Cyprus University of Technology | Faculty of Fine and Applied Arts

Doctoral Dissertation

Virtual Reality-based Simulation of Age-related Declines

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VIRTUAL REALITY-BASED SIMULATION OF AGE-RELATED DECLINES

Abstract

Albeit utterly important in an aging world, understanding and addressing elderly people's needs is no easy task, as aging relates to a complex mechanism of a natural process affecting the quality of elderly life in different ways. For this, harnessing Virtual Reality, the present research proposes a perspective-taking approach that simulates common age-related declines to provide a first-hand experience of the latter and their associated challenges. At an initial stage, the research focused on the development and the effectiveness assessment of a prototype simulation in different cases, addressing mainly the need for contemporary technological tools to facilitate elderly-friendly design. The results demonstrated its potential to induce the sense of being older and identify design weaknesses from the perspective of elderly impaired adults. The proposed simulation even outperformed other methods used for this purpose, on several measures. At a second stage, focusing on vision, a novel technical approach was implemented to generate procedural declines, giving the possibility to experience their different nuances in virtual environments. To validate the soundness of the simulation vis-à-vis its intended purpose, three tests were conducted and the results obtained were examined with regards to actual data, to assess whether the simulated effects induce similar impairments to the actual declines. Taken together, the results demonstrate that the proposed approach can be leveraged as a supportive tool in the design process, and in a broader context for understanding physical problems related to aging and how these affect the life of many elderly people.

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Dedication

To my father, in loving memory.

Chapter One

Introduction

Human beings are under the state of constant changes which form and define different phases occurring during lifetime, affecting both the body and mind (G. Payne and D. Isaacs, 2012). One of these phases is the elderly adulthood, also referred to as *Third Age*. From the deterioration of vision to the spine curvature and from the loss of muscle strength to hearing impediment, elderly adulthood is often characterized by increased levels of difficulty, but not necessarily incompetence, despite the general perception that elderly people are weak and cannot be self-dependent (Adams-Price and Morse, 2009).

According to the projections of population growth, by 2050, in almost all regions of our planet, one in four people will age over 60 years old (Desa, 2015). While this demographic change reflects a positive aspect, that is the increase of life expectancy, it also signifies a rising prevalence of problems associated with aging (Tham et al., 2014; Fukuoka and Afshari, 2017), which expect to affect the quality of life (QoL) of many elderly people.

From a social point of view, this change calls for a comprehensive response to the needs of older people and their rights as active citizens of society; an issue that can affect the social balance, if left unaddressed.

This demographic transition brings about changes, from the commercial standpoint as well; elderly users/consumers, referred to as "silver market", are becoming a considerable group. As reported by Kohlbacher and Herstatt, 2010: *"Increasing in number and share of the total* *population while at the same time being relatively well-off, this market segment can be seen as very attractive and promising, although still very underdeveloped in terms of product and service offerings."*

Taken together, one can understand the emergence of placing emphasis on the wellbeing of the elderly population.

1.1 Research Context

An extensive list exists in the literature with approaches focusing on elderly people: from understanding their needs through observations, discussions and their integration in the design process and policy making (Peek et al., 2016; Merkel and Kucharski, 2019; Lilleheie et al., 2019), to addressing their necessities through dedicated solutions for aging in place, rehabilitation etc. (Rashidi and Mihailidis, 2012; Intiso et al., 2012). The last years, Virtual Reality (VR) was also added to the list (Cherniack, 2011; Corregidor-Sánchez et al., 2021; Dermody et al., 2020) providing from simulations of age-related physical and cognitive declines (Ehrenman, 2003; Jütten, Mark, and Sitskoorn, 2018) to virtual spaces, where elderly people can follow exergaming programs to improve their physical and cognitive condition (Kamińska et al., 2018; Cherniack, 2011).

This introductory chapter of the dissertation commences with the analysis of the two main thematics of the present research work. First, the factors of accessibility and ageism that affect the QoL of elderly population are presented. Then, an introduction to VR is provided along with a brief review of its history, to understand how it evolved from an entertainment medium to an "ultimate empathy machine" (Barbot and Kaufman, 2020) and an efficient support tool in the design process (Berg and Vance, 2017). After the analysis of the main concepts, the objectives of the present research along with its specific research questions are specified. Finally, the structure of the dissertation is presented, providing information on the chapters to follow.

1.1.1 Elderly Population and QoL

According to elderly people themselves, quality of life essentially means functional activity and physical health, but also healthy interpersonal relationships (Wilhelmson et al., 2005). As such, the elderly people's QoL can be affected by factors such as the inaccessibility to products and services, and the stereotyping and negative behaviours owing to their age. These factors and the way in which they affect elderly people's lives are discussed below.

Accessibility

For the elderly, a common daily task, such as prolonged walking can be laborious and time-consuming (Pereira and Gonçalves, 2011). Furthermore, the use of specific services, for instance e-services (Bevan, Claridge, and Petrie, 2005) and products, such as pharmaceutical packages (Wogalter and Dietrich, 1995) can be inhibited by the accumulated effects of the aging process. Thus, for example, small print that is illegible even from people with acute vision, is often indecipherable by low vision elderly people.

In many cases, the problems faced by the elderly are aggravated by the fact that their needs are not adequately addressed. This is shown by widely used amenities that are not compatible and suitable for elderly users, such as main public outdoor infrastructure, like roads and pavements (Turel, Yigit, and Altug, 2007; L.-h. Lee and S.-s. Chen, n.d.).

Within this context, difficulties faced by elderly people are often attributed to insufficient design, which fails to consider the characteristics of a large portion of end users, such as the elderly population. Lindsay et al., 2012 provide a comprehensive example: *"A hearing-impaired man watching a film presentation with subtitles in a museum is impaired but not disabled. But if the museum fails to provide subtitles, he becomes disabled as a direct consequence of the actions or inactions of the technicians, curators, and managers of the museum. The disability is a consequence of a failure in design."*

Recognizing this weakness, many initiatives have been pursued to address the needs of the elderly population, from individual studies to global projects. For example, around a decade ago, World Health Organization (WHO) launched a global mobilization project dedicated to Age-Friendly Cities, depicting the effort to ameliorate the QoL of elderly people. This project concerned a number of domains, such as healthcare services, housing, transportation and outdoor spaces (Neal and DeLaTorre, 2009).

Continuing the effort for a collective response, the United Nations recently proclaimed the current decade (2020-2030) as the “Decade of Healthy Ageing", targeting four key areas of action: developing age-friendly environments, providing appropriate health care services and access to long-term care, and eliminating ageism (Dugarova et al., 2017; WHO, 2020).

Ageism

Age is one of the first characteristics noticed when we meet someone (Cuddy and Fiske, 2002) and among the “big-threes” of social categorisation, together with gender and race (Stolier and Freeman, 2016). Unfortunately, this categorisation is susceptible to stereotypical views, biases and social discrimination, known with the general term *ageism*.

Ageism concerns both implicit and explicit attitudes; in the book by E. B. Palmore, 2003 several forms of ageism are described: from changes in the way of speaking to the elderly, like *baby talk* or *elderspeak*; to thinking that elderly people are deprived (*compassionate ageism*); to the anxiety of the aging itself (*gerontophobia*) and *terror management* which results from the association of elderly to death. Interestingly, ageism even exists among the elderly themselves (Bodner, 2009).

In any case, ageism has a significant impact on many aspects of elderly people’s life, like on their physical and cognitive functions, and it can even affect elderly people’s will to live (Nemmers, 2005).

1.1.2 Virtual Reality

Despite the inherent abstractness of the term "Virtual Reality", there are a number of definitions in the related literature (Steuer, 1992; Sherman and Craig, 2003). A widely adopted definition, reflecting the present research, is quoted below.

"Virtual reality is a high-end user computer interface that involves real time simulation and interactions through multiple sensorial channels modalities [...]" (Burdea and Coiffet, 2003).

Although VR has existed for more than half a century (Rheingold, 1991), only the last decade appears to be growing to such a significant extent. VR technology is now at the spotlight and does not resemble the first VR systems of the 60s (Mazuryk and Gervautz, 1996), in terms of compactness, affordability and quality.

Also, the range of VR technologies' application areas has been developed since then. During the 90s, VR began to be used extensively for purposes beyond amusement (Wiederhold, 2000). The widening of sectors that VR was applied is perceived by the number of publications issued during this period. Indicatively, in 1993 there were no professional publications, while in 1998 there were 61 (Wiederhold, 2000). As more and more researchers began to realize that VR could be potentially employed for important aspects, many VR applications emerged for experimental purposes: VR applications addressing various phobias such as acrophobia (Opdyke, Williford, and North, 1995), fear of flying (Rothbaum et al., 1996) and spider phobia (Carlin, Hoffman, and Weghorst, 1997) exemplify this decade. Also, during this period many VR applications were developed for clinical purposes: VR surgical simulators, VR based diagnostics and cognitive rehabilitation VR systems are a few examples (Satava, 1993; Taffinder et al., 1998; Székely and Satava, 1999; Mori et al., 1996; Grealy, D. A. Johnson, and Rushton, 1999).

The new millennium was destined to be of decisive importance for the VR field. The potential of VR continued to be harnessed in various domains such as engineering and education (Mujber, Szecsi, and Hashmi, 2004; Kaufmann, Schmalstieg, and Wagner, 2000), but what brought VR to the forefront, especially during the last years, is probably the VR technology itself. There are a lot of VR devices currently in the market offering a wide variety of options: low-cost and easy-to-use VR solutions, like Google cardboard VR; standalone headsets with active tracking system, like Oculus Quest; headsets with a large field of view (FOV) like the 200 degrees of Pimax Vision 8K X; and headsets that are consistent with technological advances and trends, like eye-tracking integration by Tobii in the VIVE pro eye headset, and physiological data capturing and facial expressions tracking in the HP Reverb G2 Omnicept (MacIsaac, 2015; Hillmann, 2019; Cook and Lischer-Katz, 2021; Sipatchin, Wahl, and Rifai, 2021; Yao, Lympouridis, and Zyda, 2021).

As a result of this continuous advancement and the availability of the VR technology to the general public, an ever-increasing number of studies have been conducted using VR. This is shown by the exponential fashion mode of VR-related research studies, after the release of the first commercial headsets (Figure 1.1).

Through the plethora of VR-related topics, two thematics that are relevant to the present research are examined and discussed below, namely the VR-based perspective taking approach (Ventura et al., 2020), and the use of VR in the design and manufacturing process (Berg and Vance, 2017).

VR and Perspective Taking

Perspective taking has been recognized as a source of empathic concern (Batson, 2009). According to Davis et al., 1996, when a person takes the perspective of someone else, the supposed distance separating their thoughts and feelings decreases, leading the former to consider that the thoughts and feelings of the other one are his own. Perspective taking can be affective, when the focus is on emotions, or cognitive, when the focus is on the thoughts (Healey and Grossman, 2018).

There has been an increasing amount of literature on leveraging VR to various perspective-taking scenarios. Virtual Reality Perspective Taking (VRPT) appears to have a positive

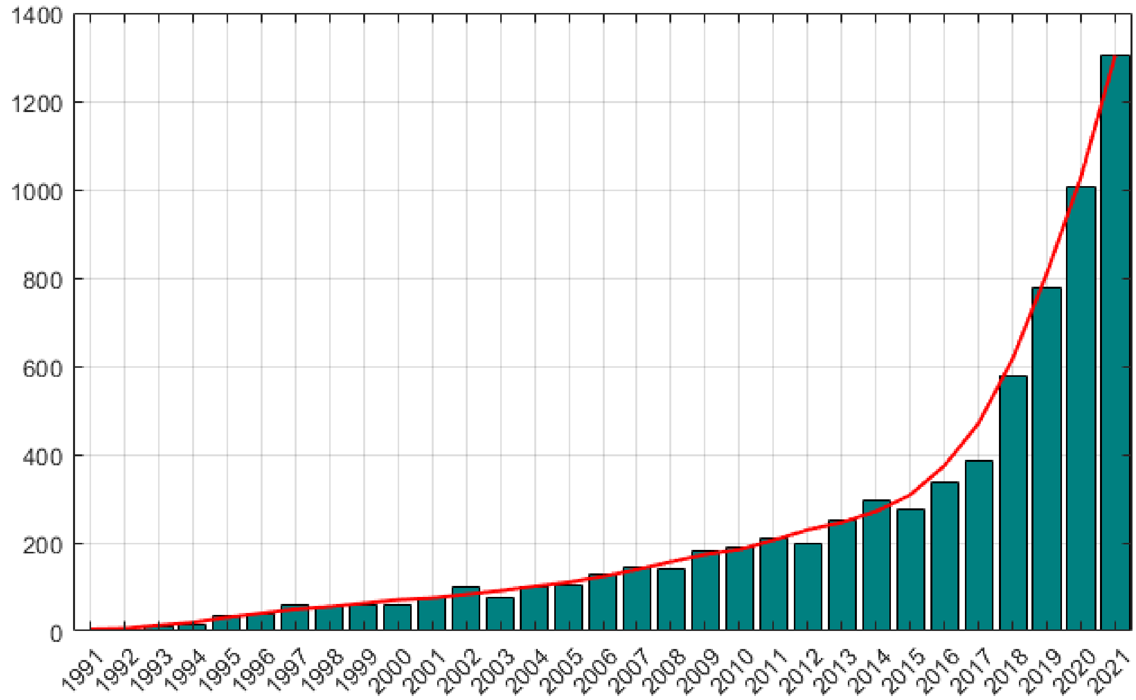

Figure 1.1 PubMed results of research studies whose title contained the keyword "Virtual Reality"

effect on prosociality, in medical education, against bullying, and racial and gender bias, to mention a few examples (Van Loon et al., 2018; Raij et al., 2009; Ingram et al., 2019; Peck et al., 2013; Beltran et al., 2021).

According to a meta-analysis conducted by Ventura et al., 2020, the two main reasons why VR is used for empathy-inducing purposes are: first, its possibility to illude the real and second that it can provide a safe and controlled environment to investigate hypotheses overcoming ethical obstacles, encountered in real experimental setups.

VR in the design and manufacturing process

Designing systems, products and services is a multi-tiered process, which involves various phases such as conceptualization and prototyping, aspects such as collaboration and decision-making, and concepts such as sustainability and accessibility. To support these aspects and

the design process in its different stages, both from an operational and economic perspective, many technological approaches have been employed; *virtual prototyping*, *virtual manufacturing* (Bharath and Rajashekar, 2015), and the recently devised *digital twin* (Grieves, 2014), to name a few.
Regarding VR, its use in manufacturing and design processes dates back to 1999 (Berg and Vance, 2017) and is mainly related, but not limited to, the initial stages of the processes.
In a survey by Berg and Vance, 2017, examples of VR technologies used in these processes to support decision making, range from driver visibility assessment and aesthetic design in the automotive industry, to communicating ideas to the members of the team. The effectiveness of VR in such cases could be epitomised by the fact that it *"allows people to make decisions about environments in increasingly natural ways"* (Berg and Vance, 2017).

It is pertinent to note that the above categories were presented as two separate fields; the purpose here was to provide some indicative examples of application areas of VR, related to the topic of the present research work. In fact, these categories are not distinct. There are cases, for example, in which VR is used for empathy in design (X. Hu, Nanjappan, and Georgiev, 2021). The Venn diagram in Figure 1.2 illustrates the relationships between the different intersecting fields.

1.2 Research Questions and Objectives

The objective of this research work is to examine the prospect of harnessing VR, to provide a perspective-taking experience through the eyes of impaired elderly adults.
The work focuses on the simulation of problems in vision, however, the simulation of other age-related problems, such as in hearing and mobility, has also been tested at an initial stage, mainly to enhance the overall simulated experience.
The aim is to lay the foundations for a validated VR-based simulation tool that can help visualize specific age-related declines and understand, first-hand, how these can affect daily

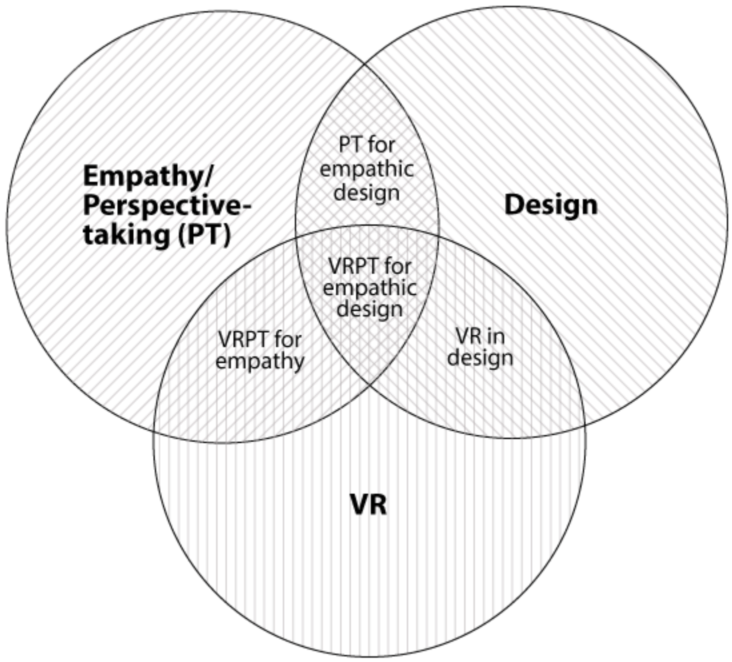

Figure 1.2 Relationships between Design, Empathy through Perspective-Taking (PT) and VR. Note that the size of the circles is random and does not indicate the number of studies per field.

tasks, service/product usage and, in broader terms, the QoL.

More precisely, the present research work sought to address and assess two aspects of the simulation: the *effectiveness*, and the *validation*. For this, the following research questions (RQs) were addressed:

RQ1 *Can the proposed simulation effectively induce the sense of being an elderly adult?*

Addressing this RQ is fundamental to assess whether the simulation can convey the proper message, that is viewing and interacting with a virtual environment (VE) from the eyes of elderly persons with common age-related deficits.

RQ2 *To what extent the proposed simulation can be useful in elderly-friendly design?*

The present research focuses on the design of products, especially essential ones. This RQ focuses on the effectiveness of the proposed simulation in the process of designing products and services that can be used by elderly adults with common problems in vision.

RQ3 *Do simulated effects in the VE represent the actual deficits of impaired elderly adults?*

Through this RQ, the present research aims at investigating the accuracy of the simulated effects in vision, by comparing them with self-reported descriptions of actual patients.

RQ4 *Can the proposed simulation effectively induce similar difficulties in VEs to the ones experienced by actual elderly patients?*

Here, emphasis is given on the way the deficits impede performance in visual tasks, and whether the simulated effects could induce similar difficulties in the VEs in people with healthy vision.

In addition to the four main RQs listed above, a secondary research question was considered:

RQ5 *To what extent the proposed simulation can help in changing negative views against aging and the elderly?*

This additional exploratory question aims at investigating whether the exposition to the simulation could result in a positive change in potentially ageist views in young population.

The present research follows an iterative design methodology. That is, as a central stage of this research, the development of the simulation was repeated to ensure a higher level of accuracy of the latter, as well as its consistency with the continuous technological advances in the field of VR.

The research work is composed of two phases, each one serving to address a different aspect:

1. The first phase was exploratory and included the initial development and the evaluation of the effectiveness of the proposed simulation in different cases, pertaining mainly to

design scenarios.

2. The second phase was revisionary and mainly focused on the technical aspect for the development of a validated, modular simulation.

1.3 Research structure

Based on the research context that was given precedently, the work presented in this dissertation is structured as follows:

Chapter 2 - Medical Context

The medical context of the research is analysed based on a thorough review of the medical literature on age-related declines, with particular emphasis on vision.

Chapter 3 - Related Work

Several relevant research studies on the simulation of age-related declines are featured and discussed.

Chapter 4 - Overview of the Methodological Framework

Based on the research questions set, an overview of the two-phased methodological framework of this research is explained.

Chapter 5 - Phase 1: Effectiveness in Conceiving the Simulated Declines and their Associated Challenges

The first phase of the research is detailed, presenting the methodology followed, along with the three different studies conducted and their results.

