceived value, and lifestyle integration.

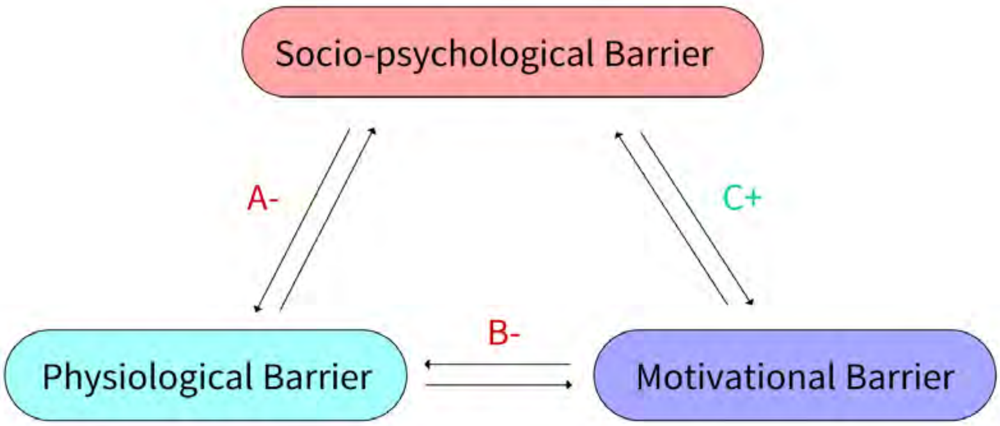

Figure 41 Interrelationships Between Core Barriers

These three barriers do not operate in isolation but form an interconnected system influencing the user's entire journey. Firstly (Relationship A), negative physiological experiences can exacerbate socio-psychological concerns; the discomfort of dizziness, for instance, might amplify technology anxiety and feelings of inability to cope. Secondly (Relationship B), persistent physiological discomfort, even if mild, can directly erode long-term motivation, acting as a constant deterrent to engagement, as suggested by the negative correlation between VRSQ scores and Positive Affect (Section 4.2.7, $\rho = -.334$, $p = .005$) and the cases of late physiological attrition in Experiment B. Lastly (Relationship C), a positive socio-psychological context, characterized by strong interpersonal trust, not only facilitates initial commitment but likely bolsters sustained motivation by providing encouragement and social reinforcement. Understanding these interrelationships is crucial for designing holistic interventions that address the multifaceted nature of older adult technology adoption.

4.6.2 Mapping Core Barriers Onto The User Adoption Process

Building upon the identification of the three core barrier factors and their interrelationships in Section 4.6.1, this section now maps these barriers onto the actual user adoption journey observed through the multi-phase experimental process. This mapping visualizes how the salience, or prominence, of each barrier dynamically shifts as older adults progress from Initial contact to attempts at sustained use. The participant funnel serves as the chronological backbone for this analysis, tracking the cohort from the initial N=86 recruits through the various attrition points (see Table 41). In Phase 1

(Initial contact), corresponding largely to Experiment A where participants (N=86) first encountered the technology, the Physiological Barrier emerged as decisively dominant. As evidenced by the 18.6% early attrition rate primarily driven by cybersickness and significantly higher VRSQ scores among those who discontinued ($p < .001$), physical intolerance acted as the principal filter, preventing N=16 individuals from completing even the first session and leaving N=70 participants. During this phase, the Socio-psychological and Motivational barriers remained largely latent for most users grappling with the immediate physical adjustment.

Table 41 Phase-wise Dominant and Latent Barriers during User Adoption

Phase	Sample Flow (Empirical Source)	Dominant Barrier	Latent/Supporting Barriers	Main Manifestation
Phase 1 – Initial contact	*Exp A:* N = 86 → N = 70 completed	Physiological Barrier	Socio-psychological (latent), Motivational (latent)	Early attrition (18.6 %); cybersickness symptoms; physical discomfort; anxiety onset.
Phase 2 – Decision Transition	*Exp B:* N = 70 → N = 40 continued	Socio-psychological Barrier	Physiological (present), Motivational (emerging)	Mid-phase attrition due to low trust/commitment; anxiety vs. reassurance; trust begins to build.
Phase 3 – Long-term Use	*Exp B:* N = 40 → N = 35 retained	Motivational Barrier	Socio-psychological (helpful), Physiological (present)	Late attrition (motivation decline); sustained adopters maintain enjoyment, value, and trust.

The subsequent Phase 2 (Decision Transition) encompassed the critical juncture where the N=70 completers of Experiment A decided whether to commit to the longer-term Experiment B, resulting in N=40 participants proceeding. During this phase, the Socio-psychological Barrier became dominant. The significant influence of social tie strength on continuation decisions (χ^2, $p = .01$) highlights that elements such as trust and anxiety were paramount, representing mid-phase attrition related to low trust or commitment issues. While the Physiological Barrier remained present for some, its dominance waned as the focus shifted to psychological readiness. Finally, Phase 3 (Long-term Use), represented by the six-session repeated-exposure period of Experiment B (N=40 to N=35), saw the Motivational Barrier rise to prominence. Late-phase attrition during this period was primarily linked to waning interest or perceived lack of value, underscored by the finding that only intrinsic motivational predictors, particularly Competence and

Challenge, predicted sustained positive affect. The entire dynamic process, illustrating the shifting salience of barriers across these three phases and their interrelationships (Arrows A, B, C as identified in 4.6.1), is visually synthesized in Figure 42.

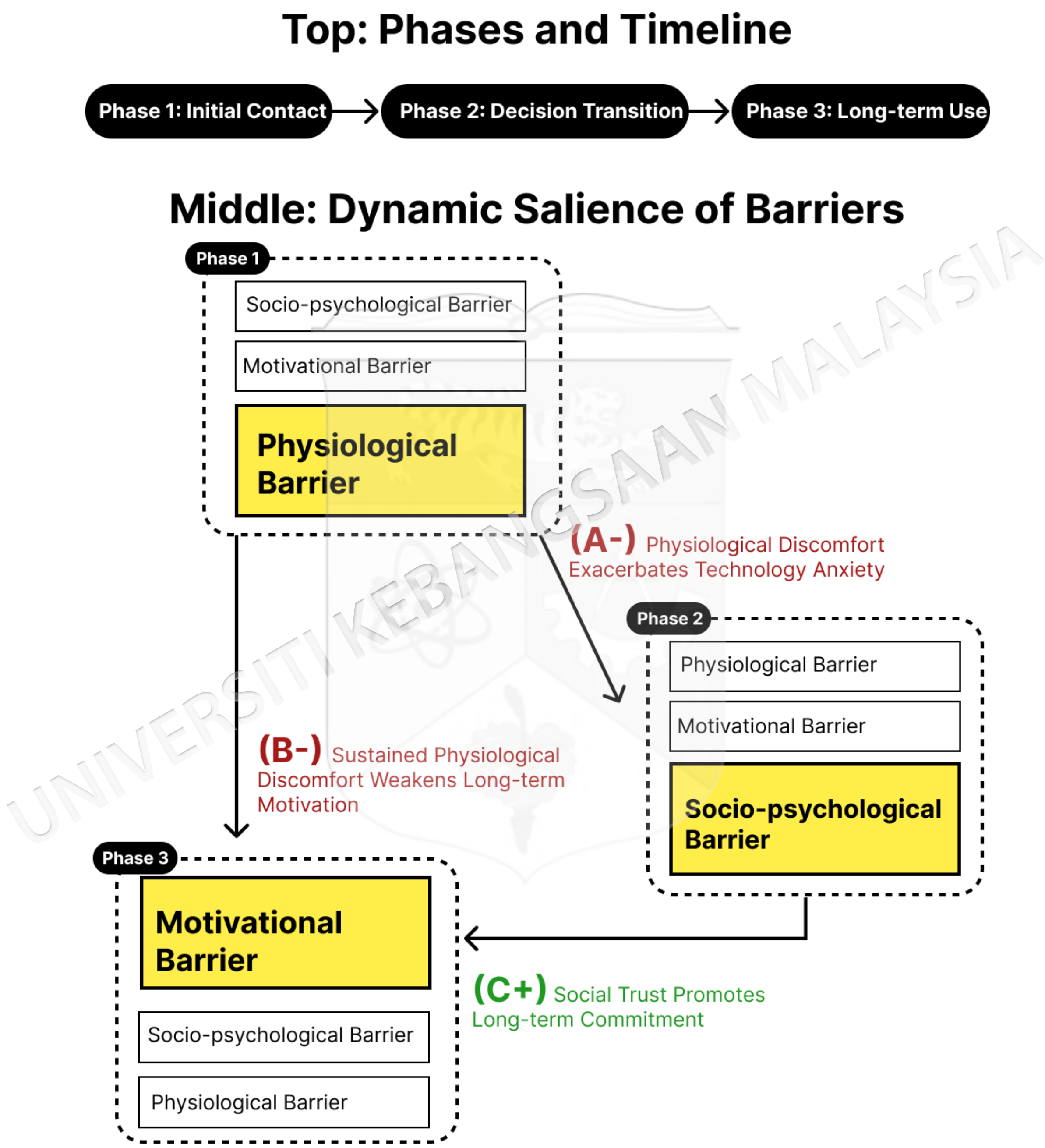

Figure 42 Conceptual of The Dynamic Barrier Framework

4.6.3 Abstracting Into A Theoretical Framework

Synthesizing Section 4.6.1's barrier identification and Section 4.6.2's phase mapping, we abstract a generalized Dynamic Barrier Framework (DBF) (Figure 43) that explains how barrier salience evolves across the adoption journey of older adults using immersive technologies. The process unfolds in three sequential yet overlapping phases with distinct dominant barriers and plausible attrition points.

Phase 1 – Initial contact (Physical Adjustment).

The Physiological Barrier is dominant and may yield Early Attrition due to bodily intolerance to immersive stimuli; socio-psychological and motivational barriers remain largely latent, while technology anxiety tends to rise.

Phase 2 – Decision Transition (Developing Trust).

The Socio-psychological Barrier becomes dominant, conditioning commitment and helping to explain Mid-stage Attrition related to trust and perceived safety; the physiological barrier is still present and motivational factors start to emerge, while trust typically builds.

Phase 3 – Long-term Use (Maintaining Value & Interest).

The Motivational Barrier governs sustained engagement or Late Attrition as enjoyment, perceived usefulness, and competence–challenge fit shape persistence, supported by socio-psychological factors in a helpful role and with residual physiological constraints still present; motivation may weaken without continuing value.

In line with our evidence, three directional tendencies organize the transition across phases:

(A) greater physiological discomfort is associated with higher technology anxiety (early risk),

(B) sustained physical strain undermines motivation over time,

(C) stronger social trust/support bolsters long-term commitment.

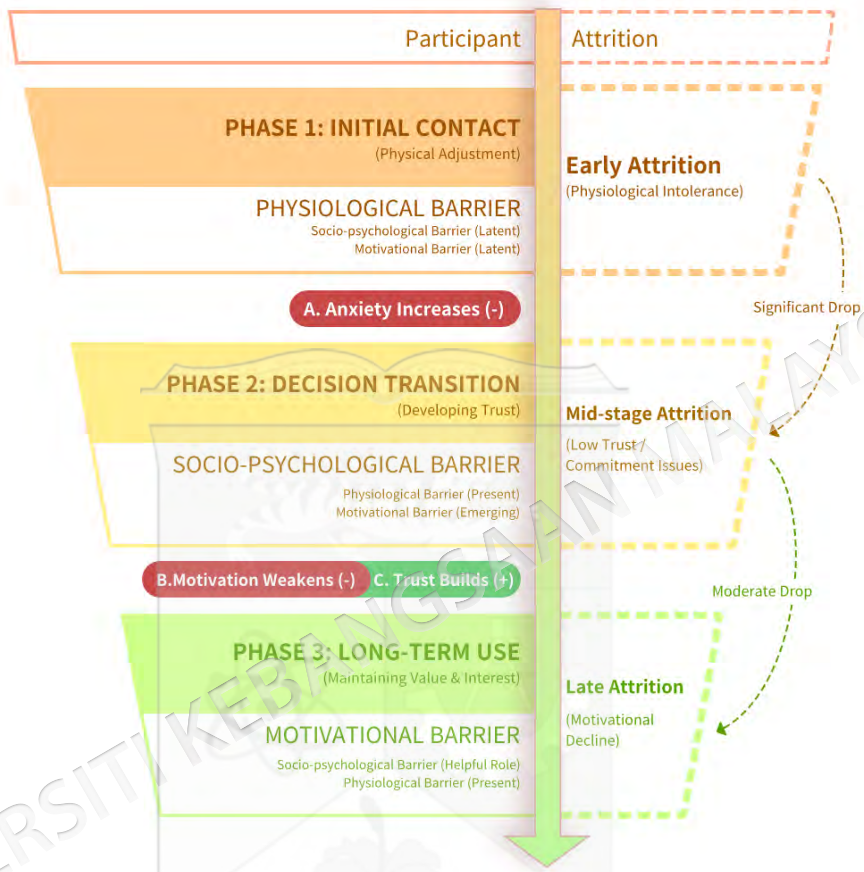

Figure 43 Dynamic Barrier Framework final version

4.7 Framework Validation

4.7.1 Expert Panel And DBF Evaluation Scheme

As summarized in Table 42, the expert panel consisted of 13 individuals with substantial academic training and long-term professional engagement in domains directly relevant to VR-supported exercise for older adults. Most held postgraduate degrees, with 7 experts (53.8%) having a master's degree and 4 (30.8%) holding a doctoral degree (PhD/MD), whereas only 2 (15.4%) reported a bachelor's degree or below. Nearly half occupied professor or senior academic titles (6, 46.2%), complemented by associate professors or equivalent associate senior titles (2, 15.4%) and 5 experts (38.5%) serving as lecturers, assistant professors or mid- to senior-level industry practitioners. In terms of experience, more than half of the panel had over 20 years of relevant work (7, 53.8%), with the remainder distributed across 5–10 years (4, 30.8%) and 11–20 years (2, 15.4%). Taken together, the figures in Figure 44 indicate that the panel was composed primarily of senior academics and practitioners with extensive track records in research, clinical practice and technology deployment. The 13 experts were independent from the thesis work, were recruited from different institutions in China, and were not involved in the game development, data collection, data analysis, supervision, or thesis committee.

The disciplinary composition shown in Table 42 closely mirrors the multi-layered structure of the Dynamic Barrier Framework (DBF) and the three research objectives. Core backgrounds covered geriatrics, aging studies and age-friendly design (6, 46.2%); sport science, rehabilitation and digital health products (7, 53.8%); virtual reality, human–computer interaction and game design (5, 38.5%); psychology, health behavior and user experience research (3, 23.1%); and educational technology, serious games and training system development (4, 30.8%), with no experts classed as "other fields." This cross-disciplinary configuration ensures that physiological, socio-psychological and motivational perspectives derived from RO1 and RO2 are all represented, while also providing specialist VR/HCI and user-experience expertise needed to appraise the DBF in RO3. Consequently, the characteristics documented in Table 42 support the credibility of the panel's judgments and strengthen the content and theoretical validity of the framework.

Table 42 Expert characteristics and disciplinary background

Characteristic	**Category**	**n**	**%**
Education level	Doctoral degree (PhD/MD)	4	30.8
	Master's degree	7	53.8
	Bachelor's degree or below	2	15.4
Academic/clinical title or professional role	Professor / senior academic title	6	46.2
	Associate professor / associate senior title	2	15.4
	Lecturer / assistant professor / mid-level or senior industry practitioner	5	38.5

... to be continued

... continuation			
Years of relevant experience	5–10 years	4	30.8
	11–20 years	2	15.4
	>20 years	7	53.8
Core disciplinary background[1]	Geriatrics / aging studies / age-friendly design	6	46.2
	Virtual reality / human–computer interaction / game design and development	5	38.5
	Sport science / rehabilitation / digital health products	7	53.8
	Psychology / health behavior / user experience research (UXR)	3	23.1
	Educational technology / serious games / training system development	4	30.8
	Other fields	0	0.0

Note. N = 13. Percentages are calculated within each characteristic and may not total 100% because of rounding.
[1] Core disciplinary background was a multiple-response item; percentages reflect the proportion of experts endorsing each field.

As shown in Figure 44, the Dynamic Barrier Framework (DBF) integrates the empirical findings from RO1 and RO2 into a time-ordered account of older adults' engagement with VR exercise. The central column depicts three sequential phases, Phase 1: Initial contact (Physical Adjustment), Phase 2: Decision Transition (Developing Trust), and Phase 3: Long-term Use (Maintaining Value & Interest)each dominated by a primary barrier type (physiological, socio-psychological, and motivational, respectively). The left-hand ovals represent three cross-phase mechanisms derived from the experimental data: A. Anxiety Increases (–), B. Motivation Weakens (–), and C. Trust Builds (+). These mechanisms operate across phases rather than within a single stage, and help explain why participants either progress from initial contact to sustained use or, alternatively, become more vulnerable to dropout despite satisfactory usability and performance outcomes identified in RO1.

The right-hand side of Figure 44 links these barriers and mechanisms to phase-specific attrition patterns, thereby connecting the DBF to real-world disengagement trajectories. Early Attrition (Physiological Intolerance) is primarily associated with unresolved physical discomfort during Phase 1; Mid-phase Attrition (Low Trust / Commitment

Issues) reflects insufficient trust and fragile commitment during Phase 2; and Late Attrition (Motivational Decline) emerges when perceived value and interest cannot be maintained in Phase 3. Together, this configuration provides a coherent bridge from the quantitative usability and comfort profiles (RO1) and the empirically derived barrier structure (RO2) to the subsequent expert validation and refinement of the framework in RO3, ensuring conceptual continuity across the chapter.

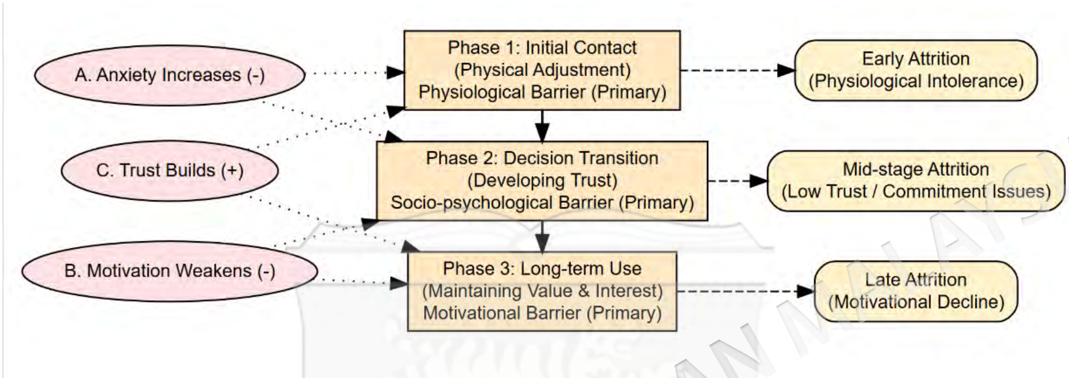

Figure 44 Dynamic Barrier Framework: phases, mechanisms, and attrition patterns

Note. The framework illustrates three sequential phases of VR engagement, Initial contact, Decision Transition, and Long-term Use, each dominated by a primary barrier (physiological, socio-psychological, and motivational, respectively). Three cross-phase mechanisms (A: Anxiety Increases; B: Motivation Weakens; C: Trust Builds) influence participants' progression across phases. Attrition patterns (Early, Mid-phase, Late) reflect the dominant barrier at each phase and represent potential dropout points throughout the engagement process.