Chapter 6 - Phase 2: Technical Approach and Methodology of Age-related Visual Deficits' Simulation

The second phase of the research is explained, introducing the technical approach and the methodology.

Chapter 7 - Phase 2: Validation

The method followed to assess the simulation's validation is analysed and the results obtained from the experimental evaluation are presented.

Chapter 8 - Conclusions

General conclusions regarding the overall research work are presented, together with limitations and suggestions for future work.

Chapter Two

Medical Context

The present research work deals with the simulation of physical declines associated with advancing age. For this, a detailed investigation into the related medical literature is necessary to understand the pathology, the pathophysiology, the clinical features of the declines and how the latter affect the overall QoL of many elderly people. In this chapter, an analysis of the medical background on which this research was based is provided.

Before delving into the analysis though, it is important to provide an explanation on the use and scope of the term "elderly", in the framework of this research.

2.1 Defining "elderly"

This section provides the characteristics compounding the elderly population in the context of this research.

– **Age**

"Elderly people" and "old age" are terms characterising age groups, yet they are relative and there is no precise age over which someone is clearly considered an elderly person (Wiles, 1987). In most developed countries worldwide, people over 65 years old are referred to as elderly, since this age is related to the retirement (Kowal and Dowd, 2001). In the context of this research, the term "elderly" mainly refers to people over

75 years old, as this age group is characterized by the greatest demand in medical and social care (Sixsmith, 2000).

- **Autonomy**

  The process of aging is unique for different individuals (Kowal and Dowd, 2001) and the onset and progression of age-related deficits depend on many factors apart from age, such as the hereditary traits (Klein, Mauldin, and Stoumbos, 1994) and the overall lifestyle (Taira et al., 2002). The present research refers to elderly people who experience physical age-related problems, such as visual and hearing deterioration, but do not suffer a total loss and can live an autonomous life.

- **Declines**

  Aging is a multidimensional phenomenon that affects many aspects of a person's life, from physical changes to complex consciousness disorders and behavioural changes (G. Payne and D. Isaacs, 2012; Geerligs et al., 2015). The latter include, inter alia, difficulties in decision-making process, mood and sleep disorders, memory and attention deficiencies (Tymula et al., 2013; Charney et al., 2003; Green et al 2011; Racine and Cabeza et al 2009). The multidimensional nature of aging renders the overall process of modelling age-related changes, a highly complex task. Following the concept of aging suits, the proposed research focuses on changes in human senses and the musculoskeletal system. As such, it does not involve simulating parameters, like cognitive declines. Succinctly put, it is hypothesized that the elderly people referred to in this research are *cognitively advantaged* (Dixon and Frias, 2014).

In the remainder of this chapter, common age-associated changes in the senses and the musculoskeletal system are described and their clinical features are provided. Special emphasis is laid on visual declines, given its salience in the present research.

2.2 Age-related Declines in Vision

Human visual system (HVS) is first and most affected by age, with the first sign appearing in the early adulthood, that is the gradual decline of visual acuity (L. Frisén and M. Frisén, 1981). During middle adulthood, visual problems such as presbyopia begin to affect many people's QoL (Luo et al., 2008). During late adulthood, the deterioration of visual acuity is particularly evident, as several diseases like cataract, macular degeneration and glaucoma significantly affect the vision of many elderly people, hence their daily functioning (G. Payne and D. Isaacs, 2012).

A number of studies have explored the link between the visual problems and risks incurring in the elderly population. A study by Owsley et al., 1991 indicated that older people represent the age group that accounts for most vehicle accidents, suspecting visual problems among the factors of this. Another study by Harwood, 2001 concluded that the chances of falling in older people double due to visual problems. Problems in vision seem to affect elderly people's life in such a significant extent that according to Forsell, Jorm, and Winblad, 1997 are among the causes associated with suicidal thoughts in the elderly.

In the following subsections, specific common eye diseases of the elderly are described. Table 2.1 shows a list of visual declines, their symptomatology, classification, non-invasive methods of detection and factors that influence their onset and deterioration.

2.2.1 Cataract

Cataract is one of the most prevalent, yet reversible, eye disorders associated primarily with age. Based on estimations of the WHO, about 20 million people lack useful vision due to cataract disease (Pascolini and Mariotti, 2012). According to Bloemendal et al., 2004, the incidence of age-related cataract is: 45% for adults between 55–64 years old, about 75% for adults 65-74 years old, and about 88% for people over 75 years old.

Age-related cataract is progressive and is associated with the increase in lens density,

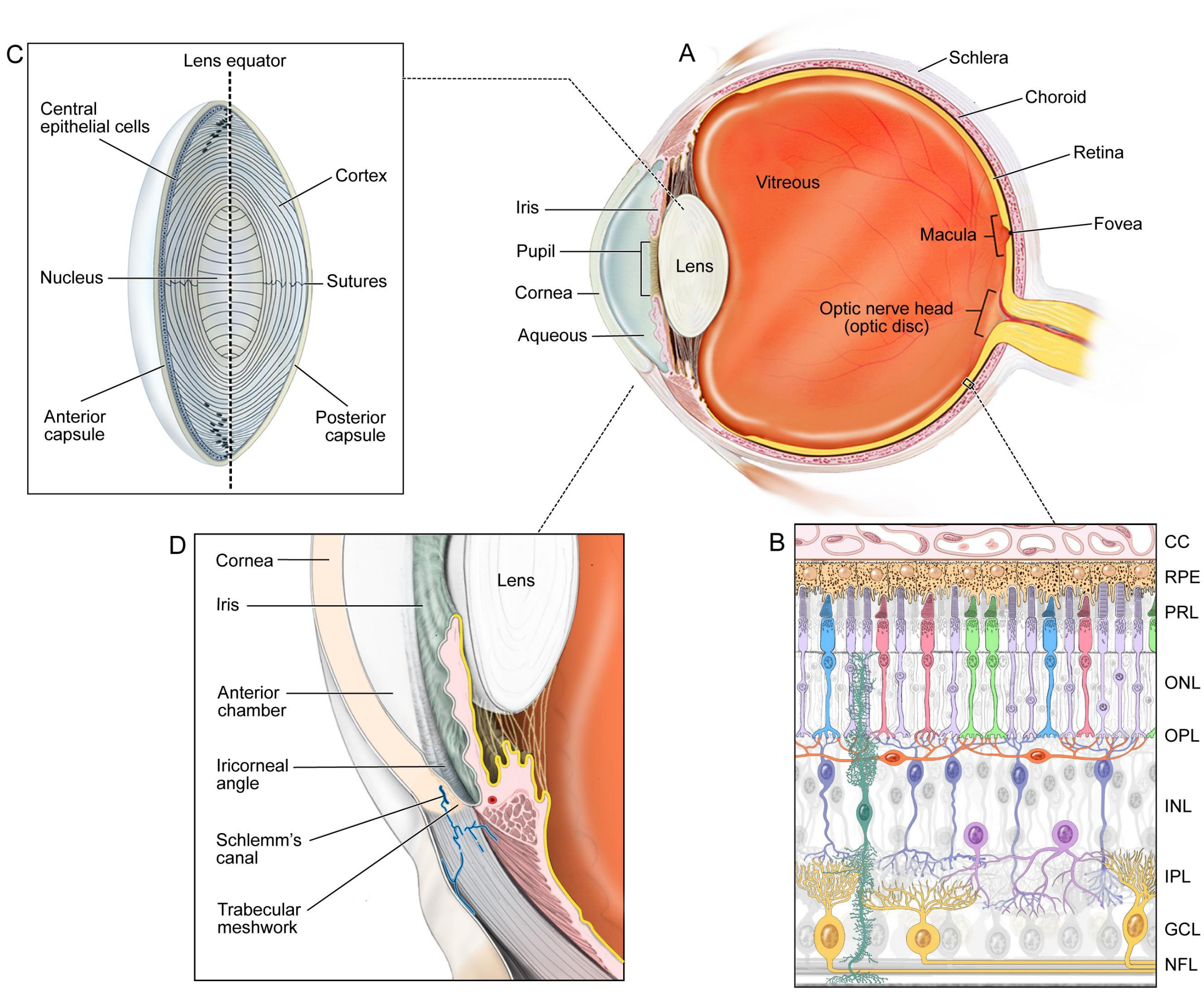

Figure 2.1 Anatomy of the eye © National Eye Institute (NEI)

due to composition and structure changes in the lens (Bloemendal et al., 2004; Aliancy and Mamalis, 2017), giving a characteristic appearance to the affected eyes (see Figure 2.3). This resulted opacification obstructs the light from reaching the retina properly, hindering the clarity of vision (Leibowitz et al., 1980). Here, it is pertinent to mention that a light reduction also occurs in non-cataract patients. More specifically, after the age of 30, the quantity of light reaching the retina is linearly reduced, resulting in a reduction to one third at the age of 60, compared to the corresponding amount at the age of 20 (Gittings and Fozard, 1986; V. G. Payne and L. D. Isaacs, 2017).

Figure 2.2 Simulation of the vision of a cataract patient. © National Eye Institute (NEI)

There are three common cataract types, based on the affected area of the lens: Nuclear Cataract (NUC), Cortical Cataract (COR), and Posterior Subcapsular Cataract (PSC) (Thylefors et al., 2002). Depending on the type of cataract, this disease can be associated with a series of symptoms, some of which are described below.

In NUC, the *nucleus* of the lens (Figure 2.1, C) is affected, resulting in yellow to brown opacification (see Figure 2.3) (Thylefors et al., 2002; Quillen, 1999). NUC is associated with gradual contrast decrease, and difficulties in discerning colors and recognizing faces (see Figure 2.2) (Allen and Vasavada, 2006; Thylefors et al., 2002).

In COR, the anterior cortex is affected (Figure 2.1, C) and is characterized by the appearance of "radial spokes" (see Figure 2.3) and more central opacification (Thylefors et al., 2002; Quillen, 1999). Some clinical features of this form are related to driving difficulties due to glare, especially during night driving. Instead, activities in the daylight are easier because of the pupil contraction (Thylefors et al., 2002).

In PSC, the posterior region of the lens is affected (Figure 2.1, C) and contrary to COR, it poses more problems in activities during daylight and less problems at low light, when the pupil is dilated (Thylefors et al., 2002).

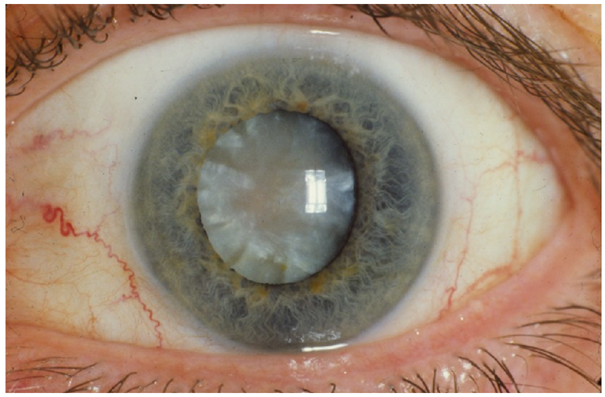

Figure 2.3 A hypermature age-related cortico-nuclear cataract with a brown nucleus. © National Eye Institute (NEI)

2.2.2 Age-related Macular Degeneration

Age-related Macular Degeneration (AMD) is a common disease among the elderly population (Bourne et al., 2013), expecting to affect 288 million people in 2040 (Wong et al., 2014). One of the first manifestations of AMD is distorted vision (Tolentino et al., 1994) appearing in the center of the VF. According to self-reported data, this distortion, known as *metamorphopsia*, is causing the image to appear "bendy", "crooked", "wavy", "wobbly" or "wiggled" (Taylor et al., 2018).

AMD severity is classified into three stages: early, intermediate and advanced (A.-R. E. D. S. R. Group et al., 2000). Early AMD is a mild stage, not often characterized by particularly distinct symptoms (Jager, Mieler, and Miller, 2008). Later, symptoms become more intense with some patients, for instance, complaining of disability glare (Taylor et al., 2018). At the late stage of AMD, symptoms become prominent with visual scotomas[1] (Figure 2.4) in the central or pericentral visual field (VF) for the dry (non-neovascular) form and more severe symptoms such as sudden visual loss due to retinal hemorrhage, for the wet (neovascular) form of advanced AMD (Jager, Mieler, and Miller, 2008).

[1]Spots hindering vision appear in the form of relative scotomas and may evolve to absolute scotomas (Nazemi et al., 2005).

Figure 2.4 Simulation of macular scotomas occuring mainly in patients with advanced AMD. © National Eye Institute (NEI)

2.2.3 Glaucoma

Glaucoma—the main cause of irreversible blindness globally (Weinreb, Aung, and Medeiros, 2014)—is a set of visual deficits (Quillen, 1999) in which the outflow of the aqueous humour, the fluid filling the anterior and posterior chambers of the eye (Figure 2.1, D), is obstructed leading to increased intraocular pressure (IOP) (M. Johnson, 2006). The IOP, in turn, damages the retinal ganglion cells (RGCs) and causes thinning of the nerve fiber layer (C. X. Hu et al., 2014). The expression *"silent thief of sight"* is used to describe the insidious nature of glaucomatous damage that often goes unnoticed, especially at the early stages (D. A. Lee and Higginbotham, 2005).

There are two main types of glaucoma: Open Angle Glaucoma (POAG) and Angle-closure Glaucoma (PACG), with the most common being the POAG (D. A. Lee and Higginbotham, 2005). In POAG, initially, a peripheral VF loss occurs. Then, when the optic nerve starts to get damaged, this can cause central vision loss. PACG owes its name to the narrowness of the angle between the iris and the cornea that follows the damage. This blocks the aqueous humour flow, causing problems such as blurry vision and visual haloes (D. A. Lee and Higginbotham, 2005).

According to Khaw and Elkington, 2004, in the terminal stage of glaucoma, a severe lack of peripheral vision may occur, causing an effect known as “tunnel vision”. Note that tunnel vision is used in several simulations of glaucoma vision, available online (see Figure 2.5). However, studies from Crabb et al., 2013; and C. X. Hu et al., 2014 question the frequent occurrence of this symptom in patients with glaucoma and argue that the loss of peripheral vision is manifested mainly as “blurred patches” (Crabb et al., 2013).

Figure 2.5 Simulation of tunnel vision in a glaucoma patient. © National Eye Institute (NEI)

2.2.4 Diabetic Retinopathy

As its name suggests, Diabetic Retinopathy (DR) is a visual complication of diabetes which affects the retina (Porta and Bandello, 2002). The problem stems from the *retinal vascular permeability* that hyperglycemia—or high blood glucose—causes. This damage can result in the formation of microaneurysms and the so-called *exudates* (Quillen, 1999; Crawford et al., 2009). The latter are molecules, such as lipids and proteins that enter the retina due to capillary leakage and can be concentrated in the center of the macula, affecting the visual acuity (Ferris et al., 1996).

The above are clinical signs of the first stage of DR, which is called non-proliferative diabetic retinopathy (NPDR). Mild, moderate and severe stages are the three subclassifications of NPDR (Bhardwaj, Jain, and Sood, 2021). During NPDR, symptoms, like blurry vision, dark spots (2.6) and floaters may occur (Morello, 2007), but at this stage DR can also be asymptomatic (Sisodia, Nair, and Khobragade, 2017).

The second stage of DR is called proliferative (PDR). At this stage, the damage can lead to ischemia—the lack of oxygen to the retinal cells (Semeraro et al., 2015). As a result of this, retina starts to produce new blood vessels, a process referred to as neovascularization. After this stage, severe complications may occur, like haemorrhage in the vitreous or retinal detachment (Quillen, 1999).

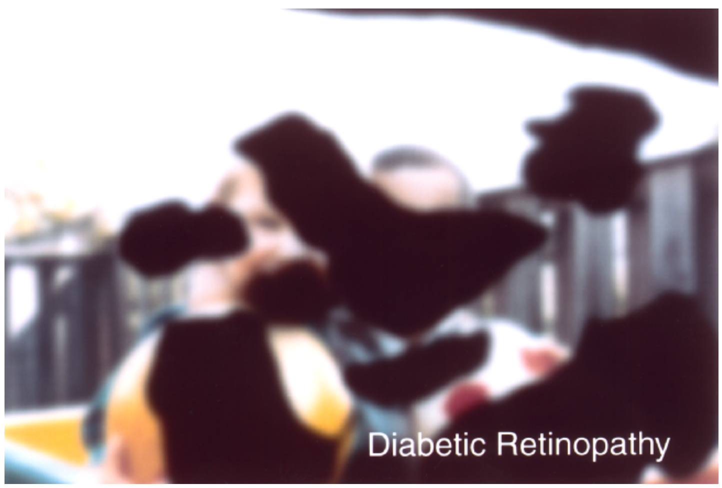

Figure 2.6 Simulation of vision in Diabetic Retinopathy. © National Eye Institute (NEI)

It is important to note that DR is not directly linked to aging. In fact, it is the leading cause of vision loss in people of working age (Porta and Bandello, 2002). However, DR is closely related to the duration of diabetes (Yau et al., 2012), affecting 80-85% of patients who suffer from diabetes for more than ten years (Sisodia, Nair, and Khobragade, 2017). Therefore it is often observed in elderly diabetes patients, but not necessarily to the extent that this condition threatens their vision (Hirvelä and Laatikainen, 1997).

Remarkably, glucose levels and visual symptoms in DR are directly linked, with several patients being aware of this in the study by Coyne et al., 2004. This correlation is reflected in

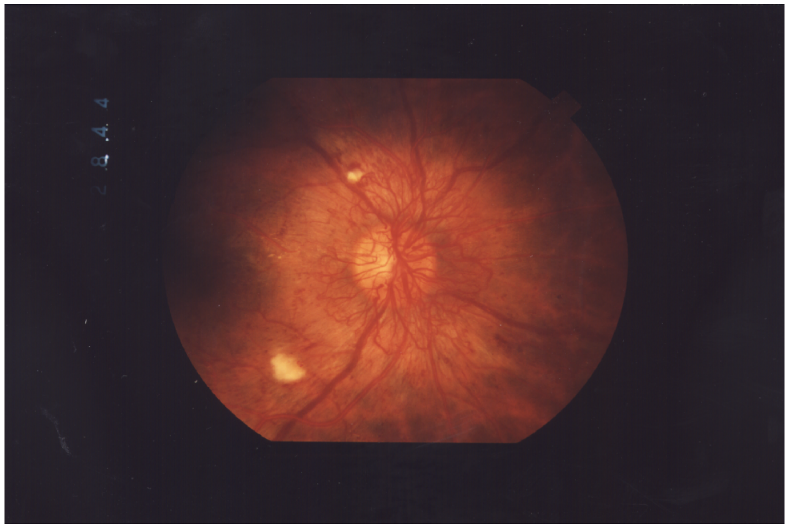

Figure 2.7 Proliferative retinopathy, an advanced form of DR, occurs when abnormal new blood vessels and scar tissue form on the surface of the retina. © National Eye Institute (NEI)

the fact that visual symptoms do not persist, but rather "come and go" even within minutes as a result of the fluctuations in glucose levels.

Here, it is pertinent to mention that according to Khoo et al., 2019, the incidence of DR and its evolution are also affected by the psychological state of the patient.

2.3 Age-related Declines in Hearing

As we age, the structures of the inner part of the ear responsible for converting the mechanical sounds in nerve impulses deteriorate; due to programmed cell death, the so-called apoptosis (Birren and Schaie, 2001), and other pathologies such as reduced blood circulation (Krishnappa and Naseeruddin, 2014; Ponton et al., 2000). Also, the processing of nerve impulses in the auditory cortex is reduced (G. Payne and D. Isaacs, 2012).

Aging and auditory perception are so closely related[2] that the perception of specific sound frequencies can be a reliable indicator for a person's age estimation (Ilyas, Othmani, and Naıt-Ali, 2020).

[2]High-frequency hearing test (National Geographic TV): https://youtu.be/sZHWY1KBHwc

First signs of changes in the human auditory system appear in the middle age. When a person reaches 50 years old, a loss of hearing acuity appears in middle and high frequencies, which gradually spreads to all frequencies (Birren and Schaie, 2001).

Hearing loss is one of the most common chronic health impairments in the elderly population. Around 1 every 3 persons between 61 and 70 years old and more than 2 every 3 persons older than 85 years old, are affected by hearing loss (Walling and Dickson, 2012). Hearing difficulties cause problems in elderly people's daily living, such as difficulty in hearing especially in noisy environments (Gates, 2012) and difficulty in following and/or participating in a normal conversation (D. A. Jones, Victor, and Vetter, 1984).

2.4 Age-related Declines in the Musculoskeletal System

A significant change in the human musculoskeletal system of both men and women is the loss of height (Figure 2.8). After the age of 45, the height of the human body begins to decline due to intervertebral fibrocartilage lesion and the reduction of the articular cartilage thickness. Indicatively, the decrease in height is calculated at around two to three centimeters per decade, however there are studies reporting smaller (0.5 to 1.5 cm/decade) or larger decrease (2.5–5 cm/decade) (Perissinotto et al., 2002). Further loss of height occurs during late adulthood when the degenerative disc disease causes spine curvature (G. Payne and D. Isaacs, 2012). The later, referred to as bent spine syndrome or *camptocormia* is not necessarily of muscular etiology, but in the elderly it mainly appears as such, and progressively gives to the aged body a characteristic posture of forward bending (Lenoir et al., 2010).

Additionally, over the years, skeleton-related deformations accompanied with reduced muscle strength force elderly people to adopt a different walking pattern, which is characterized by markedly slower pace (Winter et al., 1990; Mian et al., 2006). A study by Himann et al., 1988, conducted with 438 subjects, indicates the age of 62 years as a benchmark for change in gait. In particular, it appears that before that age, a negligible decrease in walking speed occurs (1-2%/decade), while after that age, the decrease soares at more than 12% and 16% per decade for women and men, respectively.

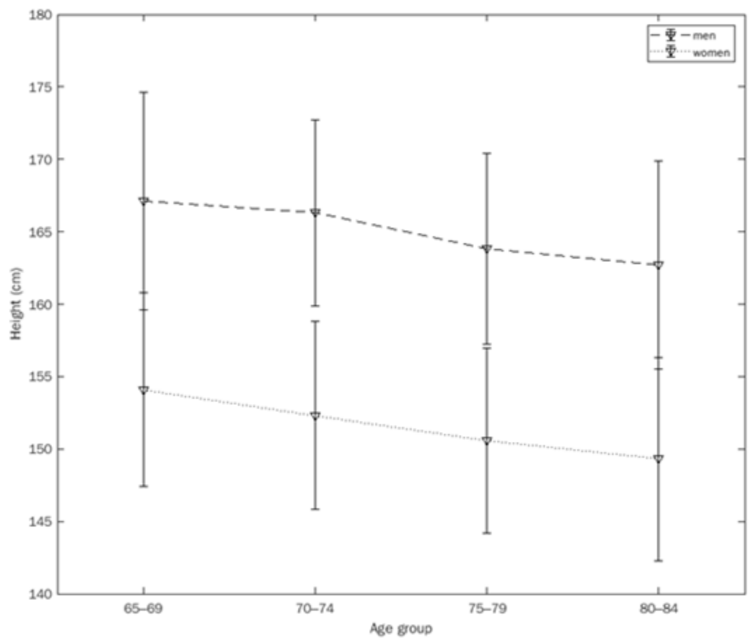

Figure 2.8 Height (in cm) per age group, based on anthropometric measurements in the elderly (Perissinotto et al., 2002)

Another characteristic of elderly adults' locomotion is the reluctance and difficulty they sense when it comes to lifting their feet to overcome an obstacle or climb the stairs (Himann et al., 1988).

Finally, a significant change occurs in another musculoskeletal related aspect, that is the gripping strength. More precisely, due to deterioration of muscle strength (L. Ploutz-Snyder, Manini, and R. Ploutz-Snyder, 1999) at the age of 80, gripping strength is expected to be reduced by 50 percent (G. Payne and D. Isaacs, 2012).

It is important to mention that other problems can affect the musculoskeletal system attributed to cognitive declines, such as the Parkinson's disease, but these are outside the scope of this research.

2.5 Summary

In this chapter, deficits and changes associated with aging were described. A special emphasis was given on problems in vision, as this is the main topic of the present research. In the next chapter, related work is scrutinized, with several physical and virtual simulations being presented.

Table 2.1 Summary table of age-related visual deficits, their symptomatology, classification, non-invasive methods of detection and factors that influence their onset and deterioration.

Age-Related Deficits	Signs & Symptoms/ Clinical Features	Non-invasive Examination/ Quantitative Assessment	Classification / (Clinical) Grading Scale	Risk/Extrinsic Factors
AMD	Metamorphopsia (La Cour and Friis, 2002) Central scotomas "Scallop"-shaped borders, steplike patterns (Nazemi et al., 2005) Heterogeneity (Taylor et al., 2018)	***Amsler grid*** for metamorphopsia but not for RS (Jager, Mieler, and Miller, 2008) ***M-Charts*** (Matsumoto et al., 2003) ***Interactive Line Manipulation*** (Ichige et al., 2019)	A.-R. E. D. S. R. Group et al., 2000 **Early AMD:** mild visual loss blurred vision, visual scotomas, decreased contrast sensitivity, abnormal dark adaptation need for brighter light read small print difficulty often asymptomatic (Jager, Mieler, and Miller, 2008) **Intermediate AMD:** geographic atrophy (Jager, Mieler, and Miller, 2008) **Advanced/late AMD:** **Non-neovascular:** visual loss with central or pericentral visual scotomas (Jager, Mieler, and Miller, 2008) **Neovascular:** sudden, profound visual loss (Jager, Mieler, and Miller, 2008)	Age (65+) Caucasian Heredity Smoking Obesity Hypertension (Jager, Mieler, and Miller, 2008) Iris color (blue) (N. M. Bressler, S. B. Bressler, and S. L. Fine, 1988)
NUC	Gradually reduced contrast Reduced color intensity Central lens opacification Yellow/brown discoloration (Allen and Vasavada, 2006) (Quillen, 1999) (Thylefors et al., 2002)	Full list provided in Morris, Fraser, and Gray, 2007	***The WHO Cataract Grading Group*** (Thylefors et al., 2002)	(Allen and Vasavada, 2006) Smoking Diabetes Corticosteroids
COR	Light scatter Light transmission disruption Night driving difficulty (Allen and Vasavada, 2006)	***Cataract Symptom Scale (CSS)*** (Gothwal et al., 2009)	***Lens Opacities Classification System (LOCS III)*** (Chylack et al., 1993)	Diet (malnutrition) Acute dehydrating diseases Exposure to UV B
PSC	Daytime driving difficulty Reading difficulty (Thylefors et al., 2002)			
Glaucoma	Degeneration of optic disk Loss of peripheral VF (Quillen, 1999)	***Perimetry*** Full list provided in (Sample and C. A. Johnson, 2001)	Open Angle Glaucoma (POAG) Angle-closure Glaucoma (PACG) (D. A. Lee and Higginbotham, 2005)	Age Elevated baseline IOP (Coleman and Miglior, 2008)
DR	Blurred vision Scattered scotomas Retinal detachment Metamorphopsia Increased glare sensitivity color, contrast sensitivity problems (Fante, Durairaj, and Oliver, 2010)	***Early Treatment of Diabetic Retinopathy Study (ETDRS)*** (P. Mitchell et al., 2008)	(Quillen, 1999) ***Nonproliferative:*** macular edemas asymptomatic blurred/distorted central vision ***Proliferative:*** vitreous hemorrhage and/or traction retinal detachment. 7 stages -ETDRS classification system (P. Mitchell et al., 2008): None, Minimal NPDR, Mild NPDR, Moderate NPDR, Severe NPDR, PDR and High risk PDR	Diabetes duration Blood sugar levels Blood pressure levels (Yau et al., 2012)

Chapter Three

Related Work

When it comes to specific population groups such as the elderly, whether it is about addressing their needs or dealing with problems directly or indirectly related to aging, it is fundamental to understand their condition and how the latter affects their overall QoL. Towards this end, various approaches that allow younger people to understand the effects of aging have been employed, from systematic to more empathic methods (Sankowski and D. Krause, n.d.) and in general, different method classifications exist in the literature (Kaulio, 1998). In the context of this research, these methods are categorized into two groups: the non-simulated and the simulated approaches. More information about the two groups are given in the next sections. Emphasis is given to simulated approaches, since this is the core subject of the present research work.

3.1 Non-simulated approaches

With the term "non-simulated approaches", this research refers to analytical methods based mainly on data collection, through interviews, observation etc., typically, to record and understand the needs of the elderly users. Non-simulated approaches include, inter alia, methods such as *Field Research*, *Participatory Design* and *User Personas*.

Before proceeding with the description of the non-simulated approaches, it is important to clarify the latter case. According to Pruitt and Adlin, 2010 personas are *"fictitious, specific, concrete representations of target users"*. Thus, one could argue that user personas fall under the category of simulated approaches. This is for example the case with Massanari, 2010 who states that personas *"are simulations of people, perhaps built on empirical evidence, but simulations nonetheless"*. However, in this research, the narrative nature of personas corresponds better to the theoretical framework of non-simulated approaches, thus they are considered as such.

There are numerous studies on the use of non-simulated methods in the elderly-friendly or elderly-centered design. In a study by Demirbilek and Demirkan, 2004, Participatory Design (PD)—an approach in which users and stakeholders are involved in the design process— is found to be a convenient solution of perceiving elderly people's needs and requirements, in a design use case. A review by Merkel and Kucharski, 2019 indicates that PD is widely used in Gerontechnology, that is the development of technological systems towards Ambient/Assisted Living (AAL). In the study by LeRouge et al., 2013 the effect of elderly personas in design was considered through the perspective of consumer health technologies.
There are cases in which these methods were used to understand or highlight a condition and its associated impact factors (Matthews, 1982; Peek et al., 2016). For example, a Field Research—on-site—approach was employed by Peek et al., 2016 to determine which factors affect the use of technology by elderly people, as part of a broader objective to support aging in place.

Although non-simulated approaches can be effective, they are associated with several disadvantages that should be considered. For example, the study by Brigham, 2013 reports that personas can be associated with stereotypical views towards the profile users. Other disadvantages include inappropriate use or no use of personas at all, even when these are available. Meredith, 1998 points out the disadvantages of field research, describing that it is a demanding and time-consuming process, which requires thorough triangulation. Also, a good knowledge of the method and procedures to be followed are required to be properly conducted; a point that according to Meredith, 1998 tends to be lacking.

As far as elderly users are concerned, non-simulated approaches are accompanied by additional challenges. For example, Lindsay et al., 2012 state that in PD, it is difficult to achieve targeted conversation and receive specific feedback from the elderly users. Joshi and Bratteteig, 2016 emphasize the difficulty in terms of recruiting time and the usual experiences of loss of short-term memory of the elderly users.

3.2 Simulated approaches

According to Shannon, 1975, simulation is *"the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies [...] for the operation of the system."* By definition, as aging is a situation involving various aspects, needs and challenges that need to be understood first-hand to be addressed and evaluated properly, simulations constitute a suitable approach.

Perspective-taking approaches through deficits simulations has been the subject of numerous investigations in real-life settings, virtual environments, alone or in combination. The number of relevant studies indicates the interest in the use of Extended Reality (XR)[1] technologies and especially VR in such simulations. This is not surprising since many simulations have benefited from the use of XR to enhance the immersion of the user and facilitate the perspective-taking approach, especially through embodied experiences (Yee and Bailenson, 2006; Peck et al., 2013).

In this research, the simulated methods are subdivided in two categories, namely the physically-based and the computer-generated simulations, which are discussed in the next two sections. Table 3.1 presents a comparison of the two methods, in terms of use in experimental settings.

[1] An umbrella term covering Augmented Reality, Virtual Reality and Mixed Reality (Ratcliffe et al., 2021).

3.2.1 Physically-based Simulations

In real environments, a typical form of aging simulation is the *aging suits* (Lavalliere et al., 2017); a method still used in specific cases to give a hands-on experience of what is like to live as an elderly person with specific age-related deficits.
For example, Age Gain Now Empathy System (AGNES) is an aging suit developed at the Massachusetts Institute of Technology (MIT) (Osawa and Imai, 2013; Singer, 2011). It includes a full body uniform and a helmet connected with elastic cords to prevent the free movement of the neck and torso, achieving in that way the lack of mobility experienced by elderly people. AGNES also utilizes specialized accessories such as goggles with filters and earplugs to simulate the age-related changes in vision and hearing respectively (Figure 3.1).

Figure 3.1 AGNES aging suit developed by AgeLab ©MIT

A similar suit, called 'Age Man Suit', was developed by researchers to impart knowledge to medical staff on the needs of aged people (*Suit lets medical students experience symptoms of old age* n.d.). This suit consists of a vest which exerts pressure on the area of the chest making simple tasks seem intensive, ear-protectors which hinder hearing, a yellow filter affecting the eyesight, and pads affecting joints' flexibility.

In a similar vein, the age simulation suit GERT (*GERontologic Test suit GERT* n.d.) provides a set of discrete components that can be composed to simulate a number of age-related impairments, such as physical limitations, senile tremor, and an unbalanced gait effect (through special overshoes, Figure 3.2). Additionally, GERT provides a set of goggles that simulate six different eye conditions: macular degeneration, unilateral retinal detachment, cataract, diabetic retinopathy, glaucoma, and retinitis pigmentosa. Note that three of these simulation goggles were used in a comparison study conducted as part of this research work (see Section 5.5)

Figure 3.2 Overshoes of GERT aging suit inducing an unbalanced walking effect. Image taken from www.produktundprojekt.de

In practice, aging suits have been used in various cases. For example, AGNES was used by the MIT AgeLab researchers in cooperation with Massachusetts Bay Transportation Authority to identify the challenges faced by elderly people when using public transportation (Joseph F Coughlin et al., 2013).

Other examples include their use in the development of applications for elderly people (Holzinger, Searle, and Nischelwitzer, 2007), in the product design process (Panek et al., 2004), in medical education (Huber et al., 2012) and in teaching *Universal Design* to university students (Nicolle and Maguire, 2003).

Aging suits have been also used in the automotive industry for design purposes, but according to J. Coughlin, 2007 there is no evidence of their effectiveness, because vehicle manufacturers prefer not to emphasize the use of aging suits to avoid negative connotation.

Lavalliere et al., 2017 examined the impact of aging suits on various aspects of human mobility and on simple daily tasks' performance such as buying specific products from a grocery. The results of their study are consistent with the literature on the aged body and show that the aging suits cause an overall fatigue and frustration to the users, affecting their performance on daily tasks. The advantage provided by aging suits is summarized in that they offer an integrated solution to simulating several physical age-related deficits from visual impairment to decreased mobility.

Other, sophisticated physically-based approaches exist but these focus only on the HVS. These approaches utilise eye contact lenses “encapsulating” visual problems that can then be directly applied to healthy-vision people, simulating specific eye-conditions. For example, in the study by Heitmar and Attardo, 2016 three different contact lenses with different spectral transmissions were created, to study whether the lens opacification in cataract patients has any effect on the blood oxygen saturation on the retinal vessels.

Another very interesting, though ultimately ineffective, approach used contact lenses simulating central scotomas to test the validity of this approach for its intended purpose, namely to be used by general population samples for economic policy making purposes (Czoski-Murray et al., 2009).

3.2.2 Computer-generated Simulations

Computer-generated simulations do not have the discrete character of the aging suits, in the sense that they are not developed for the sole purpose of an aging simulation system. Also, the existing approaches have principally targeted visual deficits. Table 3.2 summarizes recent computer-generated simulations and their characteristic features.

An early elaborate effort towards computerized simulation of eye disorders was first reported 20 years ago when a dark spot was printed on an acetate film to approximate central scotomas, while subjects' eye-movements were recorded using an eye-tracking system (E. M. Fine and Rubin, 1999). With the evolution of technology and computer graphics, this approach transformed into computer-generated immersive simulations (Vinnikov, Allison, and Swierad, 2008).

The advance of XR technologies propelled numerous simulations of visual deficits in virtual and semi-virtual environments (Ai et al., 2000; Krösl, Bauer, et al., 2018; Jin, Ai, and Rasmussen, 2006). Use cases range from universal accessibility in architecture design (Krösl, Bauer, et al., 2018), to addressing information needs of patients and their relatives (Stock, Erler, and Stork, 2018).

In the field of Augmented Reality (AR), Ates, Fiannaca, and Folmer, 2015 have transformed a VR headset into an AR system using wide-angle cameras, to apply several filters on the rendering of a real environment, and simulate specific eye disorders for accessibility purposes. A similar approach has been used in Werfel et al., 2016, with the additional incorporation of hearing impairments as part of the simulation. Recently, integrating gaze-contingent effects using eye-tracking technology, Krösl, Elvezio, Luidolt, et al., 2020 simulated cataract symptoms of adjustable severity in an AR system, evaluated by real cataract patients.

Likewise, many VR-based approaches have been proposed. Krösl, Elvezio, Wimmer, et al., 2019 have developed a VR-based simulation of specific cataract symptoms, such as blurred vision, contrast and light sensitivity. It is worth noting that this approach takes into account both the actual vision of the user and VR headsets' limitations to calibrate the simulation and provide a similar experience to all users.

In terms of implementation, the most typical method to simulate visual deficits in VR consists in applying post-processing effects to the images (J. Lewis et al., 2011). A more refined approach described by Stock, Erler, and Stork, 2018, uses actual visual field data to represent how real glaucoma modify patients' vision.

To date, the aspect of heterogeneity has mainly relied on adjusting the intensity of the effects,

	Physically-based simulation	VR-based simulation
Cost	Increased cost dedicated to the simulation	VR is used in various applications, so the net cost for the simulation is eventually reduced
Flexibility	Minimum - need to test in a real environment	Maximum - a VR headset is sufficient
Experimental setup effort	Time consuming and tiring process	Easy application
Simulation	Various effects can be simulated. However, it is difficult or impossible to adjust the intensity of the effects.	Not all age-related declines can be simulated without further physical equipment. However, it is relatively easy to adjust the type and intensity of the effects.
Side effects	Potential body fatigue from the suit, friction burn	Potential motion sickness (Rodriguez, 2016)
Participants	Increased preparation time may result in reduced number of participants	Ease of use makes it more appealing to volunteers
Scenarios	Difficulty and increased risk in simulating extreme scenarios	Ideal for extreme scenarios in a safe and controlled environment (Ventura et al., 2020)

Table 3.1 Comparative table of the two simulated methods in terms of use in experimental settings

like the amount of bluriness. Exception to this is the work by P. R. Jones and Ometto, 2018 who follow a sophisticated method based on mathematical models to simulate customized visual deficits.

3.2.3 Hybrid Simulations

Some researchers combined the flexibility of XR-based simulations in creating artificial visual problems and the additional capabilities provided by the aging suits, such as mobility limitations, to achieve a hybrid solution and provide a more comprehensive testing of specific design cases, such as the design of a car.

An example of a hybrid simulation is the one created at the Immersion Lab of Ford Motor company (Ehrenman, 2003). Within this context, engineers employed VR in combination with an aging outfit (High-Tech Geezer Suit) and a mechanical model with the basic components of a car (steering, throttle, brake, etc.) to develop an integrated aging simulation system. This system was intended to allow young automotive designers to adapt the design and car ergonomics in such a way as to offer a better and safer driving experience to elderly drivers. This work is a typical example of a hybrid aging simulation system that combines both hardware and software components.