4.7.2 Quantitative Validation Results: Content Validity And Perceived Fit

As shown in Table 43, experts' ratings indicate that the Dynamic Barrier Framework (DBF) achieves generally adequate to high content validity across all evaluation blocks. Mean ratings (M) for the three phase-level dimensions were all above the scale midpoint, with values ranging from 2.76 for *Phase 2: decision transition & socio-psychological barrier* to 3.08 for *Phase 3: long-term use & motivational barrier* (SD = 0.37–0.43). The corresponding S-CVI indices were 0.75, 0.63 and 0.81, respectively, suggesting that at least two thirds of experts judged most items within each phase as clear, relevant and representative (rating $\geq$ 3), with the strongest endorsement for Phase 3. Internal consistency for the phase blocks was acceptable (Cronbach's α = 0.66–0.74), consistent with the coherent barrier patterns identified in RO2.

For the cross-cutting components, mean ratings were also favorable (M = 2.92–3.12), with *Dropout phases (early/mid/late)* receiving the highest mean (M = 3.12, SD = 0.48) and the strongest scale-level agreement (S-CVI = 0.88), followed by *Mechanisms A/B/C* (M = 2.96, S-CVI = 0.77). The *Overall DBF adoption process* and *DBF diagram* blocks showed slightly lower, but still acceptable, S-CVI values (0.73 and 0.71) and moderate internal consistency (α = 0.63 and 0.58). Taken together, the indices in Table 43 indicate that experts largely concurred that the DBF dimensions, mechanisms and dropout pathways derived from RO1 and RO2 are conceptually sound, reasonably well defined and suitable for use as a theoretical and analytic model to address RO3.

Table 43 Dimension-level content validity indices for the Dynamic Barrier Framework (DBF)

Dimension	k	M	SD	Median	Min	Max	S-CVI	Cronbach's α
Phase 1: initial contact & physiological barrier	8	3.05	0.43	3.12	2.38	3.75	0.75	0.74
Phase 2: decision transition & socio-psychological barrier	8	2.76	0.37	2.62	2.38	3.38	0.63	0.66
Phase 3: long-term use & motivational barrier	8	3.08	0.40	3.20	2.38	3.75	0.81	0.74
Mechanisms A/B/C	4	2.96	0.44	3.00	2.25	3.75	0.77	0.57
Dropout phases (early/mid/late)	4	3.12	0.48	3.00	2.25	3.75	0.88	0.56
Overall DBF adoption process	4	2.94	0.49	3.00	2.25	3.75	0.73	0.63
DBF diagram	4	2.92	0.48	3.00	2.25	3.75	0.71	0.58

Note. *k* = number of items within each evaluation block. Mean ratings (*M*) were computed by first averaging all items within a block for each expert, and then averaging across the 13 experts (1–4 scale). S-CVI (scale-level content validity index) represents the proportion of ratings ≥ 3 across all items in a block. Cronbach's α provides an index of internal consistency based on the items within each block.

As illustrated in Figure 45, experts' ratings show a consistent pattern of generally favourable content validity across DBF dimensions, with all mean scores exceeding 2.5 on the 1–4 scale. The three phase-related dimensions cluster around the upper range, with *Phase 3: long-term use & motivational barrier* and *Phase 1: initial contact & physiological barrier* achieving the highest means (approximately 3.1), whereas *Phase 2: decision transition & socio-psychological barrier* is visibly lower but still above 2.7. The cross-phase components follow a similar trend: *Dropout phases (early/mid/late)* attains the strongest endorsement (mean ≈ 3.1), followed by *Mechanisms A/B/C*, *Overall DBF adoption process* and the *DBF diagram* (means ≈ 2.9–3.0). The overlaid

S-CVI bars corroborate this pattern, with the highest agreement for the dropout phases and Phase 3 (S-CVI ≥ 0.81), somewhat weaker but still acceptable values for Phase 1 and the mechanisms (S-CVI ≈ 0.75–0.77), and the lowest values for Phase 2 and the overall/diagram blocks (S-CVI ≈ 0.63–0.73). Together, the distributions in Figure 45 reinforce the conclusion that the DBF dimensions derived from RO1 and RO2 are largely judged as clear, relevant and representative for addressing RO3, while signalling that the socio-psychological phase and the more synthetic representations warrant slightly closer attention in subsequent refinement.

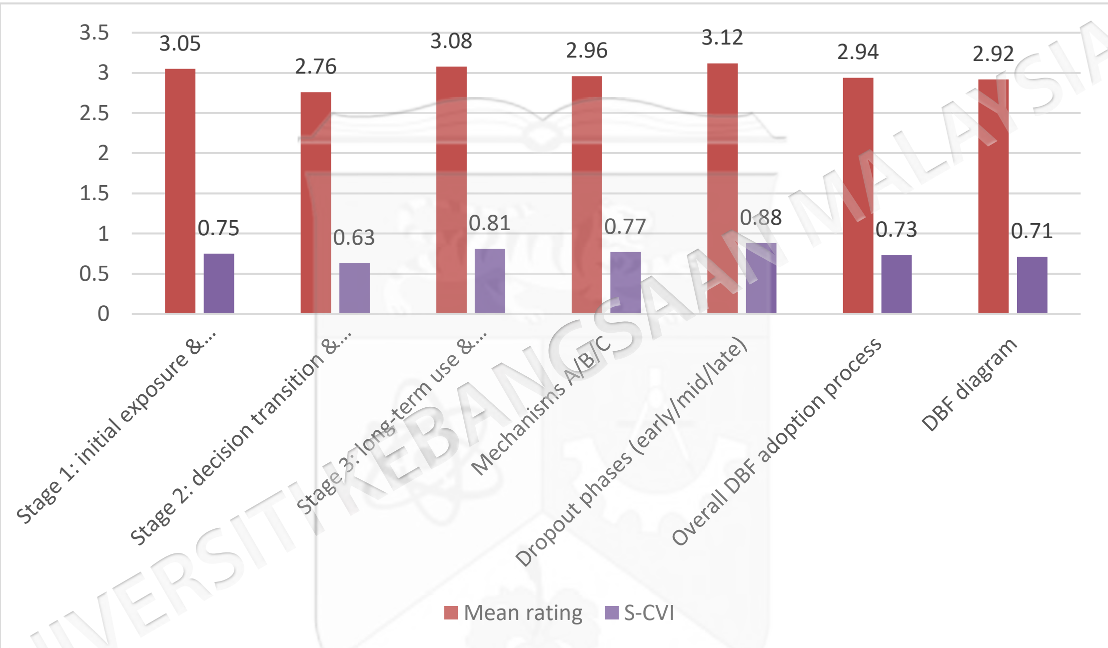

Figure 45 Mean ratings and S-CVI values across DBF dimensions

Note. Bars represent experts' average ratings (1–4 scale) for each DBF dimension, with higher values indicating stronger content validity. Red bars show S-CVI values, representing the proportion of ratings ≥3 within each dimension. Phase 1 and Phase 3 achieved the highest mean ratings, whereas Phase 2 and cross-phase mechanisms showed relatively lower values but remained above 2.5.

4.7.3 Expert Feedback: Gaps And Directions For Refinement

As illustrated in Figure 46, experts' mean ratings across the four evaluation criteria were consistently above the scale midpoint for all three phases of the DBF (2.69–3.27 on a 1–4 scale), indicating generally satisfactory content validity. Phase 1 (initial contact) received the highest scores on clarity (M = 3.27) and representativeness (M = 3.08), suggesting that the early-phase constructs and indicators are perceived as especially well defined and closely aligned with experts' understanding of physiological adjustment. Phase 3 (long-term use) showed the strongest endorsement on relevance (M = 3.08) and usefulness (M = 3.23), consistent with the view that motivational processes and sustained value are central for explaining older adults' continued engagement observed in RO1 and RO2.

By contrast, Phase 2 (decision transition) systematically attracted the lowest ratings on all four criteria, with a particularly noticeable dip in clarity (M = 2.69) and slightly lower scores for relevance (M = 2.73) and representativeness (M = 2.77). This profile indicates that, while the socio-psychological transition phase is conceptually important for linking physiological adjustment to long-term motivation, its operationalization in the current DBF is less precise than for Phases 1 and 3. In the context of RO3, these results point to Phase 2 as the primary target for refinement, especially in sharpening construct boundaries and exemplars, while retaining the overall three-phase structure supported by the stronger ratings for the initial and long-term phases.