Title	Author(s)	Year	Advantage	Disadvantage	Aim	Technical approach	Diseases/Symptoms
Head mounted display design tool for simulating visual disabilities	Väyrynen, Colley, and Häkkilä, 2016	2016	Task-based study (navigation in a VE)	Static built-in effects; no adjustment	Empathy in design	Overlay images; built-in effects	AMD Cataract Myopia Glaucoma
A VR-based user study on the effects of vision impairments on recognition distances of escape-route signs in buildings	Krösl, Bauer, et al., 2018	2018	Simulation adjusted based on user VA and display limitations	No adjustment	Examining the impact of visual problems on recognizing escape-route signs	Gaussian blur; post-processing effects	Reduced VA Cataract Mild AMD
Degraded Reality: Using VR/AR to simulate visual impairments	P. R. Jones and Ometto, 2018	2018	- Gaze-contingent effects - Portable	Environment - HDRI skyboxes	Teaching/empathy Accessibility	Based on mathematical models	Disability Glare Blur Spatial distortions Perceptual filling-in Color vision deficits
Realistic Simulation of Progressive Vision Diseases in Virtual Reality	Stock, Erler, and Stork, 2018	2018	Simulation based on perimetry data		Testing apps and devices for people with visual problems; informing patients/ relatives	Post processing effects; intensity adjustment; stage selection	Cataract Glaucoma AMD
ICthroughVR: Illuminating Cataracts through Virtual Reality	Krösl, Elvezio, Wimmer, et al., 2019	2019	Simulation adjusted based on user VA and display limitations	Used premade textures	Patient understanding	Image effects	Cataract
Seeing other perspectives: evaluating the use of virtual and augmented reality to simulate visual impairments (OpenVisSim)	P. R. Jones, Somoskeöy, et al., 2020	2020	Gaze-contingent effects	Tested everyday tasks (lack of validation)	Investigating induced difficulties	P. R. Jones and Ometto, 2018	
CatARact: Simulating Cataracts in Augmented Reality	Krösl, Elvezio, Luidolt, et al., 2020	2020	Works in different modes (VR, AR, 360 image); Evaluation with patients	Some effects lack flexibility	Patient understanding	Advanced version of previous system (Krösl, Elvezio, Wimmer, et al., 2019)	Cataract

Table 3.2 Recent XR-based simulations of visual impairments

3.3 Discussion

To facilitate the understanding and realization of elderly people's needs, many approaches have been proposed, from analytical methods to perspective-taking. In the context of this research, these methods are divided into two categories: the non-simulated and the simulated approaches. The first category involves methods, like field research and participatory design. The second category includes both physical simulations in the form of aging suits and computer-generated methods.

Focusing on the second category to which this research relates, it seems that virtual worlds offer a breeding ground for realistic simulations. Albeit less flexible with respect to the simulation of musculoskeletal declines, VR-based simulations are far ahead in terms of quality and naturalness of the static visual effects provided by the aging suit's goggles. That is, they include several realistic features, such as gaze-contingent, dynamic effects, which can be adjusted in real time.

The relative ease of creating and testing scenarios, as well as the affordability and accessibility of VR technologies contributed to their use in a wide range of applications, especially in areas where visual stimuli are of central importance.

In this chapter, different studies that contributed to this topic, were reported. Three identified research gaps engaged the interest of this research work.

The first one relates to the application of such simulations and their effectiveness in the design field. While various studies have been conducted on the basis of using VR-based simulations in the design, such as the study by Krösl, Bauer, et al., 2018 and Väyrynen, Colley, and Häkkilä, 2016, the product design and in particular the design of essential products like medicines—an admittedly important issue for the elderly—had not been studied. Also, no evidence existed on the effectiveness of VR-based simulations in relation to other methods used for this purpose. Therefore, one of the primary objectives of this research was to explore the effectiveness of the VR-based simulation as a supportive tool in the elderly-friendly design of essential products and compare it with other methods.

The second research gap pertains to the technical aspect of the simulations and more precisely the aspect of *heterogeneity*. The existed work mainly provided variability in the form of adjusting the intensity of the simulation, rather than the appearance. There are cases where the simulations are "unique" like in the case of Stock, Erler, and Stork, 2018, but these relate to simulations that have emerged from real patient data and their appearance cannot be modified.

Exception to this is the work by P. R. Jones and Ometto, 2018 who followed a sophisticated method based on mathematical models to simulate customized simulated effects. Unlike their approach, to generate more naturalistic simulations, this research introduces the aspect of *randomness* in deficits that are generated procedurally in a patient-independent manner. Thus the proposed system is capable of generating an arbitrarily large number of cases.

Finally, the third identified research gap relates to the self-reported problems and the relative difficulty that these simulations induce in healthy adults and the lack of comparison with data from actual patients. Only one study was found in the related literature, that of P. R. Jones, Somoskeöy, et al., 2020. In this recently-published work, the affected performance is examined in the case of one simulated condition, whereas as part of the present research, a more thorough investigation was conducted with two simulated conditions. Also, in the work by P. R. Jones, Somoskeöy, et al., 2020, only quantitative data were considered, while in the present research a mixed method approach was followed to cover both the impaired performance induced and the appearance of the simulated effects.

3.4 Summary

This chapter explored various approaches used to understand and address the needs of elderly people. Emphasis was laid on computer-generated simulations, as this is the main focus of the present research. To establish the main aspects of the proposed simulation, similar XR-based studies and especially simulations harnessing VR, were studied and evaluated. This allowed the identification of the main weaknesses and research gaps in existing simulations that this work aims to address.

The following chapter provides an overview of the general methodology followed throughout this research.

Chapter Four

Overview of the Methodological Framework

Towards an effective and valid simulation, the present research work followed a two-phased approach, on the basis of an iterative methodological design. This chapter provides an overview of the two-phased approach followed. The first phase focused on the development of the prototype simulation and its application in three experiments to assess its effectiveness in different cases. Following the results and the feedback obtained throughout the first phase, the second phase focused on the technical upgrade of the simulation and its systematic validation to assess whether it is suitable for its intended purpose. Figure 4.1 presents the overall methodological framework of the two-phased approach followed in this research. More details for each phase are given in the remainder of this chapter.

4.1 Phase 1

The research on the VR-based simulation of declines associated with aging comprised, in a first step, a thorough overview of the related literature. The ensuing steps towards the implementation of the simulation were based on the key bibliographic findings with regard to declines associated with vision, hearing, muscle strength, stature and mobility. Moreover,

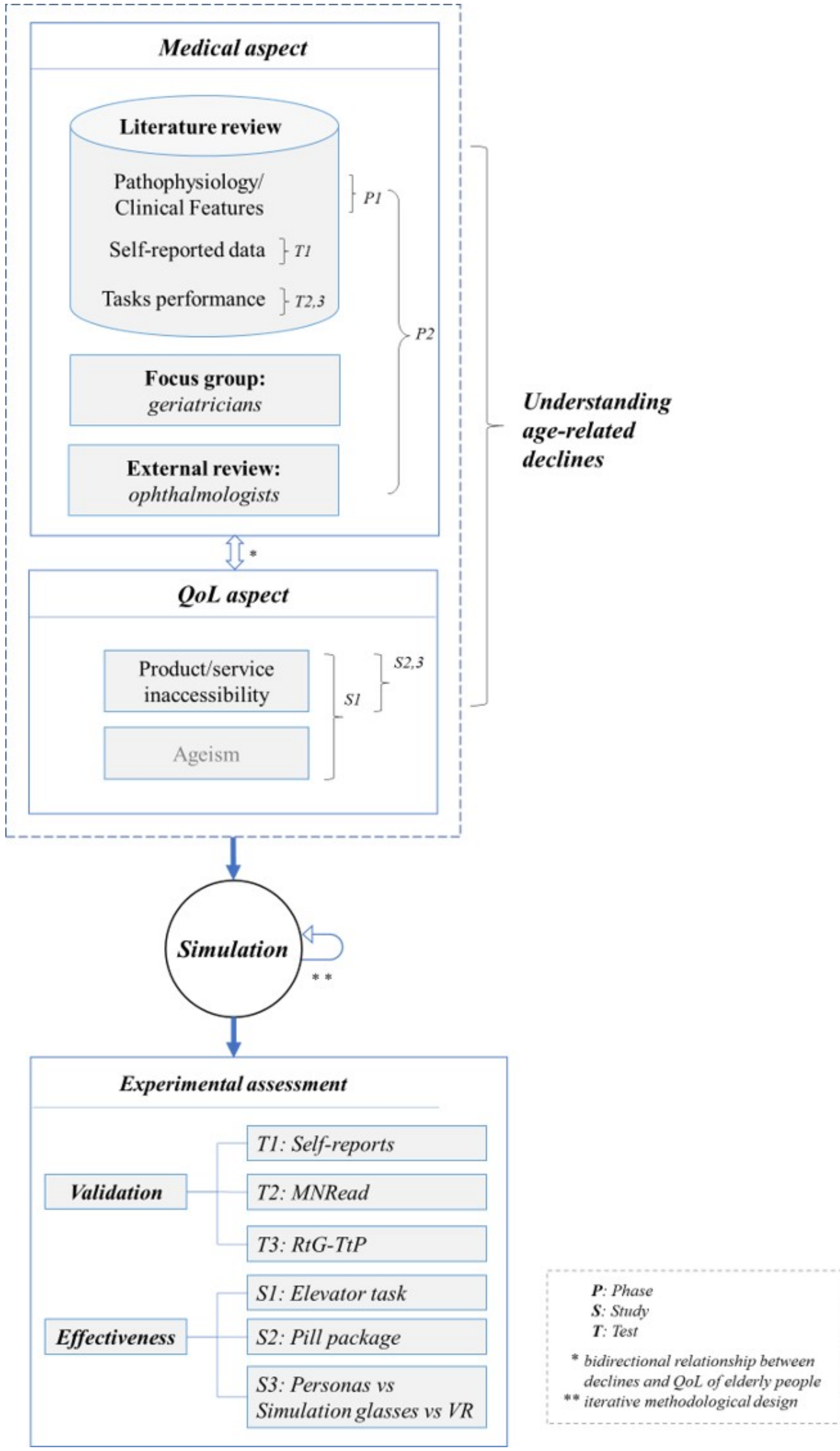

Figure 4.1 The general framework of the present research

visual material collected from online sources and the experience from the use of a physical aging suit were considered. Following the development process, the simulation was applied in three different studies and both quantitative and qualitative data were obtained and analysed.

An overview of the aging effect simulation methodology and the experimental evaluation during the first phase is given in the remainder of this section, while a detailed description is provided in Chapter 5.

4.1.1 Simulation

The initial method of simulating age-related declines in VEs was defined and approached according to literature data, as these were detailed in Chapter 2. Thus, several age-related effects were simulated both directly and indirectly in VEs to allow users to virtually experience the associated challenges.

Technically, the simulation of the visual declines was developed using built-in effects of the game engine used. Albeit lacking adequate flexibility, these effects provided a first indicative presentation of specific declines. In addition, hearing loss simulation included sound level reduction. Finally, other changes were simulated in a non-direct way. More details on the prototype simulation are presented in Section 5.1.

To evaluate the effectiveness of the simulation, three different experimental scenarios were devised. In all three cases, the same version of the initial simulation was used with minor variations in the parameters. For this purpose, a specially designed VE of a building interior was modelled, as well as four virtual copies of everyday products.

The following subsection discusses briefly the three studies conducted in the experimental evaluation process of the first phase.

4.1.2 Experimental Investigation

As indicated previously, three studies were carried out with different objectives and experimental scenarios. For the first two studies, two variations of the VE were developed: the control condition in which no effects were applied and the simulated condition. The two variations allowed the user to interact with the simulation through the eyes of a healthy young adult and an elderly person with specific age-related problems, respectively.

The first study was an exploratory prospective study, aiming at examining different aspects with regard to the simulation's effectiveness. The first aspect was the potential evocation of a sense of being an elderly adult. The second aspect was a possible influence on positive change of views towards the elderly and the aging in general. The last objective was to test whether the simulation could help designers experience problems faced by the elderly users/consumers. As part of this first study, subjects were requested to complete a simple task involving using an elevator in a simulated VE. Their reactions were registered using pre- and post-questionnaires, to assess any changes resulting from experiencing an everyday situation as an older person (see Section 5.3).

The next two studies focused on product design. More specifically, the objective of the second study was to investigate whether by using a simulated VE, it is feasible to detect design faults on pill packages that could prevent the correct use by elderly consumers (see Section 5.4).

Through the third study, the effectiveness and other aspects of the VR-based simulation in the evaluation stage of a product design process were tested, this time in comparison with other methods. More specifically, the packaging evaluation of widely used products was studied, through the scope of three methods used: the personas of elderly consumers, the simulation goggles of an aging suit and the proposed VR-based simulation. The purpose was to define which of the three methods is optimum during the stage of elderly-friendly product design evaluation (see Section 5.5).

Overall, important results were yielded from these three studies, regarding the effectiveness of the simulation in inducing the sense of being an elderly adult and exhibiting age-related impairments and their associated challenges in different cases, pertaining mainly to design.

4.2 Phase 2

One might reasonably argue that the effectiveness in understanding the problems faced by elderly people does not necessarily imply that the simulation does represent the actual problems. Towards this end, the aim of the second phase was to examine the accuracy of the simulation in serving its intended purpose, that is to evoke similar challenges to those faced by elderly impaired adults.

For this, the second phase of the present research focused on the simulation of declines in the VHS. The review of the literature continued with an emphasis on patients' reported data and the way in which the age-related declines affect specific tasks' performance. In parallel, a synergy was developed with a group of geriatricians towards evaluating the simulation during the development process, and external views were obtained from ophthalmologists. Finally, specific methods were employed to assess simulation's validation through three tests in the VEs.

More information about the technical upgrade and the validation assessment of the simulation are given below. A detailed description is provided in Chapter 6.

4.2.1 Simulation

Particular emphasis was placed on the technical part, to provide a novel simulation that can generate "unique" cases of visual effects in both intensity and appearance; the combination of these two elements represent in a more accurate way actual impairments' features. For the technical upgrade of the prototype simulation, advanced techniques were used to demarcate the visual fields in the VE and to add an element of distinctiveness in the visual effects. In addition, a representation of virtual aged hands was incorporated into the simulation to give the sense of body-ownership and enhance the sense of altered perspective (Slater et al., 2010).

4.2.2 Experimental Investigation

In this phase, the evaluation assessment concerned the validation of the simulation, rather than its effectiveness in use cases. This was examined by conducting three different tests in the VE.

First, to test whether the features of the simulated effects correspond to that of the descriptions provided by actual patients, self-reported data of the latter were compared to the corresponding self-reports of subjects with healthy vision in the simulated VEs (see Section 7.2).

Additionally, to assess the congruence between the relative difficulty induced by the simulation and the actual difficulty posed by real visual problems, two different tests were conducted in VEs, the MNRead test (Section 7.3.2) and the Reach-to-grasp and Transport-to-place test (Section 7.4.2).

For the most part, the results obtained from the three tests were consistent with actual data conducted with visually impaired elderly adults.

4.3 Summary

In this chapter, the overall structure of the methodological approach was presented. Having reviewed briefly the two-phases followed in this research work, in the next two chapters, the two phases are presented in detail and the results of the associated studies conducted are analysed.

Chapter Five

Phase 1: Effectiveness in Conceiving the Simulated Declines and their Associated Challenges

The work presented in this chapter constitutes the first step of the present research towards simulating age-related declines in VEs. In this phase, the development of the prototype simulation relied mainly on the review of the literature on the physical changes due to aging, as described in Chapter 2. In addition, during the first phase, the research focused on the initial experimental investigation to address the RQs regarding the effectiveness of the simulation. More precisely, the assessment focused principally on two aspects:

1. The induced sense of being an elderly adult

2. The aspect of conceiving challenges posed by age-related declines, pertaining mainly to product/service usage

To test these aspects, the simulation was applied in three studies, each time using a different experimental scenario. For all three studies, the same simulation was used with minor variations in the parameters. That is, in the first study, age-related changes in vision, hearing and the musculoskeletal system were considered, while in the other two studies, the simulation included only the declines in vision, as their subject was related to visual stimuli.

This chapter is structured as follows: it commences with the description of the methodology followed for the implementation of the prototype simulation. Then, the work related to the three studies of the initial experimental investigation is presented along with the results and general conclusions drawn from the latter.

5.1 Prototype Simulation of Age-related Declines in Virtual Environments

Simulating declines in VEs assumes a knowledge of the physiological conditions associated with aging, so that such conditions can be virtually rendered. For this, based on the information gathered from the medical literature, a methodological approach was designed to simulate specific common age-related declines in the human visual, auditory and musculoskeletal system.

Before describing the simulation methods for the different modalities in the following subsections, it is important to note that, where medical literature data were available, the intensity of the simulated effects was adjusted accordingly. In cases where there was no such availability, the intensity was adjusted empirically.

5.1.1 Simulation of Age-related Declines in Vision

Similar to other studies (J. Lewis et al., 2011; Stock, Erler, and Stork, 2018), the simulation of the visual declines was achieved using camera filters, known as *post-processing effects*. These effects are applied during the last stages of the rendering process manipulating the whole image (Unity, 2022a; Unity, 2022c). Post-processing effects are frequently used in video games and applications to enhance or alter the image, especially for non-photorealistic results ("*expressive rendering*") (Lansdown and Schofield, 1995; Magdics et al., 2013). In our case, these were used with a view to realistically simulate problems such as blurred vision. As mentioned previously, the implementation of the simulation was mainly based on the medical bibliography. For the visual declines, we also referred to visual material of similar simulations available in online medical platforms, such as the National Eye Institute (*National Eye Institute* n.d.). Regarding the third study (see Section 5.5) for the sake of comparison, the intensity and appearance of the effects were adjusted appropriately, to approximate the simulation provided by the goggles of the aging suit used.

As part of the initial phase of the simulation, the symptoms of cataract, AMD and glaucoma were addressed. Additionally, another characteristic of the aging eyes approached in the proposed simulation is that of the eyelid drooping (ptosis). More details about the effects and how they were applied in each case are given below.

Cataract

Beginning with the cataract simulation, as discussed in Section 2.2.1, depending on its type, it can be associated with a series of symptoms, such as blurred, yellowish vision (xanthopsia)[1], glare sensitivity and dull colors (Aliancy and Mamalis, 2017; Elliott, Gilchrist, and Whitaker, 1989). Also, due to the opacification of the lens[2], the amount of light reaching the retina is reduced in cataracts (Leibowitz et al., 1980).

The proposed simulation focused mainly on nuclear cataract, which is one of the most common types of age-related cataracts (Beebe, Holekamp, and Shui, 2010). Symptoms were simulated using three Unity's built-in effects: the *blur image effect* (Unity, 2022b), and the *color grading* and *bloom* effects of the post-processing set of filters (Unity, 2022c). Specifically, the blur effect was used to simulate the blurred vision caused by the clouding of the

[1]Being a cataract patient, Claude Monet used to paint predominantly with yellow and purple colors due to xanthopsia and difficulties in discriminating colors (Dan, 2003)

[2]Light reduction also appears as a general condition due to the aging of the eyes (Gittings and Fozard, 1986; V. G. Payne and L. D. Isaacs, 2017).

lens. For the experimental evaluation, the intensity of the blur effect was set to approximately 30% (see Figure 5.1, left). The color grading effect was used to adjust image's color and luminance. Through this effect, the image contrast was reduced by 20% and a yellow tint was selected to simulate dull colors, and yellowish vision respectively (Harini and Bhanumathi, 2016; Blom, n.d.). In addition, the color grading effect was used to reduce the image brightness, to approximate the reduction of the light reaching the retina. The amount of the reduction was fixed to approximately one-third (see Section 2.2.1) to correspond to the actual deficit (Gittings and Fozard, 1986). Finally, the bloom filter was used to produce the glare effect that is characteristic of the sensitivity of people with posterior subcapsular cataract but can also occur in the other types of cataracts (Elliott, Gilchrist, and Whitaker, 1989). Figure 5.1 (left) shows the simulation of the cataract effects in the VE.

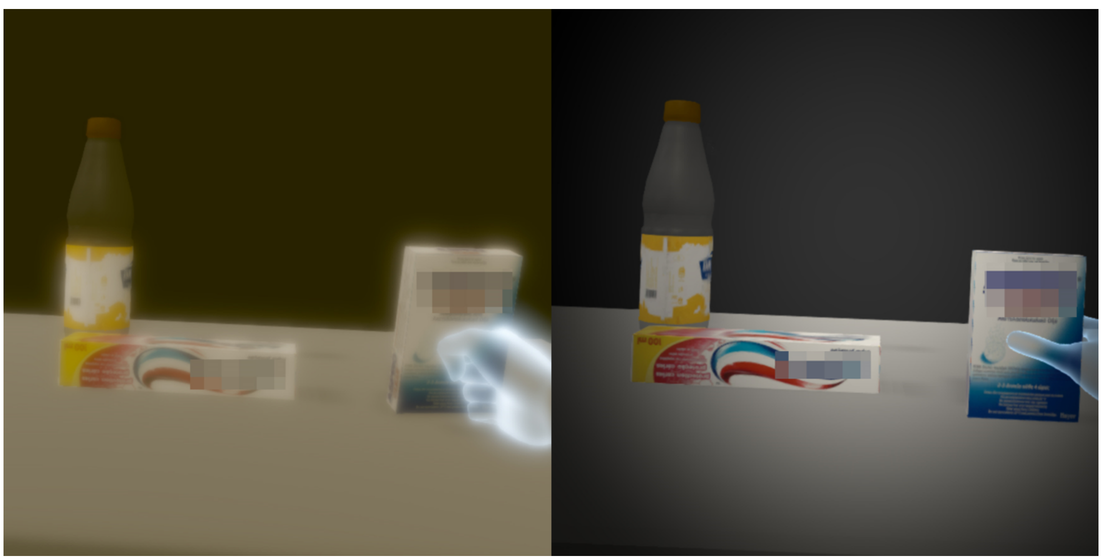

Figure 5.1 View of the VE in Study 2, using the prototype simulation of cataract (left) and glaucoma (right)

Age-related Macular Degeneration

For the case of AMD, the simulation in this phase was limited to scotomas, which occur mainly in the advanced stage of the disease, but are also likely to occur in earlier stages

(Jager, Mieler, and Miller, 2008). To approximate scotomas that appear at the central VF, overlay textures which were created using a raster graphics editing software were applied in the center of the viewport (see Figure 5.3, right).

Figure 5.2 View of the two variations of the VEs in Study 1 (control - left, simulated - right)

Glaucoma

As seen in Section 2.2.3, glaucoma is an eye condition that mainly affects the peripheral vision. In this first phase of the research work, based on visual material collected from online medical platforms, a case of acute peripheral vision loss (tunnel vision), which occurs in the final stages of the disease (Khaw and Elkington, 2004) was simulated. Similarly to the AMD, to simulate this effect, overlay mask textures were used covering the peripheral FOV with a black, semi-transparent coating (figure 5.1, right).

Ptosis

According to a survey by Sridharan et al., 1995 conducted in a random sample of 400 people over 50 years old, drooping was present in 11.5% and with an increasing prevalence over time. Thus, it was considered relevant to include this age-related change in the simulation. To approximate the reduced eye openness and the partial blocking of vision due to ptosis, the values of the virtual camera's viewport coordinates were empirically manipulated.

5.1.2 Simulation of Age-related Declines in Hearing

As presented in Section 2.3, sound perception is closely related to the age of an individual (Ilyas, Othmani, and Naıt-Ali, 2020). According to Farage et al., 2012, by the age of 60, a quarter of the ability to hear audible speech is decreased and from about this age onwards, 8.5 dB per decade are lost. Hearing loss causes problems in the daily life of the elderly as low-level sounds go unperceived and the communication becomes difficult, especially in noisy environments (Farage et al., 2012).

As part of the present research work, the simulation of hearing problems was a secondary aspect that was incorporated and tested only as part of the first study (see Section 5.3). Precisely, in this study, the defective acoustic perception in the simulated VE was approached by silencing low-level sounds like the machinery noises (elevator ascent/descent, door opening/closing) and by reducing the intensity of high-pitched sounds, like the warning and alarm tones by approximately 40%.

The experimental scenarios of the second and third study were related to product packaging design, thus sounds and hearing loss simulation were considered inapplicable.

5.1.3 Simulation of Age-related Declines in the Musculoskeletal System

In Section 2.4, several common declines associated with increased age in the human musculoskeletal system, such as changes in height, gait and muscle strength were discussed. Due to the nascent nature of the commercially available VR technologies during the first phase, and the fact that musculoskeletal problems were among the secondary elements of this research, these were approached indirectly. More details on the method followed for each decline are given below.

Height loss

A noticeable decline that the human body undergoes due to aging is that of height loss, which begins to occur after the age of 45 (V. G. Payne and L. D. Isaacs, 2017). The average amount of height loss is calculated at two to three centimeters per decade (Perissinotto et al., 2002).

The visualization of the differences in body height was implemented by the vertical displacement of the camera in the VE; the height of the virtual camera was reduced by 3.5% in the age-simulated VE, compared to the one in the control condition. Due to the variation in height between people of the same age group, this was selected based on the average values provided in relevant anthropological studies (Perissinotto et al., 2002; V. G. Payne and L. D. Isaacs, 2017).

Gait

According to a study by Himann et al., 1988 after the age of 60, the gait speed decreases by more than 12% for women and 16% for men, per decade.

To simulate the slower-paced walking pattern of the elderly, the value of the movement speed in the simulated VE was reduced by one-quarter, compared to the value of the speed in the control condition.

Obstacle avoidance

As described in Section 2.4, another mobility-related characteristic is the reluctance and difficulty that elderly people face when trying to pass an obstacle or climb the stairs (Himann et al., 1988).

To incorporate this element in the simulated VE, the variable *skin width* of the character controller was used. Character controller is a class developed by Unity, achieving an easy control and navigation of a player and the interaction of the latter with the virtual environment (Unity, 2022e). The skin width variable controls the amount of penetration between virtual colliders; by lessen the value of skin width, the virtual character appears to get stuck when colliding with objects. Thus, the user must insist until the character can eventually move on.

Gripping strength

Finally, another decline in the musculoskeletal system due to age that was targeted by the proposed simulation, is the loss of gripping strength which can deteriorate by 50% until the age of 80 (G. Payne and D. Isaacs, 2012).
To approximate the attenuation of gripping strength in the elderly, an additional difficulty was introduced in manipulating handles that appear in the VEs. For example, in the first study (see Section 5.3), users were required to turn a virtual object multiple times. To simulate the loss of grip strength in the simulated VE, the users needed to perform twice the number of click-and-drag mouse operations compared to the corresponding number of operations required for performing the same task in the non-simulated VE. In this case, as no additional accessories to impede hand movement were added, the simulation was approached indirectly by simulating the result, that is the fact that an elderly adult would need to double the effort to complete the task, compared to a young adult.

5.2 Implementation

As discussed earlier, to achieve the simulation of the visual effects, post-processing effects were applied to the image, using the built-in stack of Unity (Unity, 2022d). For the design of the 3D models used in the three studies (elevator, virtual copies of products) the Autodesk Maya software was used.

Generally, the details used in the VEs were fixed in a way that the application achieved the target frame rate limited by the used hardware. The experiments were run on a desktop PC Intel Core i7-6700 3.4GHZ (16GB DDR4 RAM) equipped with an NVIDIA GeForce GTX 1070.

For the visualisation of the VE, the Oculus Rift headset was used. Here, it is pertinent to note a difference between the three studies related to users' experience, which varied due to the concurrent VR technologies upgrade. More precisely, in the first study, the headset used was a prototype——Oculus Rift DK1 (Development Kit 1)— which included head orientation tracking only. In the period intervening between the first and the next two studies, a commercial version of the headset was released (Oculus Rift CV1) with both rotational and positional tracking available. Thus, this headset was preferred to be used in the next two studies for a more immersive experience.

Additionally, while in the first study, the interaction was achieved using the standard computer peripheral devices, in the next two studies, the VR controllers (Oculus Touch) were used for a more intuitive manipulation of the virtual objects in the VE.

5.3 Study 1: Performing a Simple Daily Task in an Age-simulated VE

The aim of the first study was to investigate the effectiveness of the initial simulation mainly in inducing the sense of being older and changing possible negative views towards the elderly (Zavlanou and Lanitis, 2016). As indicated previously, the initial system for simulating aging effects in the VE incorporated age-related adjustments pertaining to vision, sound, body height, mobility and muscle strength. The experimental investigation involved the use of the simulated VE in a dedicated test scenario. The scenario of the application, the experimental setup and the results are presented hereinafter.

5.3.1 Experimental Scenario

The central element of the simulation's VE was the elevator of a multi-storey building that the user was required to use to perform a simple task, namely to transfer an object from the second to the ground floor. The objective's simplicity was determined in that way to allow users to focus on the environment and their relationship with it, rather than on how to carry out the task. Nevertheless, the task was not predictable from the beginning, as when returning to ground floor, the elevator would malfunction. The user was then asked to find a solution to escape the stranded elevator, using the instructions for dealing with emergency situations (Figure 5.3). This extra twist allowed users to experience, more intensively, the age-related limitations.

(a) (b) (c)

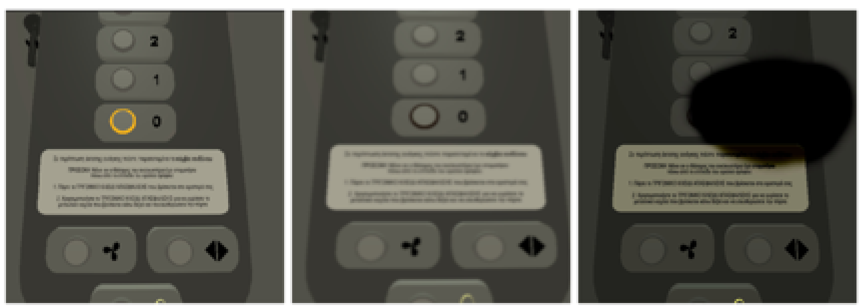

Figure 5.3 From left to right: (a) view of the non-simulated VE, (b) view of the blur effect simulating cloudy vision and (c) view of the dark spot effect simulating AMD's symptom in the VE of the Study 1

For the experimental evaluation, two variations of the VE were implemented. The variation A referred to the simulated VE, for which different parameters were manipulated to emulate age–related effects, as described in Section 5.1. The variation B referred to the control condition, in which no effects were applied.

5.3.2 Virtual Environment

As a perspective taking approach, the simulation was implemented in first-person view and users' head direction in the VE was synchronized with their real head direction thanks to the rotational tracking system, embedded in the VR headset. For this initial evaluation, where no dedicated equipment was available, users were navigating in the VE using the keyboard arrows, while other virtual actions, such as the assets' picking and the 3D elevator buttons' activation, were performed with mouse interactions.

The VE was designed from scratch based on the actual interior of the building in which the study took place. More precisely, the 3D objects were created based on actual measurements, and for the mood of the virtual space, the lighting parameters were suitably configured so that the conditions approximate the actual ones.

A difference between the actual and the virtual environment concerned the elevator doors. For these, instead of using a solid, opaque material to resemble the actual one, a transparent material was used to give the user the sense of upward and downward movement during the task. The speed of the virtual elevator was adjusted based on visual feedback, to approach the speed of the real elevator considered, which was calculated at 0.8 m/s.

5.3.3 Experimental Setup

The aim of the assessment was to determine whether subjects in the simulated condition had the sense of being older. In addition, the study aimed at assessing any change in attitude towards the elderly, as a result of using the simulation. Finally, interviews were conducted with four subjects who had some kind of expertise in the design field, to obtain their views regarding the use of the proposed simulation as a supportive tool in Universal Design.

As part of the experimental evaluation, subjects followed a four-step process: pre-questionnaire completion, simulated condition, control condition and post-questionnaire. Figure 5.4 illustrates the experimental setup. It is assumed that the order in which the two different conditions of the study were presented did not affect subjects' answers, as the questions did not relate to the difficulty of the mission.

To achieve triangulation, a mixed-method approach was followed in which questionnaires, interviews and observation were used for registering the impressions of the users. After their interaction with each condition, subjects were asked to indicate their perceived age in the two VEs.

Regarding the questionnaires, these were consisted of two parts: The first part—completed before subjects tested the simulated condition—included 12 statements related to elderly adults and aging in general (see table 5.1), asking people to indicate whether they agree or not with the statements on a Likert scale from 1 to 5, where 1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree and 5: strongly agree. The questionnaire was formed based on material found in questionnaires of similar content such as the Aging Perceptions Questionnaire (APQ) (Barker et al., 2007) and a short quiz with various facts and misconceptions related to aging (E. Palmore, 1977).

The second part which was completed after the subjects tried both variations, included the same statements as the first questionnaire. The objective was to register any deviation of the responses to the same questions before and after the use of the simulation.

Finally, users had to complete a questionnaire with general questions about the overall experience from their interaction with the VEs, including rating their interest, the sense of immersion and innovation of the application.

The experience was assessed by 14 subjects - 4 males and 10 females aged between 22 and 34 years old. Subjects were informed that the study involved testing two VEs, but they were not given additional information about the aim of the study.

Table 5.1 Descriptive statistics of the responses in the pre- and post-questionnaire

ID	***Statement***	***PRE*** *(mean* $\pm SD$*)*	***POST*** *(mean* $\pm SD$*)*	***p value Ha: pre>post***	***p value Ha: pre<post***
S1	Old people are boring and tiresome	2.357 ±0.929	2.214 ±1.051	0.291	0.709
S2	I enjoy spending time with older people	3.500 ±0.760	3.643 ±0.842	0.918	0.082
S3	I would like to make elderly people's life easier	4.286 ±0.469	4.500 ±0.519	0.905	0.095
S4	I think I will change a lot when I will grow old	4.071 ±0.730	3.857 ±0.864	0.136	0.864
S5	Old people are capricious	3.286 ±0.825	3.143 ±0.864	0.217	0.783
S6	Elderly people can't live an autonomous life	2.929 ±0.997	2.857 ±0.949	0.291	0.709
S7	Elderly people have the right to have a good QoL	4.717 ±0.469	4.714 ±0.469	0.500	0.500
S8	I always respect older people	4.857 ±0.363	4.714 ±0.469	0.082	0.918
S9	I have changed a lot since I was young	4.143 ±0.770	4.000 ±0.784	0.082	0.918
S10	I get angry when I think that I grow old	2.643 ±0.929	3.000 ±0.784	0.973	0.027
S11	The use of technology (e.g. VR) could help younger people understand elderly people's problems	3.786 ±0.893	4.214 ±0.802	0.945	0.055
S12	I get angry when I think that some basic products/ services are not designed to be used by older people	2.357 ±0.929	2.214 ±1.051	0.291	0.709

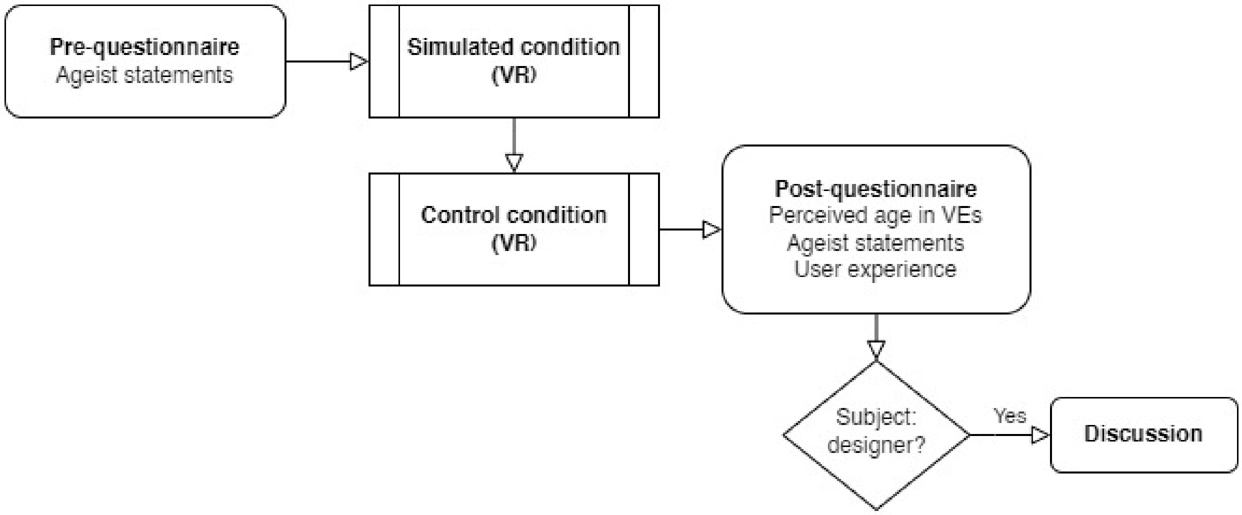

Figure 5.4 Experimental setup of the Study 1

5.3.4 Results

As mentioned earlier, after testing both conditions, subjects were asked to record the age they thought they had during the interaction with each VE. Their responses were compared with the actual age of the subjects.

Repeated-measures ANOVA with Bonferroni post-hoc analysis showed that subjects' perceived ages in the simulated VE were significantly higher than their actual ages ($p<0.001$) at a 95% confidence level (see Table 5.2). Conversely, subjects' perceived age in the control condition were not significantly different from their actual ages ($p=0.069$) (see Figure 5.5). In more detail, 10 out of 14 subjects indicated an age ≥ 60 years old during the age-simulated condition, while during the control condition, they indicated an age ≤ 30 years old. Among these 10 subjects, 6 stated an age between 60 and 74 years old and 4 subjects indicated an age greater than or equal to 75 years old. The remaining 4 subjects did not realize that the experience in the simulated VE corresponded to the experience of elderly people.

Regarding the questionnaires, interestingly, subjects' responses to specific statements such as *"old people are capricious"* and *"elderly people can't live an autonomous life"* had a

Table 5.2 Post Hoc Comparisons - Subjects real and perceived ages in the two conditions of Study 1

		Mean Difference	SE	t	p_{bonf}
SIM	CTRL	37.500	4.705	7.970	< .001
	REAL	48.857	4.705	10.384	< .001
CTRL	REAL	11.357	4.705	2.414	0.069

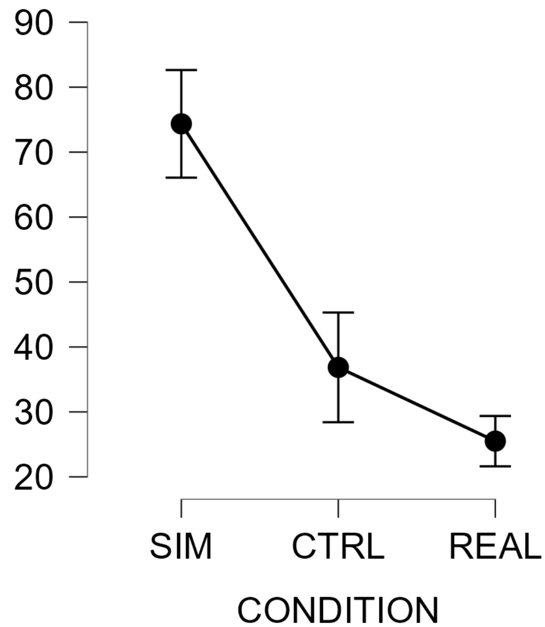

Figure 5.5 Subjects real ages and perceived ages per condition, in Study 1

mean value of 3.286 ± 0.825 and 2.929 ± 0.997 respectively, in the pre-questionnaire. Paired samples t-test analysis was used to compare the differences between the responses. Except for S10, no significant difference was observed at the default level. Interestingly, in S10, a statement regarding feeling angry when thinking of getting old, the answers showed a significant increase after testing the simulation. It is worth noting that borderline significance was observed in S11. In general, although the results were not statistically significant, a positive change was observed in most statements after the simulation.