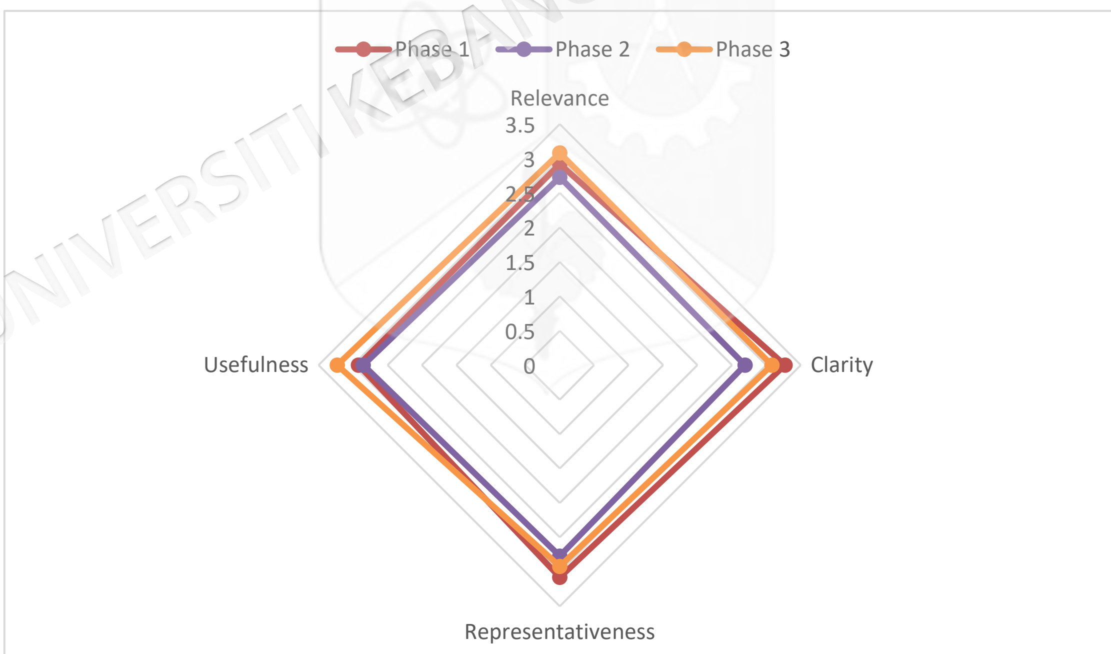

Figure 46 Profiles of the four evaluation criteria across phases

Note. Radar chart showing experts' mean ratings (1–4 scale) for four evaluation criteria, relevance, clarity, representativeness and usefulness, across the three phases of the DBF (Phase 1: initial contact, Phase 2: decision transition, Phase 3: long-term use). Higher scores indicate stronger perceived content validity on that criterion. The plot illustrates that relevance and usefulness are generally rated high across phases, whereas clarity dips slightly at Phase 2.

As shown in Table 44, experts perceived the DBF as making a clear and multifaceted theoretical contribution. In Panel A, two contribution categories received the strongest support: 38.5% of experts (n = 5) highlighted the DBF as a dynamic three-phase framework clarifying how physiological adjustment, trust and motivation jointly shape older adults' engagement with immersive VR, and an equal proportion (38.5%, n = 5) emphasised its value in synthesising prior work on early, mid- and late-phase dropout in technology-supported exercise. A smaller, but still substantial, subgroup (23.1%, n = 3) viewed the DBF primarily as an analytical model for understanding user dropout in immersive VR/MR exercise based on repeated real-world trials. Panel B further indicates that the overall perceived fit of the framework with experts' own practice was mainly partial-to-basic rather than high: one expert rated the framework as poor fit (7.7%), nine experts rated it as partial fit (69.2%), three rated it as basic fit (23.1%), and none rated it as high fit. This yielded a mean overall fit score of 2.15 (SD = 0.55) on the 1–4 scale.

Panel C of Table 44 provides more fine-grained, experience-based confirmation of DBF assumptions. All experts (100%, n = 13) agreed that the peak of dropout tends to occur in the mid-phase of VR exercise, directly reinforcing the DBF's emphasis on a vulnerable transition phase. Large majorities indicated that technology-related anxiety is highest during the first 1–2 sessions (76.9%, n = 10), that engagement becomes more stable once trust has been established (76.9%, n = 10), and that motivation, interest and novelty are key drivers of sustained participation in the later phase (76.9%, n = 10). Social support and perceived health/functional improvement were also frequently endorsed (61.5%, n = 8 each), aligning with the motivational barrier in Phase 3, whereas just over half of the experts confirmed that early physiological discomfort triggers initial dropout (53.8%, n = 7) and that some aspects of later-phase participation do not fully match their own experience (53.8%, n = 7). Taken together, these patterns indicate that the core mechanisms and dropout phases proposed in RO1 and RO2 map closely onto experts' real-world observations, while also signalling specific areas, particularly nuances of later-phase engagement, where the DBF can be further refined under RO3.

Table 44 Experts' perceptions of DBF's theoretical contribution and real-world fit

Panel A. Perceived theoretical contribution (Q46)

Theoretical contribution category*	n	%
A. Dynamic three-phase framework clarifying how "physiological adjustment – trust – motivation" jointly shape older adults' engagement with immersive VR	5	38.5
B. Providing a structured "user dropout" framework that synthesises prior findings on early, mid and late attrition in technology-supported exercise	5	38.5
C. Offering a dedicated analytical model for understanding user dropout in immersive VR/MR exercise settings based on repeated real-world trials	3	23.1

Panel B – Overall fit rating (Q50)

Rating level	n	%
1 = poor fit	1	7.7
2 = partial fit	9	69.2
3 = basic fit	3	23.1
4 = high fit	0	0

Panel C – Experience-based confirmation of DBF assumptions (Q49)

Experience statement*	n	% selected
G. The peak of dropout tends to occur in the mid-phase of VR exercise, rather than at the very beginning or the very end.	13	100.0
B. Technology-related anxiety is usually highest during the first 1–2 sessions.	10	76.9
C. Once trust has been established, participants' engagement becomes noticeably more stable.	10	76.9
F. Motivation, interest and novelty are the key drivers for sustaining participation in the later phase.	10	76.9
D. Social support (family / peers) has a substantial impact on whether older adults continue.	8	61.5
E. Health / functional improvement is an important reason for continued use.	8	61.5
A. DBF's assumption that early physiological discomfort is a major trigger for initial dropout matches my real-world experience.	7	53.8
H. Some aspects of the later-phase participation pattern do not fully match my own experience.	7	53.8
I. Other comments (open-ended).	0	0.0

4.7.4 Discussion: Theoretical Implications Of Dbf Construction

The expert validation provides convergent support that the Dynamic Barrier Framework (DBF) functions as a coherent, actionable explanation of older adults' adoption and attrition in immersive VR/MR exergaming. Across the panel's quantitative ratings, the framework demonstrated strong perceived fit and content validity, and the evaluation scheme showed acceptable internal consistency, indicating that experts were not only aligned in how they interpreted the DBF constructs, but also in how they judged their relevance to real-world use. Substantively, the panel's feedback reinforced the DBF's central theoretical claim that attrition is dynamic and phase-dependent: physiological adjustment operates as an early gatekeeper, trust-related concerns become salient during the transition from trial to commitment, and motivational dynamics dominate sustained participation. In this sense, the validation results do more than confirm face validity; they indicate that the DBF's phased structure and barrier taxonomy offer a stable vocabulary for explaining why users discontinue at different points in the adoption journey, and for linking observed dropout patterns to distinct, theoretically meaningful mechanisms.

At the same time, the expert feedback also clarifies where the framework requires refinement to maximize theoretical precision. Relative to Phase 1 and Phase 3, Phase 2 received comparatively lower evaluations on clarity and representativeness, suggesting that the trust-building transition is the most conceptually complex and context-sensitive portion of the DBF. This does not undermine the framework; rather, it highlights the need to sharpen construct boundaries and provide more explicit exemplars that distinguish trust-related barriers from adjacent socio-psychological and motivational constructs (e.g., when anxiety and perceived risk function as antecedents of trust versus downstream consequences of discomfort or low competence). Several experts also noted that late-phase participation patterns may vary by setting and user profile, implying that Phase 3 may benefit from clearer scope conditions describing when and for whom motivation becomes the primary driver of persistence. Taken together, the validation indicates that the DBF is theoretically sound and empirically grounded, while also identifying a focused agenda for refinement, especially in Phase

2, so that the framework can more precisely guide both explanation and stage-matched design interventions.

Phase 2 trust-building is therefore operationalised as the transition in which users evaluate safety, control, confidence, social reassurance, and personal fit before deciding whether to continue beyond initial exposure.

4.8 CONCLUSION

This chapter presented the empirical results and integrative discussion of the study and addressed all three research objectives through a sequential logic of identification, construction, and validation. First, the findings from Experiment A and Experiment B showed that older adults' engagement with immersive exergames is not shaped by a single static factor, but by a stage-dependent process in which dominant barriers shift over time. During initial contact, physiological discomfort, especially cybersickness-related symptoms, functioned as the primary early filter. At the transition stage, socio-psychological factors, particularly trust, safety concerns, and anxiety toward the technology, became more salient in shaping willingness to continue. During repeated exposure and longer-term use, motivational factors, including perceived competence, challenge fit, and sustained value, emerged as the key determinants of continued engagement. Together, these findings provide clear empirical support for understanding attrition as a dynamic and evolving process rather than as a one-time usability problem.

Building on these empirical patterns, this chapter constructed and validated the Dynamic Barrier Framework (DBF) as a phase-sensitive explanatory model of older adults' adoption, engagement, and attrition in immersive exergaming. The framework integrates three sequential phases, Initial Contact, Decision Transition, and Long-term Use, and explains how physiological, socio-psychological, and motivational barriers vary in dominance while remaining interrelated across the adoption journey. The expert validation results further indicated that the DBF possesses acceptable clarity, coherence, content validity, and practical relevance, supporting its value as both a theoretical contribution and a design-oriented framework for future immersive exercise interventions for older adults. Overall, this chapter establishes a coherent bridge from empirical evidence to framework development and provides the foundation for the broader conclusions, contributions, and future directions discussed in Chapter 5.