Regarding the evaluation of the application itself as well as the user experience from

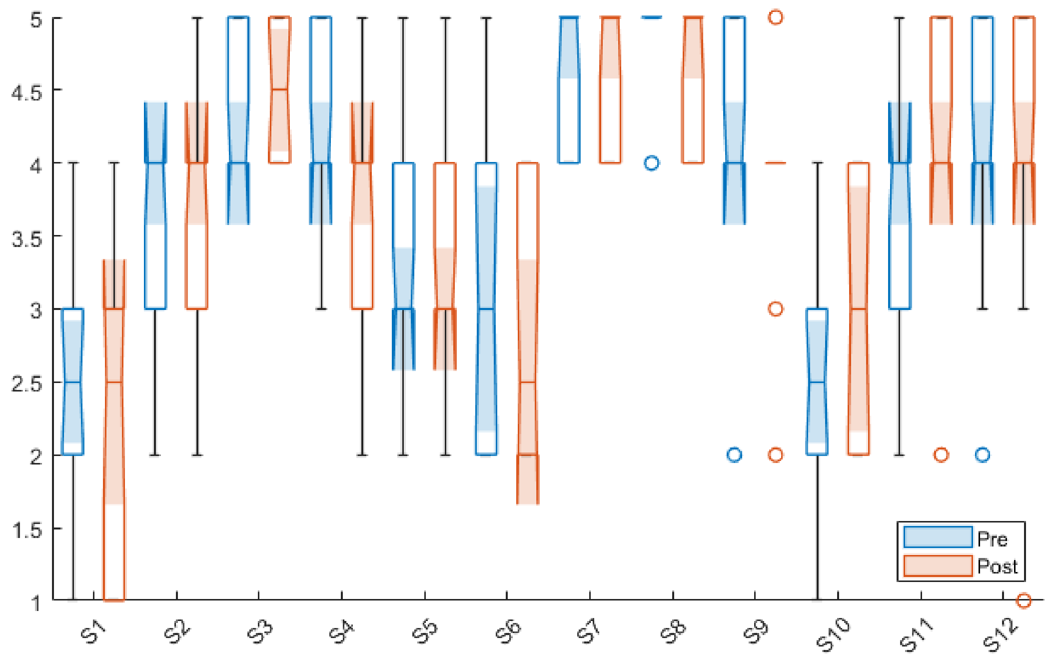

Figure 5.6 Subjects ratings to statements related to the elderly, by condition, in Study 1

the VEs, the following results were obtained (Figure 5.7): most subjects (64%) considered the use of the VR-based aging simulation, an interesting experience. The majority of the subjects (86%) rated their sense of immersion in the VEs higher than the average (50% fully immersed and 36% immersed). In all four aspects of the VR experience, there is a statistical significance (single sample proportion t-test, $p<0.05$) between the percentage of the positive responses (above average) and the negative responses (below average).

Finally, regarding the design-related questions, subjects were asked to report and elaborate on specific elements that make an elevator friendly to users regardless of age. The same question was asked both before and after testing the VEs. Before testing the VEs, subjects mentioned the use of grab bars and highlighted the importance of voice feedback. After testing the simulation, subjects suggested increasing font size on labels, using button lighting, placing auxiliary objects properly, and designing more visible instructions.

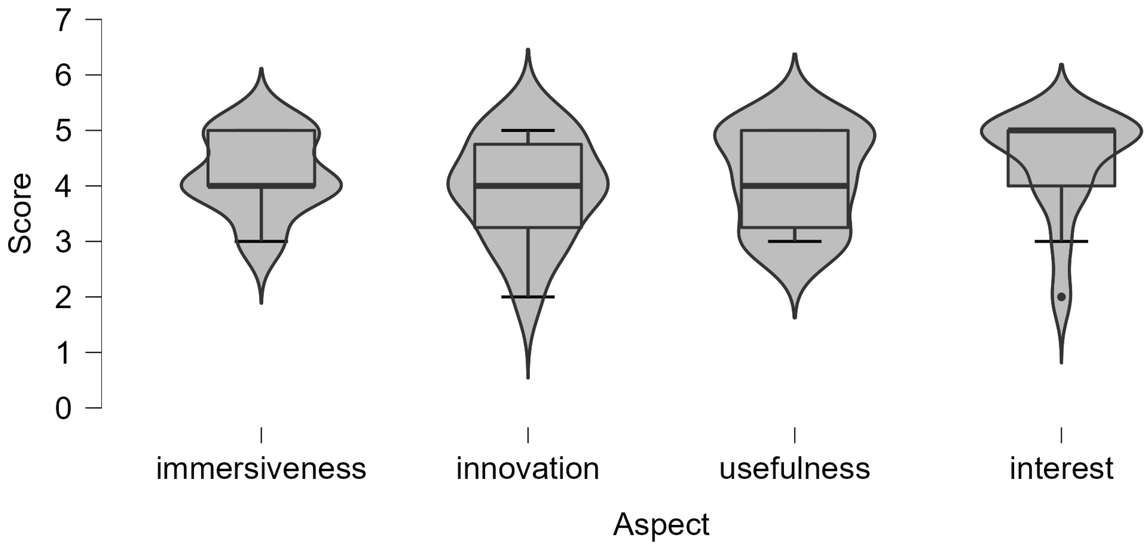

Figure 5.7 Boxplots of subjects' views on the VR experience of Study 1

5.3.5 Discussion

The results regarding the perceived ages in the two conditions signified that the primary objective of the simulation was achieved, that is to induce the perception of being older.

Regarding the questionnaires, before subjects' exposure to the simulated condition, neutral to positive mean values were noted only in specific ageist statements. Except for one statement, no significant change was observed in subjects' responses before and after experiencing the simulated conditions. Overall, these results suggest a possible presence of a ceiling/floor effect. That is, most of the statements had a relatively marginal score before the interaction with the simulated condition, showing that anyway the subjects did not concur with ageist opinions and did not support the documented tendency for stereotypical views and generalisations against the elderly (E. B. Palmore, 2003). Thus, naturally, the simulation could not produce any significant effect.

Interestingly, a significant change was observed in the statement about feeling angry when thinking of getting old. This feeling of anger may be related to the *frustration* to which Lavalliere et al., 2017 referred to, regarding the simulated effects of the aging suits. Although anger is considered a negative emotion, there is evidence that can be related to motivation

(Carver and Harmon-Jones, 2009). However, in the absence of further data, no conclusions can be drawn about what this significant increase in anger reflected in this case.

An interesting finding that emerged from the observation during subjects' interaction with the simulated VE was that of the forward extension of subjects' head to approach an object/text and have a clearer view of the latter. This was a spontaneous movement that subjects made, although they were informed that positional tracking was not available. Given its consistency with the responses to the user experience questionnaire, the forward movement of the head, performed several times during the study, can imply subjects' immersion.

Regarding the design-related questions, before testing the VEs, comments about age-friendly elevators were more generic. Instead, after testing the simulation, the elements mentioned were more elderly-oriented and more influenced by the design of the virtual elevator per se. This shows that such simulations could be used to effectively detect specific product design weaknesses and make the products friendlier to elderly users. This potential of the proposed VR-based simulation was confirmed by the discussions with young designers which revealed an interest in the simulation, claiming its innovation and usefulness in the design process.

For this feasibility study, three caveats need to be highlighted. First, the small sample size which did not allow for concrete conclusions. As this first study was exploratory and aimed mainly at investigating whether the simulation could elicit the sense of aging, other indices such as the effect of the simulation on biases against the elderly and aging, could not be adequately assessed. For this, in the future, we recommend a larger-scale study with at least 40 participants or based on a power analysis prior to the study.
Second, the limited availability of VR technologies at the time of the study. As mentioned earlier, a prototype VR headset with limited features was used, which hindered the intuitiveness of the interaction with the simulation. To address this, in the follow up studies, we used the latest version of the VR headset that had just been released. This version featured positional tracking and dedicated VR controllers for a more intuitive interaction with the

virtual objects and in general, a more immersive experience.

Finally, another factor that may have influenced the experimental investigation is the use of an explicit questionnaire. Admittedly, it is not trivial to properly obtain young people's views and this is reflected in the introduction of the book by E. B. Palmore, 2003. Future studies could explore this further by using implicit measures, like in the study by Beadle et al., 2015 in which empathy and other empathy-related emotions were assessed through indirect questionnaires that were supposedly measuring the effect of playing a game over a period of time.".

In general, the positive feedback received in the first study especially during the design-related post-discussions has given the impetus to continue the research with a more specific objective, namely the design of products and services. Thus the two subsequent studies, as discussed in the next sections, aimed at investigating the role of the proposed simulation in the design process.

5.4 Study 2: Implementation and Evaluation of the Simulation in the Design Process

The aim of the second study, detailed in this section, was to investigate whether it is feasible to detect design faults on pill packages that could prevent the correct use of pharmaceutical products by elderly people with age-related visual problems (Zavlanou and Lanitis, 2019).

5.4.1 Experimental Scenario

During the interaction with the VE, subjects were asked to locate information on a virtual pill box, identical to a real one, to assess whether the information was presented in a way that elderly people with specific visual declines could read it without problems.

Similar to the first study, the implemented protocol included two conditions: a control and a simulated VE. The two conditions allowed the subjects to interact with the VE through the eyes of an adult with healthy vision and an elderly person with specific age-related visual problems, respectively. In the context of this study, the simulation included the visual problems described in Section 5.1.1, as the subject was principally related to visual stimuli. The VE used in this study consisted of a three dimensional object—-the virtual copy of a real pill box—, and a grey background with depth perception (see Figure 5.8), similar to the default environment of a design software.

The pill box was placed at the center of the scene on top of a 3D table. That way, the VE corresponded to the real one where the subjects conducted the study, sitting in front of a desk (Figure 5.8). Generally, a minimal VE design was adopted to further reinforce the focus to the actual task, namely locating and reading information on the virtual box.

As part of the study, subjects were requested to locate and read aloud:

1. The name of the medicine
2. The active pharmaceutical ingredient (API) in mg
3. The indications about the medicine
4. The expiry date (EXP) of the medicine

For the 3D modeling of the pill box, scanned images of the six sides of the actual packaging were used. Using a raster graphics editing software, two alternative virtual pill boxes were modelled by duplicating, mixing and matching existing text (Figure 5.9). This eliminated the carry-over effect, ruling out the possibility that the subjects remembered the previous information, instead of reading it during the second condition. Thus, the name of the medicine, the API in mg, the indications and the expiry date were different between the control and the simulated VE.

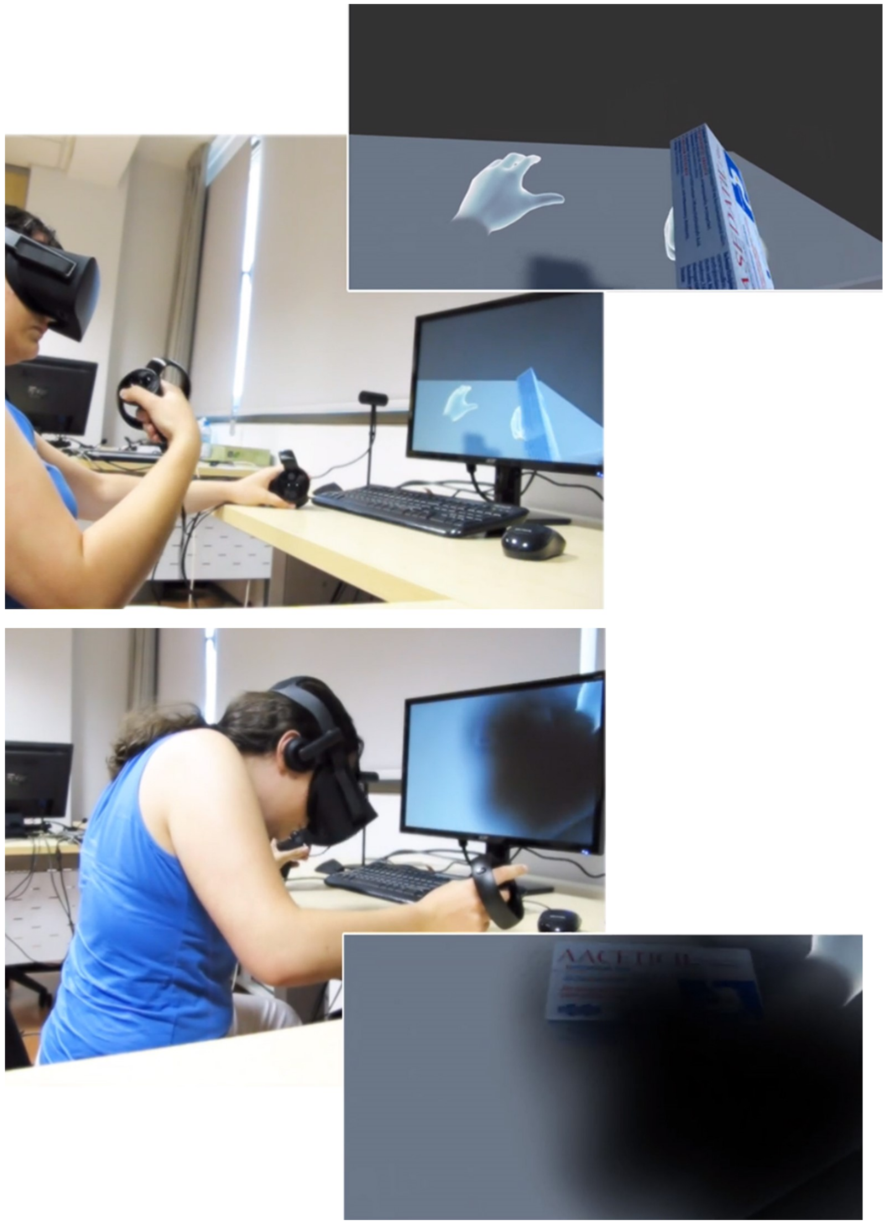

Figure 5.8 Picture captured during the interaction with the control (top) and the simulated VE (bottom) in Study 2

5.4.2 Experimental Setup

The experimental setup was composed of four distinct steps, detailed below.

Step 1: Subjects were given an actual pill box, like the one presented in the VE, and were asked to examine it for approximately one minute without having further information

Figure 5.9 Faces of the pill box labelling, showing the differences between the actual packaging (top) and its two versions created for the control (middle) and the simulated VE (bottom). Some information is pixelated to hide the trademark.

on the tasks they would later perform.

Step 2: Subjects were asked to wear the VR headset and use the controllers to interact with a rectangular three-dimensional object in the dimensions of the pill box. Instead of the actual packaging information, each face of the 3D model was covered with a different solid color. The purpose was to help subjects get acquainted with the different perspectives and the handling of controllers' options (grabbing, rotation etc.). During this step, there were no time restrictions, and the subjects were free to familiarize themselves with the interaction and the VE. It should be noted that most subjects asked to proceed to the next steps after less than a minute of interaction with the virtual object, indicating that the handling was clear and easy to learn.

Step 3: After the preliminary steps of familiarity with both the real and the virtual model of the box, subjects proceeded to the main part (see Figure 5.8). At this point, each subject was randomly assigned to one of two groups. The first group (group A) started the experience using the simulated VE and then carried on with the control VE, while the second group (group B) performed the experience in the opposite order. Thereby, previous knowledge and/or familiarity with the one or the other VE did not factor into their overall performance in the tasks and their answers in the questionnaires.

Step 4: After the interaction with each of the two VEs, subjects were given a questionnaire related to the ease of completion of the four requested tasks and were asked to provide answers on a 5-point Likert scale (where 1: the task was not easy at all, to 5: the task was extremely easy to perform).

In the evaluation process there were also questions regarding the user experience. More particularly, subjects were asked to rate on a 5-point Likert scale (where 1: poor, to 5: excellent) the sense of presence (A1), the physicality of the 3D object's manipulation (A2) and the pleasantness of the experience (A3).

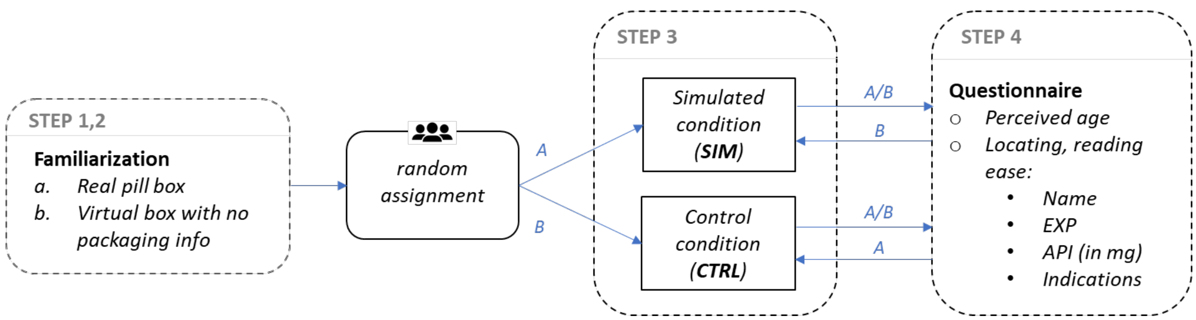

Figure 5.10 Experimental set up of the Study 2

The experiment was assessed by 23 subjects (9 males and 14 females) aged between 18 and 34 years old with normal or corrected to normal vision. Subjects were informed that the study involved testing two VEs, but they had no information about the aim of the study. Apart from the pre- and post- questionnaires, similarly to the first study, subjects were asked to quote their perceived age in each of the two variations of the VE.

5.4.3 Results

Paired samples t-test was used to compare the responses given after trying the control (CTRL) and after trying the simulated condition (SIM). For all tests, the alternative hy-

pothesis specifies that CTRL was greater than SIM. Assumptions check were conducted for all questions; normality tests with Shapiro-Wilk showed no deviation.
Table 5.3 presents descriptive statistics on the locating and reading ease of the information and Figure 5.11 plot the differences between each pair of answers in the two conditions.

According to the results from the questionnaire regarding tasks' difficulty as well as the observation during the experiment, in general, locating and reading the information on the pill box was clearly easier in the CTRL condition compared to the SIM (Table 5.3).

	Locating ease							
	Name		**EXP**		**API mg**		**Indications**	
	CTRL	**SIM**	**CTRL**	**SIM**	**CTRL**	**SIM**	**CTRL**	**SIM**
Mean	4.826	4.739	4.565	4.130	4.739	4.261	4.043	3.000
SD	0.491	0.541	0.788	1.325	0.864	1.214	1.296	1.414
SE	0.102	0.113	0.164	0.276	0.180	0.253	0.270	0.295
p	0.302		0.081		0.023		0.004	

	Reading ease							
	Name		**EXP**		**API mg**		**Indications**	
	CTRL	**SIM**	**CTRL**	**SIM**	**CTRL**	**SIM**	**CTRL**	**SIM**
Mean	4.783	3.913	4.087	2.696	4.739	3.739	3.565	1.304
SD	0.518	1.083	0.949	1.222	0.689	1.251	1.409	0.635
SE	0.108	0.226	0.198	0.255	0.144	0.261	0.294	0.132
p	0.001		0.036		0.003		<0.001	

Table 5.3 Descriptive statistics on subjects' ratings regarding locating and reading ease of the information on the pill box packaging in the Study 2

More precisely, no significant differences were found between the two conditions in locating the name and the expiry date. This was not surprising given that the expiry date was

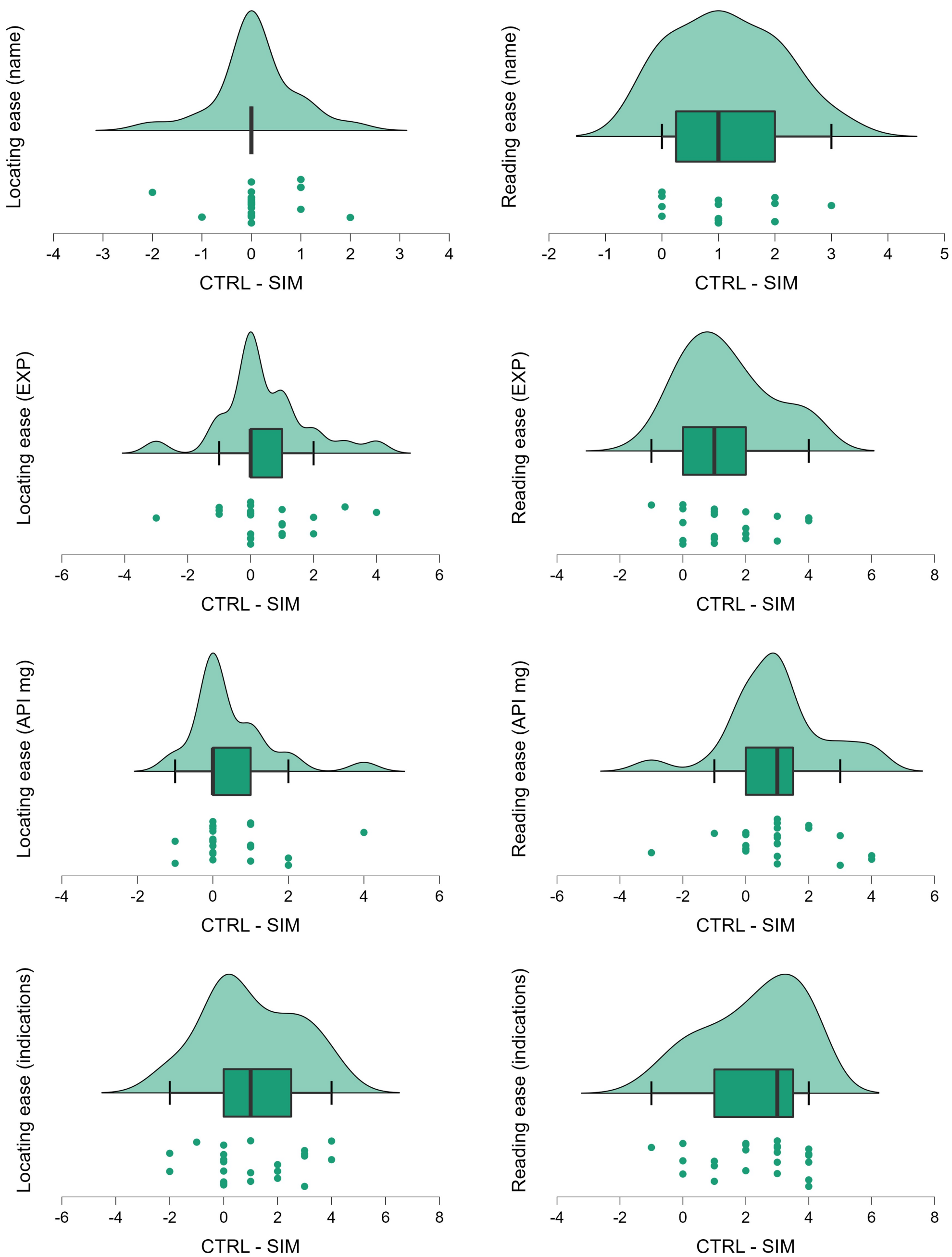

Figure 5.11 Rainclouds plotting the difference in the ease of locating (left column) and reading (right column) the information on the 3D box of the medicine, between the two conditions. The points represent the difference resulted from the subtraction of the indicated ease in the simulated from the indicated ease in the control condition for each subject, while the horizontal graphs show the distribution of the data and the boxplots show the central tendency and error for each case.

indicated on the side of the box separately, where one would expect it. Instead, there was a significant difference in locating the API and the indications. Significant differences were also observed in all scores ($p<0.05$) concerning the reading part of the information between the CTRL and the SIM condition.

While some information such as the name and the amount of the active ingredient was legible in both conditions, other, such as the indications were illegible by most of the subjects during their exposure to the SIM condition.

Interestingly, in the SIM condition, as the information about the indications was not legible, four subjects relied on an icon of a stomach which was placed at the front side of the package (Figure 5.9) to understand the purpose of the medicine. Based on this, these subjects were misled and stated that the purpose was to relieve stomach pain, while the specific icon was there to indicate that the pill box contained gastro-resistant tablets. One of these subjects was even unable to recognize the figure and stated that it corresponded to the shape of a throat, thus responded that the pill was intended for sore throat relief.

In the question about the design elements that one would change in the package, while in the CTRL condition the answers were more or less distributed, in the SIM condition, the majority (15 subjects) concluded that the main defect of the package was the font size (Figure 5.12). It is worth noting that subjects who indicated the font size in the first place, did not change their choice after the SIM condition. More than 20% of the subjects (n=5) stated that they would not change anything about the packaging in the control VE. Contrarily, in the simulated VE, all subjects had a negative aspect to note.

For the perceived ages in the two variations of the VE, compared to subjects' actual age, the results are presented in Table 5.4 and Figure 5.13. Repeated measures ANOVA test with post hoc analysis showed that:

– the perceived age in the CTRL condition and subjects' actual age did not differ significantly ($p>0.05$)

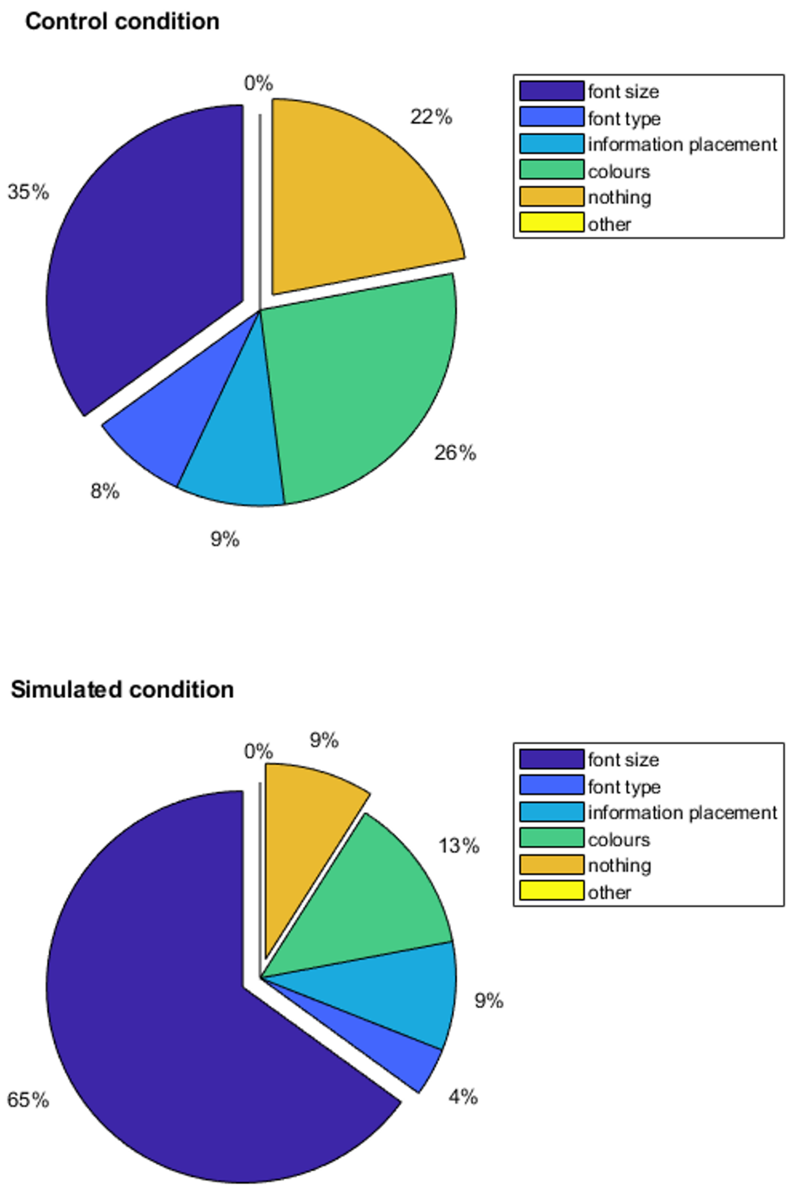

Figure 5.12 Responses to the question "What would you change about the packaging?" in the control condition (top) and the simulated condition (bottom) in the Study 2

– the perceived age in the SIM condition and subjects' actual age differed significantly ($p<0.001$)

– the perceived age in the CTRL condition and the perceived age in the SIM condition differed significantly (p<0.001)

Table 5.4 Post hoc comparisons - perceived, real ages in Study 2

		Mean Difference	SE	t	p_{bonf}
SIM	CTRL	37.500	4.705	7.970	< .001
	REAL	48.857	4.705	10.384	< .001
CTRL	REAL	11.357	4.705	2.414	0.069

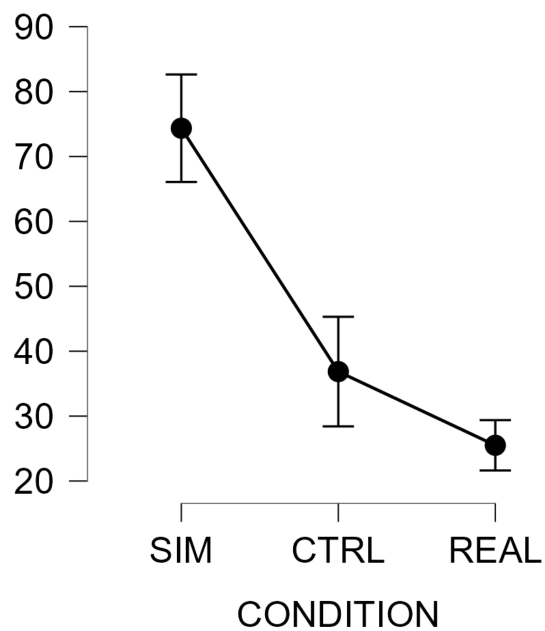

Figure 5.13 Perceived and real ages in Study 2

Regarding the overall experience in the VEs, the feedback was positive (Figure 5.14) as the mean values of all relevant questions exceeded the average (Table 5.5).

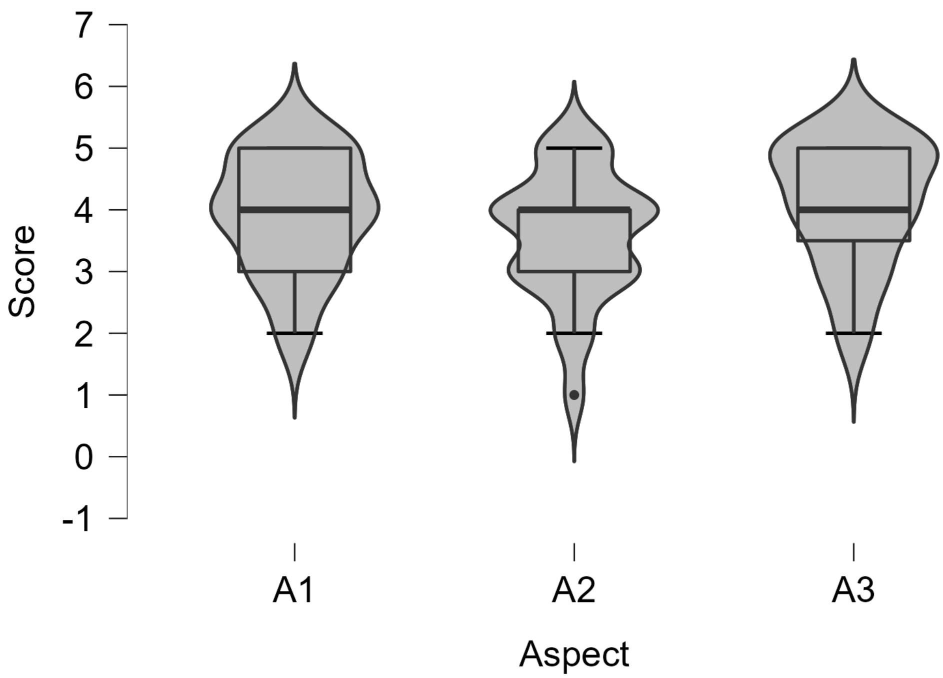

Figure 5.14 Boxplots of subjects' Likert scale ratings regarding the following aspects: sense of presence (A1), physicality of the object manipulation (A2) and overall pleasantness of the experience (A3) in the Study 2

5.4.4 Discussion

Overall, the results obtained from the second experiment suggested that reading and, in some cases, even locating important information on a pill box is affected to a significant extent in the simulated VEs. This finding is in line with the literature on challenges that elderly people with visual impairments face when handling their medication (Zhi-Han, Hui-Yin, and Makmor-Bakry, 2017).

Given the results reported, such problems could be avoided if designers were able to visualize the packaging from the perspective of elderly people, effortlessly detect design defects and ultimately design a more elderly-friendly packaging.

Regarding the perceived ages, similar to Study 1, the results indicated that the simulation induced the sense of being an elderly person, even without having prior information about the aim of the study.

Table 5.5 Descriptive Statistics regarding the aspects of the overall experience in the Study 2

	Score		
	A1	A2	A3
Valid	23	23	23
Missing	0	0	0
Mean	3.913	3.565	4.087
Std. Deviation	0.949	1.037	0.996
Minimum	2.000	1.000	2.000
Maximum	5.000	5.000	5.000

Although the experience was about the visualization of visual problems and tasks that posed difficulties to the subjects, the overall pleasantness of the experience was positively rated. This is very important for cases where the simulation tool is used in the design process, as an unpleasant experience could result in sidelining of the simulation tool.

Finally, there were some negative yet interesting comments that could improve the experience in the future. For example, a subject stated that the read-aloud process of answering the questions reduced the sense of immersion. Another subject mentioned that the transparent virtual hands (Figure 5.8) reduced the sense of presence.

5.5 Study 3: Product Packaging Evaluation through the Eyes of Elderly People: Personas vs. Aging Suit vs. VR-based Simulation

As discussed in detail in Chapter 3, various methods exist to support the understanding and realisation of elderly people's needs. Among these are methods to allow designers to take the role of elderly users and identify the physical and other challenges associated with aging (Lavalliere et al., 2017). However, no comparison could be found vis-à-vis their effectiveness and usefulness in the design process.

Towards this end, in the third and last study of the first phase, specific methods of conceiving challenges associated with product usage through the eyes of elderly users, were examined in terms of effectiveness and other aspects (Zavlanou and Lanitis, 2018). More specifically, the packaging evaluation of widely used products was studied, through the scope of three methods used:

1. Personas of elderly consumers
2. Simulation goggles of the GERT aging suit (see Figure 5.15)
3. VR-based aging simulation (see Section 5.1.1)

The purpose was to define which of the three methods is optimum during the evaluation stage of elderly-friendly product design.

5.5.1 Experimental Scenario

As part of this study, the case of assessing the packaging of widely used products in terms of suitability by elderly consumers with age-related problems in vision was examined. The selected cases included basic, everyday products, namely: a milk bottle, a toothpaste box and a pill box packaging (Figure 5.1). Similarly to the previous studies, three common age-related visual diseases were involved: AMD, cataract and glaucoma.

For the personas, descriptions of elderly user profiles were created based on the diseases in a way to correspond to the goggles and the VR-based simulation. More precisely, three different personas were created: a persona of a 75-year-old woman suffering from AMD, a persona of a 69-year-old man suffering from cataract, and a persona of a 78-year-old man suffering from glaucoma. Personas' descriptions were based on information extracted by

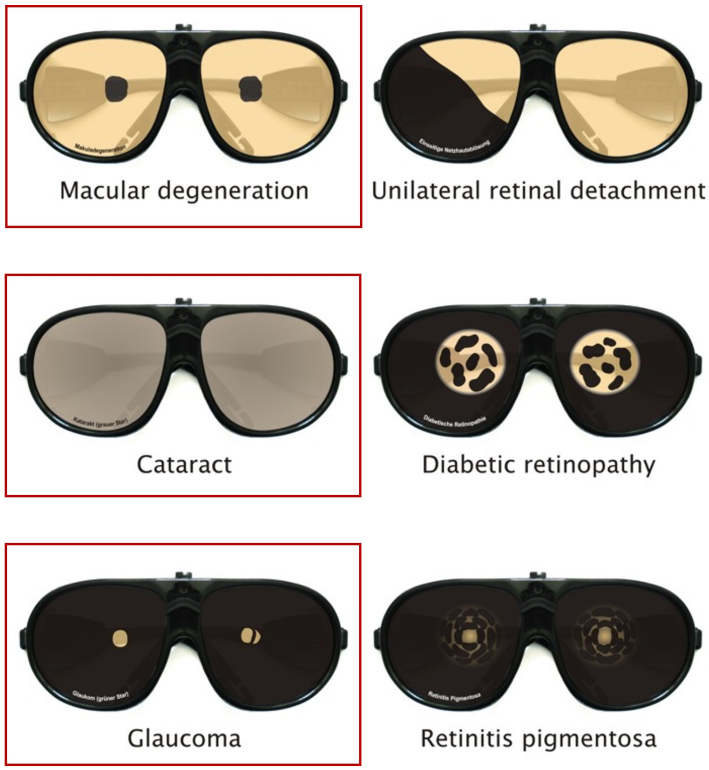

Figure 5.15 Simulation goggles provided by the GERT aging suit. Original photo taken from www.produktundprojekt.de. Red rectangles indicate the ones that were used in Study 3.

Mayo Clinic website (*Mayo Clinic* n.d.). Through the personas description, subjects were informed about the symptoms associated with each disease and the main problems faced by these personas in their everyday lives, such as difficulty in reading small print on packages. Finally, subjects were provided with pictures showing how each persona sees compared to someone with normal vision (Figure 5.16). In the case of the evaluation of the packaging using the personas method, the actual packages of the three products were used.

For the goggles case, the corresponding pair of glasses of the three deficits provided by the GERT aging suit (*GERontologic Test suit GERT* n.d.) were used as indicated in Figure 5.15.

Finally, for the VR, following a similar approach with the one of the second study, virtual copies of the actual products were created from scratch using a 3D modelling software (see

Figure 5.16 Example of a picture given to the participants in the personas method to show how the persona with cataract disease would see compared to a healthy vision person (source: *Mayo Clinic* n.d.)

Figure 5.1). The actual labels of the products were scanned and placed on the 3D models. The dimensions of the 3D models corresponded to the dimensions of the real products (measurements and 1:1 ratio used) and the materials of the 3D models approached the actual ones.

The VE was composed of a 3D table on which the three products were placed, to allow the subjects to focus on the objects and not be distracted by the rest of the environment. Subjects could also view the virtual representation of the hand controllers, through which they could manipulate the virtual packages (Figure 5.17).

5.5.2 Experimental Setup

An interview mode experiment was conducted with 9 subjects (7 females and 2 males) aged between 22 and 28 years old. All subjects were postgraduate students in Multimedia Design and had attended at least one course related to Universal Design and participated in projects related to elderly-friendly design. Prior experience of the subjects in similar projects enabled them to provide important views and opinions in relation to the suitability of different methods for product evaluation.

Subjects were equally divided into three groups, based on the method used to evaluate the product packaging. The assignment of the subjects to the groups was based on random placement.

- Group A - Subjects using the personas method
- Group B - Subjects using the simulation goggles of the aging suit
- Group C - Subjects using the VR-based aging simulation

All three groups were asked to reply to open-ended questions regarding products packaging in terms of its design elements, such as the fonts used, the selected colors, the placement of the information etc.

After evaluating the product packaging, subjects were asked to evaluate the method used to help them consider elderly users' characteristics, through a questionnaire. More precisely, they were asked to comment on the positive and negative aspects of the method they tried and to report how strongly they had experienced the role of an elderly user.

Moreover, they were asked to rate the degree of usefulness, efficiency, ease of use and utility of the method they tried on a Likert scale from 1 to 5 (1: Not at all, 2: Slightly, 3: Moderately, 4: Very, 5: Extremely).

Finally, subjects were given more information about the remaining two methods and they were asked to state which method they would choose to use in the future for packaging evaluation from the perspective of elderly users/consumers.

5.5.3 Results

Regarding the evaluation of the packaging design of the three products, within the subjects of group A, comments were ambiguous and non-consolidated (see Table 5.6). In addition, there were opposing views between the subjects who used the personas method and those who used the other two methods.

Figure 5.17 Evaluation of product packaging design using the simulation goggles (left) and the VR-based simulation (right).

Also, subjects' comments were often misplaced in the case of the personas method. For example, a subject of group A stated that the most legible labelling was the one on the milk bottle, while those who tested the simulation goggles and the VR headset claimed that the most difficult to read was the labelling of the milk bottle. Another subject of group A indicated that the color selection on the brand name of the milk bottle was not appropriate, while subjects of the other two groups reported that the color combination was an ideal choice due to contrast. A subject from group A reported that an elderly person suffering from cataract would not experience any particular problem, while subjects who tested the VR and the aging suit reported that cataract was undoubtedly the worst case, since everything was appearing very blurred and almost no information was legible.