CHAPTER V

CONCLUSION AND FUTURE WORKS

5.1 Research Summary

This thesis investigated attrition in immersive exergames among older adults and addressed the persistent gap between promising short-term benefits and sustained engagement. Although immersive technologies such as Virtual Reality (VR) and Mixed Reality (MR) are increasingly explored for health-oriented interventions, older adults often discontinue use after first contact, limiting practical value and scalability. To respond to this challenge, the thesis adopted a staged, evidence-driven research path: it first documented how and when attrition occurs, then abstracted those patterns into an explicit framework, and finally evaluated that framework's coherence and usability.

Taken together, the findings demonstrate that engagement is not static but evolves through identifiable phases in which different barriers become dominant at different points in the adoption journey.

Empirically, the thesis began with Experiment A – Initial contact (RO1), designed to capture the earliest "first-contact" period. This stage established a first-pass usability and experience profile using Subjective Game Experience (GEQ) and Physiological Comfort (VRSQ), while also recording concrete dropout reasons. The thesis then proceeded to Experiment B – Repeated Exposure (RO1), a short longitudinal extension that examined whether barriers persist, shift, or intensify during repeated engagement once novelty is no longer the dominant driver. Across the full participation funnel, attrition was substantial and patterned. Of 86 participants entering Experiment A, 16 did not complete it (14 for physiological reasons and 2 for socio-psychological reasons), leaving 70 completers (81.4%). After completing Experiment A, 30 participants did not proceed to Experiment B (42.9% attrition from Experiment A completers), while 40 proceeded (57.1% conversion). During Experiment B, 5 participants did not complete the repeated-exposure protocol (2 for physiological reasons and 3 for motivational reasons). Ultimately, 35 participants completed all stages, yielding an overall completion rate of 40.7%. This funnel evidence indicates that attrition is not random: it concentrates early and is driven by distinct barrier types that emerge at different stages of the user journey.

The VR–MR comparison clarified how mode relates to experience and performance. At the end of Experiment A, VR yielded higher immersion-related experience on GEQ dimensions, particularly Sensory and Imaginative Immersion and Flow, while Positive Affect and physiological symptoms measured by VRSQ did not differ significantly between modes. During repeated exposure in Experiment B, performance outcomes changed over time in a manner consistent with adaptation: Accuracy improved across days ($p = .021$), Average Time showed a marginal day effect ($p = .055$), and Activity Volume remained stable ($p = .978$). Importantly, the absence of significant mode effects and Mode × Day interactions across these indices suggests broadly comparable learning trajectories for VR and MR once participants remained engaged.

Synthesizing these results, the thesis proposed The Dynamic Barrier Framework (DBF) as an integrative account of attrition of immersive technology exergames among older adults. The DBF formalizes a staged adoption pathway—Phase 1: Initial Contact (Physical Adjustment), Phase 2: Decision Transition (Developing Trust), and Phase 3: Long-term Use (Maintaining Value and Interest)—and links each phase to a dominant barrier type (Physiological Barrier, Socio-psychological Barrier, and Motivational Barrier, respectively). In doing so, the framework captures a central empirical conclusion of this thesis: older adults' disengagement from immersive exergames reflects a phase-dependent process in which barrier dominance shifts over time rather than remaining static. The framework therefore supports a more precise design and implementation logic: reducing attrition requires phase-specific supports that reduce early physical burden, strengthen trust and confidence during decision transition, and sustain value and interest over longer-term use.

5.2 Revisiting The Research Questions And Objectives

The thesis was guided by the following research questions:

RQ1: What specific barriers lead to attrition during initial and repeated contacts with immersive exergames and reduce sustained engagement?

RQ2: How to construct a Dynamic Barrier Framework that explains how different types of barriers evolve across stages of attrition and engagement during adoption?

RQ3: How can the Dynamic Barrier Framework be validated for adoption, engagement, and attrition?

Correspondingly, the research objectives were defined as:

RO1: To identify key barriers that lead to attrition during initial and repeated contacts with immersive exergames and undermine sustained engagement.

RO2: To construct a Dynamic Barrier Framework that explains how different types of barriers evolve across stages of attrition and engagement during adoption.

RO3: To validate the Dynamic Barrier Framework across stages of adoption, engagement, and attrition.

RO1 was addressed through a two-part empirical program. In Experiment A – Initial contact (RO1), attrition was directly observed during first contact with immersive exergames, and dropout reasons were documented alongside GEQ and VRSQ outcomes. The funnel evidence shows that attrition began immediately and was predominantly physiological at first contact: most non-completions of Experiment A were attributed to physiological reasons (14 of 16). This pattern is consistent with the thesis's interpretation that physical adjustment comfort, tolerance, and immediate bodily responses operates as a primary filter for older adults' continuation. The same funnel logic also indicates a distinct mid-stage attrition point: among those who completed Experiment A, a substantial portion did not convert to Experiment B. This transition loss aligns with the socio-psychological domain, where concerns such as confidence, perceived suitability, or trust can condition the willingness to continue beyond trial. In Experiment B – Repeated Exposure (RO1), the thesis further observed that late-stage attrition still occurs even after conversion, but it becomes smaller in magnitude and shifts toward motivational reasons, consistent with the need to maintain interest and perceived value over time. Together, these results identify a coherent barrier sequence across stages and fulfill RO1.

RO2 was fulfilled by integrating the empirical barrier patterns into a formal staged framework. The DBF was constructed by consolidating observed dropout distributions and reasons across the participant funnel and aligning those observations with phase-specific interaction demands. The thesis thus moved from descriptive evidence (who left, when, and why) to a process structure that can explain barrier dominance over time: (i) the Physiological Barrier dominates first contact because physical adjustment must be resolved before continued engagement is feasible; (ii) the Socio-psychological Barrier becomes central during the decision transition because continuation depends on trust, perceived control, confidence, and a sense of fit; and (iii) the Motivational Barrier becomes decisive for longer-term use because sustained engagement requires value and interest beyond novelty. In this way, RO2 was achieved through explicit synthesis of the thesis's staged empirical evidence into a dynamic, phase-linked framework.

RO3 was achieved through a structured validation workflow aimed at assessing the DBF's clarity, relevance, and coherence. Expert evaluation provided quantitative content validity evidence across DBF dimensions, including phase–barrier alignment, dropout phase mapping, and interpretability of the DBF diagram. The evaluation results showed favorable ratings across blocks, with mean ratings ranging from 2.76 to 3.12 on a 1–4 scale. Content validity indices further supported the framework: S-CVI values ranged from 0.63 to 0.88 across dimensions, and internal consistency indices (Cronbach's α) ranged from 0.56 to 0.74 depending on the block. While Phase 2 and certain cross-cutting mechanisms warranted comparatively closer attention for refinement, the overall pattern supports the DBF as a defensible theoretical and analytic model for explaining attrition and guiding phase-sensitive interpretation. Therefore, RO3 was fulfilled.

5.3 Research Contributions

5.3.1 Construct-Level Contributions

First, the thesis clarifies attrition in immersive exergames as a barrier-driven process that can be systematically decomposed into three operational categories: Physiological Barrier, Socio-psychological Barrier, and Motivational Barrier. Rather than treating discontinuation as a generic compliance issue, the thesis specifies how each barrier manifests for older adults and demonstrates that barrier dominance shifts across time. The participant funnel provides concrete empirical grounding for this claim by linking dropout stages to barrier reasons: physiological reasons dominated early non-completion of Experiment A, transition attrition highlighted the importance of socio-psychological factors in deciding whether to continue, and motivational reasons emerged in later-stage dropout during repeated exposure. This construct-level contribution supports more precise theorization and measurement by enabling attrition to be discussed and analyzed in phase-relevant terms.

The novelty of this contribution lies in shifting attrition from a general dropout outcome to a set of phase-specific mechanisms that can be measured, interpreted, and addressed more precisely.

5.3.2 Framework-Level Contributions

Second, the thesis contributes The Dynamic Barrier Framework (DBF) as an integrative model of attrition of immersive technology exergames among older adults. The DBF advances the literature by embedding barriers within a staged process, Phase 1 – Initial contact (Physical Adjustment)., Phase 2 – Decision Transition (Developing Trust)., and Phase 3 – Long-term Use (Maintaining Value & Interest). rather than treating barriers as static, interchangeable lists. Conceptually, this framing explains why many interventions appear promising at first contact yet fail to scale: success in Phase 1 does not guarantee conversion through Phase 2, and conversion does not guarantee Phase 3 sustainability. Methodologically, the DBF provides a coherent lens for organizing evidence across subjective experience (GEQ), physiological comfort (VRSQ), performance indices, and observed dropout behavior. Practically, it offers an explicit structure for designing and evaluating attrition-reduction strategies that are phase-sensitive rather than one-size-fits-all.

Compared with static acceptance models, the DBF improves explanation by showing why successful first contact does not automatically lead to continued use, and why different support strategies are needed at different phases.

5.3.3 Practical And Design-Oriented Contributions

Third, the thesis yields phase-specific implications for immersive exergame design and implementation. For Phase 1, the findings prioritize comfort-forward onboarding and conservative progression: reducing immediate physical burden and perceived risk is foundational because physiological discomfort can terminate engagement before any motivational or trust-based supports become relevant. For Phase 2, the thesis highlights the need to strengthen perceived control, competence, and trust through clear guidance, transparent feedback, and supportive scaffolding, so that older adults can confidently transition from trial to continued participation. For Phase 3, the thesis emphasizes sustaining value and interest through content variation, goal relevance, and adaptive challenge that aligns with users' evolving capabilities and expectations. Taken together, these implications translate the DBF into actionable design logic: intervention success depends on matching support strategies to the dominant barrier in each phase.

These design implications matter because they translate the framework from a descriptive model into a practical basis for staged onboarding, trust-building, and adaptive engagement support.

5.4 RESEARCH LIMITATIONS AND POTENTIAL IMPROVEMENTS

Several limitations should be considered when interpreting the findings and applying the DBF.

These limitations mainly affect the generalisability and predictive strength of the findings, rather than undermining the internal logic of the staged barrier interpretation developed in this thesis.

First, although the thesis captured both first-contact and repeated-exposure interaction, the repeated-exposure window remains relatively short and may not fully represent long-term adherence dynamics. Attrition mechanisms central to Phase 3 may involve life-context constraints, shifting health status, and routine integration challenges that require longer follow-up periods to observe. Future studies with extended durations and larger samples would enable stronger inference about Phase 3 stability and barrier transitions over time.

Second, the thesis relied on self-reported experience measures (GEQ) and symptom-based reports (VRSQ), complemented by performance indices. While this triangulation is informative, richer objective data could strengthen inference about barrier mechanisms. For example, behavioral logs (pauses, controller errors, head movement patterns), contextual measures (space constraints, caregiver presence), and wearable physiological signals (e.g., heart-rate variability, skin conductance, fatigue, or balance-relevant indicators) could help distinguish transient discomfort from persistent incompatibility and more precisely map mechanisms within each phase.

Third, the VR–MR comparison was bounded by the selected device, task design, and interaction configuration. The observed immersion advantage for VR on specific GEQ dimensions, alongside the non-significant differences in VRSQ outcomes, should be interpreted as evidence within this implementation rather than generalized as universal mode effects. Mode differences in immersive exergames are likely to be content- and interaction-dependent; future work should replicate comparisons across varied exergame designs, interaction paradigms, and support features before drawing broader conclusions about VR versus MR suitability for older adults.

Fourth, the DBF validation emphasized expert review and content validity evidence. This provides important support for conceptual coherence and usability, but additional validation is needed to establish predictive and intervention utility. Future work should test whether DBF-based phase classification improves attrition prediction, whether DBF-guided adaptations reduce dropout compared with non-tailored approaches, and whether the framework remains robust across deployment contexts such as home-based use or supervised clinical programs.

5.5 Recommendations For Future Work

5.5.1 Broader Validation Across Users and Settings

The DBF should be examined with more diverse older adult populations, including variability in mobility, health status, prior immersive technology exposure, and cultural background. Studies conducted in home or community settings with longer follow-up periods are particularly important for understanding Phase 3 dynamics and for identifying real-world constraints (space, scheduling routines, caregiver influence) that may introduce additional attrition pathways.

Future work should also examine ethical deployment issues, including affordability, equitable access, physical and cognitive ability thresholds, safety supervision, and the risk that immersive health technologies may primarily benefit older adults who already have higher resources or functional capacity.

5.5.2 Mechanism-Focused Studies Within Phases

Within Phase 1, future work should isolate which design elements most effectively reduce physiological burden and perceived risk, including onboarding protocols, calibration strategies, and comfort-oriented interaction constraints. Within Phase 2, studies should model trust development more precisely by tracking perceived control, self-efficacy, anxiety, and social reassurance across repeated interactions and testing how these factors mediate conversion from initial completion to continued participation. Within Phase 3, research should identify which motivational supports most reliably sustain value and interest, including personalization strategies, goal alignment, adaptive challenge, and meaningful feedback loops.

5.5.3 DBF-Guided Intervention And Predictive Modeling

A central next step is to operationalize the DBF as both an analytic and intervention tool. This includes building phase-sensitive indicators that can flag high-risk users early (e.g., elevated VRSQ symptoms during Phase 1; reduced enjoyment, perceived value, or engagement signals during later phases) and designing adaptive supports that respond to the dominant barrier at each stage. With richer behavioral data and longer longitudinal trajectories, predictive modeling could be developed to anticipate barrier transitions and deliver timely, personalized interventions.

Adaptive and AI-supported systems could extend this direction by using DBF phase indicators to personalize onboarding, adjust challenge, and deliver timely support in clinical, community, or home-based deployment contexts.

5.6 FINAL REMARKS

Attrition remains one of the most consequential obstacles to translating immersive exergames from promising demonstrations into durable health-support tools for older adults. This thesis argues that sustained engagement cannot be secured by optimizing a single aspect of experience, because disengagement reflects a staged process in which different barriers become dominant at different times. By identifying coherent barrier patterns, constructing The Dynamic Barrier Framework (DBF), and validating its conceptual structure, the thesis provides both an explanatory account of attrition and a practical logic for phase-sensitive design and implementation.

More broadly, the work reinforces a core implication for immersive health technology: successful adoption depends on making experiences physically manageable, psychologically trustworthy, and motivationally sustainable. Progress toward this goal will require phase-aware, user-centered designs that treat attrition as a primary outcome rather than a peripheral inconvenience, and evaluation strategies that explicitly test how design decisions shift barrier dominance across phases. Through such efforts, immersive exergames can move closer to fulfilling their potential as accessible, engaging, and sustainable tools to support older adults' health and well-being.

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APPENDIX A PARTICIPANT INFORMATION SHEET AND CONSENT FORM

Universiti Kebangsaan Malaysia (UKM)

Research Title:

Dynamic Barrier Framework of Older Adults' Adoption of Immersive Tai Chi Exergames

Section	Details
Document Title	Participant Information Sheet and Consent Form
Institution	Universiti Kebangsaan Malaysia (UKM)
Study Title	Dynamic Barrier Framework of Older Adults' Adoption of Immersive Tai Chi Exergames
Researcher Status	Doctoral Researcher
Purpose of the Study	This study aims to explore older adults' experiences, barriers, and continued engagement in immersive Tai Chi exergaming. The study also seeks to understand how physiological, psychological, and motivational factors influence the adoption and sustained use of immersive exercise technologies.
Reason for Participation	You are invited to participate because your experience as an older adult is valuable for understanding how immersive exercise systems can be designed to better support healthy aging, usability, and long-term engagement.
Nature of Participation	Participation in this study involves taking part in an immersive Tai Chi exergame session. Some participants who complete the initial session may also be invited to participate in an optional six-session follow-up study. Across these activities, participants may complete questionnaires or feedback tasks designed to understand their experience, comfort, and continued engagement.
Study Procedures	During the study, you will be asked to engage in the Tai Chi exergame activity, follow the researcher's instructions, and complete the required questionnaires or feedback tasks after the session. Your interactions, responses, and overall experience may also be observed and recorded for research analysis purposes.
Duration	The total duration of participation is approximately 40 to 60 minutes.
Possible Risks or Discomforts	Some participants may experience mild physical fatigue, dizziness, nausea, eye strain, temporary imbalance, or general discomfort when using immersive technology. If any discomfort occurs, the session may be stopped immediately.
Potential Benefits	There may be no direct personal benefit from participating in this study. However, your participation may contribute to the improvement of immersive exercise systems and help support healthier, safer, and more engaging exercise experiences for older adults in the future.
Voluntary Participation	Your participation in this study is entirely voluntary. You are free to decide whether or not to participate.
Right to Withdraw	You may withdraw from the study at any time, for any reason, without penalty, negative consequences, or loss of any rights or benefits.

Confidentiality	All information collected during this study will be treated confidentially. Personal identity will not be disclosed in the thesis, publications, presentations, or any research reports arising from this study. The data will be used only for academic and research purposes.
Data Use	The information obtained from this study may be included in a doctoral thesis, academic publications, conference presentations, and other scholarly outputs. All reported data will be presented in a way that protects participant anonymity.
Consent Statement	I have read and understood the information provided above. I understand the purpose of this study and what my participation involves. I understand that my participation is voluntary, that I may withdraw at any time without penalty, and that the information collected will be kept confidential and used only for academic research purposes. By signing below, I freely agree to participate in this study.

Participant Declaration

Item	Statement
Agreement	I voluntarily agree to participate in this research study.
Understanding	I confirm that I have understood the information presented to me regarding this study.
Rights	I understand that I may withdraw from the study at any time without any negative consequences.
Confidentiality	I understand that my personal information and responses will be kept confidential.
Consent	I hereby provide my consent to participate in this study.

Signature Section

Participant	Signature	Date
Participant Name	____________________	____________________
Participant Signature	____________________	____________________

Researcher	Signature	Date
Researcher Name	____________________	____________________
Researcher Signature	____________________	____________________

APPENDIX B
VIRTUAL REALITY SICKNESS QUESTIONNAIRE (VRSQ)

Please indicate the severity of the symptoms you are experiencing right now by selecting one response for each item.

Scale: 0 = None, 1 = Slight, 2 = Moderate, 3 = Severe

Item No.	Symptom	None (0)	Slight (1)	Moderate (2)	Severe (3)
1	General discomfort	☐	☐	☐	☐
2	Fatigue	☐	☐	☐	☐
3	Eyestrain	☐	☐	☐	☐
4	Difficulty focusing	☐	☐	☐	☐
5	Headache	☐	☐	☐	☐
6	Fullness of head	☐	☐	☐	☐
7	Blurred vision	☐	☐	☐	☐
8	Dizziness (with eyes closed)	☐	☐	☐	☐
9	Vertigo	☐	☐	☐	☐

APPENDIX C
GAME EXPERIENCE QUESTIONNAIRE (GEQ) – CORE MODULE (MODIFIED)

Instructions: Please indicate how you felt while playing the VR experience for each item by selecting the most appropriate response.

Scale Value	Meaning
0	Not at all
1	Slightly
2	Moderately
3	Fairly
4	Extremely

Note: The item "I was interested in the game's story" was removed.

Item No.	Statement	0 Not at all	1 Slightly	2 Moderately	3 Fairly	4 Extremely
1	I felt content	□	□	□	□	□
2	I felt skilful	□	□	□	□	□
3	I thought it was fun	□	□	□	□	□
4	I was fully occupied with the game	□	□	□	□	□
5	I felt happy	□	□	□	□	□
6	It gave me a bad mood	□	□	□	□	□
7	I thought about other things	□	□	□	□	□
8	I found it tiresome	□	□	□	□	□
9	I felt competent	□	□	□	□	□
10	I thought it was hard	□	□	□	□	□
11	It was aesthetically pleasing	□	□	□	□	□
12	I forgot everything around me	□	□	□	□	□
13	I felt good	□	□	□	□	□
14	I was good at it	□	□	□	□	□
15	I felt bored	□	□	□	□	□
16	I felt successful	□	□	□	□	□
17	I felt imaginative	□	□	□	□	□
18	I felt that I could explore things	□	□	□	□	□
19	I enjoyed it	□	□	□	□	□
20	I was fast at reaching the game's targets	□	□	□	□	□
21	I felt annoyed	□	□	□	□	□
22	I felt pressured	□	□	□	□	□
23	I felt irritable	□	□	□	□	□
24	I lost track of time	□	□	□	□	□
25	I felt challenged	□	□	□	□	□
26	I found it impressive	□	□	□	□	□
27	I was deeply concentrated in the game	□	□	□	□	□
28	I felt frustrated	□	□	□	□	□

29	It felt like a rich experience	□	□	□	□	□
30	I lost connection with the outside world	□	□	□	□	□
31	I felt time pressure	□	□	□	□	□
32	I had to put a lot of effort into it	□	□	□	□	□

Scoring Note: All item wordings are from the official English GEQ Core Module, except for the removal of the item *"I was interested in the game's story."*

APPENDIX D BERG BALANCE SCALE (BBS)

Instructions for the Rater: Please select one score (0–4) for each item based on the participant's performance.

No.	Item	Instruction	0	1	2	3	4
1	Sitting to Standing	Please stand up. Try not to use your hands for support.	□	□	□	□	□
2	Standing to Sitting	Please sit down.	□	□	□	□	□
3	Transfers	Arrange chair(s) for pivot transfer. Ask participant to transfer one way toward a seat with armrests and one way toward a seat without armrests.	□	□	□	□	□
4	Standing Unsupported	Please stand for two minutes without holding on.	□	□	□	□	□
5	Sitting with Back Unsupported but Feet Supported	Please sit with arms folded for 2 minutes.	□	□	□	□	□
6	Standing with Eyes Closed	Please close your eyes and stand still for 10 seconds.	□	□	□	□	□
7	Standing with Feet Together	Place your feet together and stand without holding on.	□	□	□	□	□
8	Reaching Forward with Outstretched Arm	Lift arm to 90 degrees. Stretch out your fingers and reach forward as far as you can.	□	□	□	□	□
9	Retrieving Object from Floor from a Standing Position	Pick up the shoe/slipper placed in front of your feet.	□	□	□	□	□
10	Turning to Look Behind over Left and Right Shoulders	Turn to look directly behind you over the left shoulder. Repeat to the right.	□	□	□	□	□
11	Turning 360 Degrees	Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.	□	□	□	□	□
12	Placing Alternate Foot on Step or Stool	Place each foot alternately on the step/stool until each foot has touched the step/stool four times.	□	□	□	□	□
13	Standing with One Foot in Front (Tandem Standing)	Place one foot directly in front of the other. If unable, step far enough ahead so that the heel of the forward foot is ahead of the toes of the other foot.	□	□	□	□	□
14	Standing on One Leg	Stand on one leg as long as you can without holding on.	□	□	□	□	□

Total Score: ________ / 56

APPENDIX E
BORG RATING OF PERCEIVED EXERTION (BORG-RPE)

Note: The scale ranges from 6 to 20, where 6 means *"no exertion at all"* and 20 means *"maximal exertion."*

Instructions:

While doing the exercise, please rate your perception of exertion. This feeling should reflect how heavy and strenuous the exercise feels to you, combining all sensations of physical stress, effort, and fatigue. Please select the number that best describes your level of exertion.

Score	Level of Exertion	Select
6	No exertion at all	□
7	Extremely light	□
8		□
9	Very light	□
10		□
11	Light	□
12		□
13	Somewhat hard	□
14		□
15	Hard (Heavy)	□
16		□
17	Very hard	□
18		□
19	Extremely hard	□
20	Maximal exertion	□

Selected Score: __________

APPENDIX F
DEMOGRAPHIC & HEALTH SCREENING QUESTIONNAIRE

Note: This questionnaire was used to collect baseline demographic data and screen participants for eligibility. The Chinese version was used for data collection.

Part 1. Basic Information

Item	Response
1. Name	______________________________
2. Gender	□ Male □ Female
3. Age	__________ years
4. Height	__________ cm
5. Weight	__________ kg
6. Living Situation	□ Living alone □ Living with spouse □ Living with children/family □ Nursing home

Part 2. Health Status Screening

Please tick all conditions that currently apply to you.

Item	Response
1. None (Healthy)	□
2. Hypertension (High Blood Pressure)	□
3. Diabetes	□
4. Heart Disease (e.g., coronary heart disease, heart failure)	□
5. Chronic Obstructive Pulmonary Disease (COPD) / Asthma	□
6. Other lung diseases	□ ______________________________
7. Smoking Status	□ Never □ Quit □ Currently smoking
8. Alcohol Consumption	□ Never □ Occasionally □ Frequently

Part 3. Recent Health Symptoms

Please indicate how often you have experienced the following symptoms during the past month.

Scale: 1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Always

No.	Symptom	1	2	3	4	5
1	Shortness of breath	□	□	□	□	□
2	Chest tightness or palpitations during daily activities	□	□	□	□	□
3	Frequent cough or phlegm	□	□	□	□	□
4	Fatigue after daily activities (e.g., climbing stairs)	□	□	□	□	□

APPENDIX G
TECHNOLOGY USAGE QUESTIONNAIRE

(Note: Used to assess participants' digital literacy and smartphone usage habits.)

1. **Education Level:**

   □ Primary school or below

   □ Junior high school

   □ High school / Technical school

   □ College / University or above

2. **Do you own a smartphone?**

   □ Yes

   □ No *(If No, skip the following questions)*

3. **Average daily smartphone usage time:**

   □ Less than 1 hour

   □ 1–3 hours

   □ 3–5 hours

   □ More than 5 hours

4. **Primary purposes of using a smartphone (Multiple choice):**

   □ Making calls / SMS

   □ Video calling with family/friends

   □ Social networking (WeChat, QQ)

   □ Reading news / Weather

   □ Watching videos (TikTok, Tencent Video)

   □ Shopping (Taobao, Pinduoduo)

   □ Mobile payments (Alipay, WeChat Pay)

   □ Other: __________

5. **Frequency of using social apps on smartphone:**

   □ Many times a day

   □ Once a day

□ Several times a week

□ Rarely

6. **Do you use your smartphone for online shopping?**

   □ Yes, frequently

   □ Occasionally

   □ Never

7. **Do you use mobile payments (e.g., scanning QR codes)?**

   □ Yes

   □ No

8. **Main difficulties encountered when using smartphones (Multiple choice):**

   □ Font size is too small

   □ Operation is too complex

   □ Don't know how to use certain features

   □ Physical reaction is slow

   □ Fear of making mistakes / breaking it

   □ Worried about information leakage/scams

9. **Are you willing to participate in training on how to use smart devices?**

   □ Yes

   □ No

APPENDIX H

PHYSICAL ACTIVITY SCALE FOR THE ELDERLY (PASE)

Note: Standardized scale adapted for the Chinese population.

Instructions: Please recall your activities over the past 7 days and select the most appropriate response for each item.

Part 1. Leisure, Walking, and Recreational Activities

No.	Activity	Never	Seldom (1–2 days)	Sometimes (3–4 days)	Often (5–7 days)	Less than 1 hour/day	1–2 hours/day	2–4 hours/day	More than 4 hours/day
1	Sitting activities such as reading, watching TV, or doing handcrafts	□	□	□	□	□	□	□	□
2	Walking outside for exercise or leisure	□	□	□	□	□	□	□	□
3	Light sport / recreational activities (e.g., light stretching, fishing, bowling)	□	□	□	□	□	□	□	□
4	Moderate sport / recreational activities (e.g., ballroom dancing, golf, Tai Chi)	□	□	□	□	□	□	□	□
5	Strenuous sport / recreational activities (e.g., jogging, swimming, aerobics)	□	□	□	□	□	□	□	□

Part 2. Muscle Strength / Endurance Exercise

No.	Item	Yes	No
6	Over the past 7 days, did you engage in any exercises specifically to increase muscle strength and endurance (e.g., lifting weights, push-ups)?	□	□

Part 3. Household, Caregiving, and Work Activities

No.	Item	Yes	No
7	Over the past 7 days, have you done any light housework (e.g., dusting, washing dishes)?	□	□
8	Over the past 7 days, have you done any heavy housework or chores (e.g., mopping floors, washing windows)?	□	□
9	Over the past 7 days, did you engage in home repairs (e.g., painting, wallpapering)?	□	□
10	Over the past 7 days, did you engage in lawn work or yard care?	□	□
11	Over the past 7 days, did you take care of another person (dependent child or adult)?	□	□
12	Over the past 7 days, did you work for pay or as a volunteer?	□	□

APPENDIX I

EXPERT VALIDATION QUESTIONNAIRE AND INTERVIEW GUIDE

Part 1. Expert Consent Form

Title of the Study:
Validating the Dynamic Barrier Framework for Older Adults' Adoption and Sustained Use of VR/MR-Based Exergames

Researcher:
XiaCheng Song, PhD Candidate, Universiti Kebangsaan Malaysia (UKM)

Purpose of the Study

You are invited to participate in an expert validation study of the Dynamic Barrier Framework (DBF), a conceptual model explaining the evolving barriers influencing older adults' adoption and sustained use of immersive VR/MR-based exergames. Your participation will help evaluate the framework's conceptual clarity, representativeness, practical usefulness, and academic rigor.

What Participation Involves

You will be asked to:

1. review a brief description and visual representation of the DBF;
2. complete a structured rating form;
3. optionally participate in a short follow-up interview.

The total time required is approximately 30–40 minutes.

Voluntary Participation

Your participation is entirely voluntary. You may withdraw at any time without penalty and may decline to answer any specific question.

Confidentiality

All responses will be kept confidential and used only for academic research purposes. No personally identifying information will be disclosed in the dissertation, publications, or presentations.

Consent Statement

By signing below, or by submitting your responses electronically, you confirm that:

you have read and understood the information above;

you voluntarily agree to participate in this expert validation study;

you consent to the use of your anonymized responses for research purposes.

Name of Expert: ______________________________
Affiliation / Position: ______________________________
Signature: ______________________________
Date: ______________________________

Part 2. Framework Overview

Dynamic Barrier Framework (DBF)

The Dynamic Barrier Framework (DBF) was developed from a longitudinal mixed-methods investigation of older adults' engagement with immersive VR-based Tai Chi exergames. The framework proposes that adoption and sustained use are shaped by three sequential yet overlapping phases, each characterized by a dominant barrier type whose influence changes over time.

Phase 1 – Initial Contact (Physical Adjustment)

At the beginning of use, the physiological barrier is dominant. Motion sickness, dizziness, muscle tension, and fatigue may discourage continued participation and contribute to early attrition.

Phase 2 – Decision Transition (Developing Trust)

As users gain familiarity, the socio-psychological barrier becomes more prominent. Trust, confidence, perceived safety, and usability perceptions influence whether older adults continue or withdraw, contributing to mid-stage attrition.

Phase 3 – Long-term Use (Maintaining Value and Interest)

For those who continue, the motivational barrier becomes dominant. Enjoyment, perceived competence, novelty, and sustained value determine whether long-term participation is maintained or whether later attrition occurs.

The framework also proposes three directional interrelations among barriers:

1. Physiological discomfort increases technology anxiety, contributing to early withdrawal.

2. Sustained physical strain may reduce motivation over time.

3. Social trust and support may strengthen persistence and reduce attrition.

Please refer to Figure 1 for the visual representation of the framework.

Part 3. Expert Background Information

Item	Response
Highest Qualification	□ PhD / MD □ Master □ Bachelor
Current Professional Title	□ Professor / Senior Industry Expert □ Associate Professor / Mid-Senior Industry Expert □ Lecturer / Assistant Professor / Industry Practitioner
Years of Professional Experience	□ Less than 5 years □ 5–10 years □ 11–20 years □ More than 20 years
Primary Area of Expertise (multiple selections allowed)	□ Gerontology / Aging Research / Aging-oriented Design □ Virtual Reality / Human–Computer Interaction / Game Design & Development □ Sports Science / Rehabilitation / Digital Health Products □ Psychology / Behavioral Health / User Experience Research (UXR) □ Educational Technology / Serious Games / Training System Development

Part 4. Expert Rating Form

Instructions

Please evaluate the Dynamic Barrier Framework (DBF) using the 4-point scale below.

Score	Meaning
1	Not relevant / unclear / not representative / not useful
2	Somewhat relevant / somewhat clear / somewhat representative / somewhat useful
3	Mostly relevant / mostly clear / mostly representative / mostly useful
4	Highly relevant / very clear / highly representative / highly useful

Please rate each item on the following four dimensions:

1. Relevance

2. Clarity

3. Representativeness

4. Practical Usefulness

If you assign a rating of 1 or 2 for Relevance, please briefly explain your concern.

Evaluation Item 1

Phase 1 definition and physiological barrier

Is the definition of Phase 1: Initial Contact (Physical Adjustment) and its dominant physiological barrier conceptually clear and appropriate?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 2

Phase 1 causal pathway and early attrition

Is the proposed pathway from physical intolerance and technology anxiety to early attrition accurate and sufficiently representative?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 3

Phase 2 definition and socio-psychological barrier

Is the definition of Phase 2: Decision Transition (Developing Trust) and its dominant socio-psychological barrier conceptually clear and appropriate?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 4

Explanatory adequacy of the socio-psychological barrier

Does the socio-psychological barrier (e.g., trust, confidence, perceived safety) sufficiently explain mid-stage attrition?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 5

Phase 3 definition and motivational barrier

Is the definition of Phase 3: Long-term Use (Maintaining Value and Interest) and its dominant motivational barrier conceptually clear and appropriate?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 6

Explanatory adequacy of the motivational barrier

Does the motivational barrier (e.g., enjoyment, engagement, perceived competence) adequately capture the key determinants of sustained participation?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 7

Cross-stage mechanisms (A/B/C)

Are the three proposed cross-stage mechanisms sufficiently clear, accurate, and useful for explaining dropout and persistence pathways?

(A: Physiological discomfort ↑ → Anxiety ↑; B: Physical strain ↑ → Motivation ↓; C: Social trust ↑ → Persistence ↑)

Dimension	1	2	3	4

Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 8

Three-stage attrition structure

Are the three attrition stages (early, mid, and late attrition) appropriately defined and representative of real participation trajectories?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 9

Overall coherence of the framework

Is the overall logic of the framework coherent, including the transitions between phases and the relationships among barriers?

Dimension	**1**	**2**	**3**	**4**
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Evaluation Item 10

Accuracy and readability of the framework diagram

Is the framework diagram accurate, readable, and effective in communicating the structure and relationships of the DBF?

Dimension	1	2	3	4
Relevance	□	□	□	□
Clarity	□	□	□	□
Representativeness	□	□	□	□
Practical Usefulness	□	□	□	□

Comments:

Part 5. Semi-Structured Interview Guide

1. Uniqueness and Theoretical Contributions of the Framework

Option	Statement	Select
A	The three-phase dynamic structure (physiological → trust → motivation) offers strong explanatory power.	□
B	It explains different attrition mechanisms across stages effectively.	□
C	Integrating physiological and bodily barriers into a technology-use framework is innovative.	□
D	It appropriately emphasizes the importance of trust-building in continued participation.	□
E	It is grounded in longitudinal evidence from repeated VR sessions.	□
F	It is specifically tailored to immersive VR/MR exergame use among older adults.	□
G	Compared with TAM and UTAUT, it better captures dynamic change and lived experience.	□
H	Other (please specify)	□ ____________________

Open-ended supplement:

What do you consider the most important theoretical value of the DBF?

---

2. Reasonableness of Phase Mechanisms and Transition Points

Option	Statement	Select
A	The transition from initial physiological discomfort to trust-building is clearly described.	□
B	The reduction of technology anxiety through increased familiarity is reasonable.	□
C	The transition from trust-building to motivation maintenance is adequately explained.	□
D	Cumulative physical load may affect later-stage motivation.	□
E	Some transition points between phases remain insufficiently specific.	□
F	Some hidden factors may be missing (e.g., health status, cognitive functioning, family support).	□
G	External conditions such as equipment, setting, or environment are underrepresented.	□
H	Other (please specify)	□ ______

Open-ended supplement:

Which phase mechanisms most need further refinement or strengthening?

---

3. Alignment with Real-World Experience

Option	Statement	Select
A	Initial physiological discomfort is a major cause of dropout.	□
B	Technology anxiety tends to peak during the first one or two sessions.	□
C	Once trust is established, participation becomes more stable.	□
D	Social support from family or peers strongly affects persistence.	□

E	In later phases, motivation, interest, and novelty are crucial to continued participation.	□
F	Perceived health or functional improvement is an important driver of sustained use.	□
G	Dropout often occurs in the middle of the experience period, not only at the beginning or end.	□
H	Some parts of the framework do not align with my experience.	□
I	Other (please specify)	□ ____________

Open-ended supplement:

Please share a practical case that either supports or contradicts the DBF.

---

4. Potential Biases, Limitations, and Areas for Revision

Option	Statement	Select
A	The boundaries among the three phases may be more blurred in practice.	□
B	Physiological discomfort may reappear later rather than being limited to the initial phase.	□
C	Trust may fluctuate over time rather than increase linearly.	□
D	Motivation may vary throughout the process rather than emerging mainly in the later phase.	□
E	Attrition is often driven by multiple interacting factors rather than a single dominant mechanism.	□
F	External factors such as equipment, setting, and cost are insufficiently discussed.	□
G	Individual differences are substantial and may require subgroup-specific interpretation.	□
H	Overall deviations are minor; only limited revision is needed.	□
I	Other (please specify)	□ ____________

Open-ended supplement:

From your perspective, how should the DBF be revised or supplemented?

---

5. Priorities for Future Refinement

Option	Statement	Select
A	Refining the conceptual definitions of the three barrier types	□
B	Clarifying phase boundaries and key transition points	□
C	Strengthening the theoretical justification for the cross-stage mechanisms (A/B/C)	□
D	Providing clearer theoretical comparison with TAM / UTAUT	□
E	Adding more quantitative visualizations (e.g., timelines, trend charts)	□
F	Highlighting subgroup differences among older adults	□
G	Optimizing the visual presentation of the framework diagram	□
H	The framework is already mature; only minor wording refinement is needed	□
I	Other suggestions (please specify)	□ ________________

Open-ended supplement:

What is the single most important aspect that should be revised first?