A difficulty in understanding the needs of the elderly personas was also reported within group A, although the description of the diseases and the problems associated with these diseases, as well as a picture of the symptoms were provided. This is shown by the use of phrases indicating uncertainty such as "I do not know" and "maybe". Comments like "I cannot separate the peripheral from central vision in my mind" were also reported (see Table

GROUPS		
Personas (group A)	***Goggles (group B)***	***VR (group C)***
"I do not know what I would change"	*"This (indication) should be more intense"*	*"I insist that this (colors choice) is wrong"*
"I do not know what we could do here"	*"This (indication) should be more on the centre"*	*"For sure I would change this (logo)"*
"Maybe bigger fonts..."	*"Colours should be different"*	*"That is a good choice (main info design)"*
"I cannot separate peripheral from central vision in my mind. . . "	*"I would do it like this: [...]"*	

Table 5.6 Subjects' quotes per group during the product packaging evaluation comparative study

5.6). Generally, subjects of group A found it hard to visualize the packaging through the eyes of elderly users, although they were aware of personas' problems. As a subject stated to summarize this method, "you guess and you can imagine, but you cannot really understand." On the contrary, both the simulation glasses provided by the aging suit and the VR-based simulation made the visualization possible, thus, the comments from subjects of groups B and C were more targeted, more detailed and the results more tangible. In group B, for example, less doubtful phrases were used such as "this should be [...]". This confidence and certainty in subjects' answers was more evident in the case of the VR-based simulation, where phrases like "for sure" were used several times.

Another important aspect is that subjects from groups B and C tended to compare to previous cases. Many subjects, used expressions like "as before", meaning that having a visualization of the problems, they could hold back previous images and compare them. In the case of the VR aging simulation, this was further enhanced thanks to the ease of effects' switching.

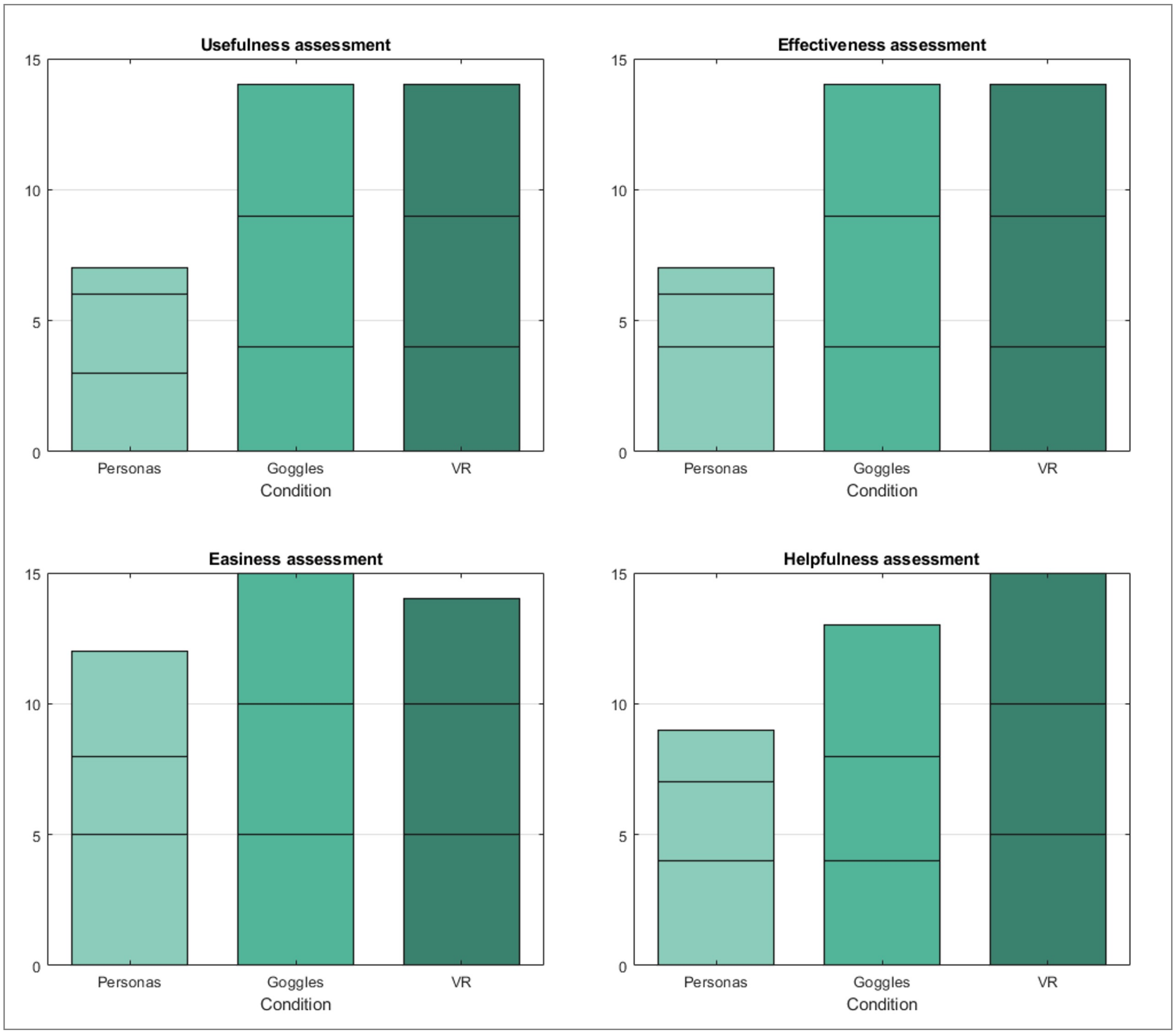

Figure 5.18 Comparison of the three methods in terms of usefulness, effectiveness, easiness and helpfulness, based on the responses to the questionnaire.

The results from the questionnaire are consistent with the results of the interviews, demonstrating that the personas method is the least preferred in the evaluation of product design through the perspective of elderly consumers. The VR-based simulation was the most preferred one; as subjects reported, it provides a protected, more interesting and pleasant environment. More precisely, in the question "Which method would you choose to use?", five subjects stated that they would choose the VR aging simulation, four subjects would choose the aging suit, while nobody would choose the personas method.

VR also preceded in terms of the perspective-taking aspect, as in the question "Which phrase better characterizes the feeling you had during the experiment?", the results were as follows:

- All three subjects of group A stated, "I felt myself. I did not feel I took the role of an elderly person."
- Most subjects of group B stated, "I felt different. Still, I'm not sure that I felt like I took the role of an elderly person."
- Most subjects of group C stated, "I felt like I took the role of an elderly person".

Figure 5.18 presents a comparison between the three methods as they arise from the answers of the subjects to the questionnaire. VR performed better that the aging suit in terms of helpfulness, but in terms of easiness, the aging suit received the highest score, as one user did not have sufficient experience with VR technology, therefore had difficulty in handling the 3D packages.

5.5.4 Discussion

Although packaging design is a fundamental element in product design (Azzi et al., 2012), oftentimes, it is not appropriately designed for elderly consumers, making the use of widely used products difficult and potentially hazardous for the latter (Vredenburgh and Zackowitz, 2009). This is supported by Study 3, in which young designers identified several design weaknesses in virtual copies of three examined products through the simulation tool.

In general, this investigation showed that the VR-based simulation had the same potential as the goggles of the aging suit, in terms of usefulness and effectiveness in the evaluation stage of product design. It slightly under performed in terms of ease of use but slightly preceded in terms of helpfulness offered to the designers, and in facilitating role-taking.

An important aspect of the VR-based simulation is that it provides an easy and direct transition between the effects thus the comparison of the different conditions is facilitated.

This aspect is rather useful to find a balance between users with diversities in terms of physical conditions and to optimize the package accordingly.

5.6 Conclusions

In this chapter, the initial investigation into the development and the evaluation of the proposed VR-based simulation of age-related declines was presented. Within three different studies, specific aging effects were virtualized enabling users to experience the perspective of elderly people having the associated problems, and understand how the latter affect the interaction with the environment and specific products/services.

More specifically, the objective of the first study was to investigate whether the addition of the aging effects and the elicited difficulty of completing a simple daily task in the simulated VE, could induce the sense of being older. The results demonstrated that the specific objective was achieved.

An additional investigation was carried out on the effect of the simulation in inducing empathy towards elderly adults and in changing potentially ageist views. Although a slight positive effect was observed, this study failed to provide robust conclusions presumably due to the small sample size and the nature of the administered questionnaire. It is concluded that to assess similar effect in future studies, implicit measures should be preferred.

Finally, during the first study, discussions with design students confirmed the potential of using such VR-based simulations in the design field as supportive tools, especially during the evaluation stage. Given this feedback, the next two experiments focused on the design aspect. As seen in Section 5.3, during this initial experimentation, we considered the simulation of different age-related deficits, like hearing loss and changes in the musculoskeletal system. From this very first work, the complexity of each component and especially of vision impairments became evident. For this, and to harness the full potential of VR in terms of visual stimuli, in the subsequent steps we focused on visual impairments.

The aim of the second experiment was to investigate whether by using an age simulated VE, it is feasible to detect design faults on pill packages that could prevent the correct use of pharmaceutical products by the elderly. The results demonstrated that VR can significantly highlight the difficulties that elderly people suffering from age-associated problems face during a seemingly easy process, such as reading pill packages' information. The results were in line with the literature (Vredenburgh and Zackowitz, 2009) and indicated that reading package's information was a significantly easier process in the control compared to the simulated VE. Subjects' performance in the tasks during the age-simulated VE highlighted the importance of inclusive design and how this may be achieved, harnessing VR.

Having demonstrated the effectiveness of the proposed method during the design evaluation process, we went one step further and compared the proposed VR-based simulation with two other methods used in product design to allow designers to step into the shoes of elderly users, namely the user personas and the simulation goggles. The results indicated that the personas method, compared to the other two, was not effective and not preferred by the design students. Both the simulation goggles of the aging suit and the VR-based simulation were effective and useful in the process of evaluating package design. A precedence was recorded in VR, as according to a subject *"it provided an immersive and interactive environment, through which elderly consumers' problems were better perceived"*.

Apart from the results obtained regarding the use of the proposed simulation in specific cases, the feasibility studies also revealed certain aspects that were targeted in a systematic iterative way, both in this and the subsequent phase of the research, to improve the simulation tool and in a more general context, the methodological approach.

First, a need anticipated and targeted from the beginning was that of continuous monitoring of advancements in the field of virtual reality, both in terms of hardware and software. This was essential throughout the whole research to keep pace with and make use of features that could improve the simulation tool. Thus, for example, as seen in this chapter, the development of the simulation was adjusted appropriately to include the use of the dedicated VR controllers and the integrated head tracking option, which were not available at the initial stages of the work. In the next chapter, we will see other options that were included and significantly improved the simulation, like the eye-tracking technology.

Another need that emerged was that for a more flexible simulation tool that could be easily adjusted to different cases. Although the flexibility provided by the built-in effects was sufficient for the purposes of the feasibility studies presented in this chapter, as a result of the work carried out for this step, we realized that in a broader context, these were limited and did not allow for an adequate development of different cases of visual impairments in an automated way. For this, as we will see in the next chapter, we considered a different approach based on dedicated, custom-made shaders for each symptom and to achieve this, medical expertise was considered in the development process.

5.6.1 Summary

This chapter elaborated on the first phase of the present research work, which was based on the prototype simulation. Various interesting aspects of this approach have emerged, particularly in terms of the sense of being older and the usefulness of the visualisation of age-related problems in the product design evaluation stage.

The next chapter focuses on the second phase of this research and more precisely on the technical approach and the methodology followed towards the development of the upgraded version of the simulation.

Chapter Six

Phase 2: Technical Approach and Methodology of Age-related Visual Deficits' Simulation

After the effectiveness assessment of the initial simulation, the next phase of the research was revisionary. It included recurring to the medical aspect, that is reviewing the literature focusing this time on patients' self-reported data and obtaining feedback from experts, to redefine the technical part and further develop the simulation itself. During this phase, the research work focused on deficits pertaining to the HVS.

The medical expertise was provided on a basis of a continuous consultation throughout the development cycle. At a first point, a group of geriatricians tested the VR-based prototype simulation, expressed their interest in holding an active role in the present research and gave some directions on the subsequent steps. At the same time, some reflections on potential uses of the proposed simulation were discussed. Specifically, there was a plan for the simulation to be used instead of the aging suit as part of their pedagogical approach with medical students, a plan which was unfortunately abandoned due to the COVID-19 outbreak and the fact that lessons were held online.

At a later stage, due to the specificity of the information required regarding the simulated effects in vision, we considered essential to seek the expertise of ophthalmologists. To this end, and in order to make the evaluation as objective as possible, through chain referrals, we formed a panel of experts independent with each other and of the present research. A very important point derived from their feedback was the need to separate the fields of vision in the virtual environment, to know the correspondence of the exact region that is affected and localize the simulated damage, according to actual cases. Another important recommendation provided was to thoroughly investigate subjective reports of visually impaired people and for this, as mentioned previously, we focused on self-reported data in the related literature.

To elucidate the context of the second phase, it is important to explain the factors that influenced the technical approach and methodology.

First, for the development of the visual effects in the initial simulation, a built-in solution was used to approximate specific age-related problems, leaving little leeway to flexibility and customization. Therefore, the main objective of the second phase was to develop a modular simulation that could be easily manipulated and adapted to different experimental setups and use cases, on the basis of a drag-and-drop implementation in the environment of a widely used game engine.

Second, the review of the related work revealed that very few studies addressed the element of heterogeneity to modulate the appearance of the simulated visual effects in the VEs and no study addressed it by incorporating randomness. Towards this end, a novel technical approach based on procedural noise was followed to provide diverse simulations.

An additional factor that affected the simulation relates to the VR technology itself, with the integration of the eye-tracking module in commercial VR headsets. In the initial simulation, visual deficits like macular scotomas were appearing as static effects, similar to the way they appear in the simulation goggles of the aging suit. As a result, they did not adequately represent the actual cases and allowed users to often bypass the simulated effects, using their peripheral vision or their heads' position. This new integration of gaze-contingent simulations, ensured that the effects follow users' gaze.

Additionally, following users' feedback from the first phase, other aspects that were considered important for the simulation were integrated, such as the representation of elderly hands to induce an illusion of body ownership (Slater et al., 2010).

The overall technical approach and methodology followed to realize the various simulations' aspects are detailed in this chapter.

6.1 Procedural Generation of Visual Deficits

The diversity characterizing the clinical features of visual conditions is an important aspect in human-like simulations. As mentioned earlier, the review of the related work revealed a dearth of diversity that, similar to other cases, could be addressed through the addition of "controlled randomness". Towards this end, as part of the present research, state-of-the art rendering techniques were employed to procedurally generate age-related deficits in VEs, giving the possibility to experience these deficits and their nuances in real time. The work drawn upon state-of-the-art feature-based approaches, such as foveated rendering and procedural noise, to provide realistic, heterogeneous effects and improve the diversity in the simulation.

In collaboration with a group of geriatricians from the Division of Geriatrics, Geneva University Hospitals (Switzerland), the work focused on specific classes of deficits exhibited in common visual problems that are directly or indirectly associated with aging, as these were described in Section 2.2. To obtain an external review, three ophthalmologists were recruited using chain referral sampling to evaluate the simulation during the development. Due to COVID-19 constraints, the evaluation was conducted through online anonymous questionnaires with rendered videos of the VR-based simulation.

In the remainder of the chapter, more details are provided on the technical methodology (Zavlanou, Huber, et al., 2021).

6.1.1 Introduction

Before describing the method to procedurally generate the age-related eye conditions, it is important to highlight certain aspects that were considered for the simulation.
First, age-related visual deficits can be unilateral or bilateral. Bilateral cases—involving both eyes—do not necessarily imply symmetry. Rather, several inter-eyes differences occur, with one of the eyes' vision being more or less impaired (Poinoosawmy et al., 1998; Quillen, 1999). For this reason, it is important to simulate different effects for each eye-camera, and offer the possibility to apply and adjust the effects independently (Figure 6.7). Note that asymmetric effects are part of a module already provided in existing VR-based simulated approaches (Stock, Erler, and Stork, 2018; P. R. Jones and Ometto, 2018).

Another step towards an accurate approximation of age-related visual impairments is to distinguish peripheral from central vision in the VE. This is essential, as different deficits affect different regions of the VF. For example, AMD affects principally the central vision, while glaucoma mainly affects the peripheral VF. A similar approach in which VF sectors are demarcated has recently gained currency in VR applications. Referred to as *foveated rendering*, this approach helps improving the performance in VEs, by leveraging how acuity decreases with eccentricity in the HVS (Patney et al., 2016; Swafford et al., 2016). Following the method from Swafford et al., 2016, the radius of the region corresponding to central vision in the VE in pixels was calculated (Figure 6.1, left).

$$R = \rho_{px}\, d_u\, \tan(\frac{\alpha}{2}) + c \tag{6.1}$$

Let d_u be the distance (in mm), between the eye and the headset's display, α the subtended visual angle of the fovea, ρ_{px} display's density in pixels/mm and c - a value accounting for tracking errors (Swafford et al., 2016). Using the Equation 6.1, the radius R of the circle defining the central vision in the VE is calculated. Note that the blending border of the equation from Swafford et al., 2016 is not used, as effects' blending is considered differently in this case. Following the same process, the radii of the other sectors of the VFs are calculated.

The calculations are consistent with the expected visual result, as according to O'Shea, 1991, approximately the 2 degrees of visual angle covered by central vision correspond to the width of ones' thumb with arm extended (Figure 6.1, right).

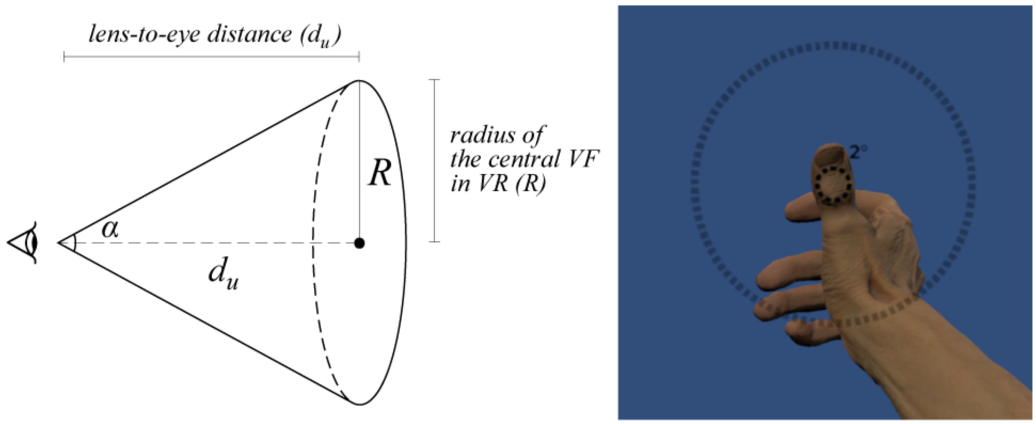

Figure 6.1 Calculation of the visual field (left) and virtual arm extended in the VE, showing how the calculation coincides with the width of the virtual thumb (right)

Additionally, as in the studies by P. R. Jones and Ometto, 2018; and Krösl, Elvezio, Wimmer, et al., 2019, the simulation is synchronized with eye-tracking data. In the present research, the eye-tracking module is part of a twofold approach. First, it is used to provide gaze-contingent simulated deficits and second to record eye-movements' trajectories, to obtain potential patterns of visual behavior during visual performance tasks.

One distinctive feature of our approach is the generation of "noisy" textures that represent the affected regions of the VF. These textures—henceforth referred to as *deficit maps*—are generated procedurally, based on user-defined parameters, both at run time and offline. To achieve this, high performance general-purpose computing on graphics processing units (GPGPU), computation-based shaders (*compute shaders*) were used to rapidly calculate the various mathematical equations that are required to generate the textures. Compute shaders are particularly used in cases where arbitrary calculations are important for realistic simulations, for example for fluids (Dharma et al., 2017) particles (Junker and Palamas, 2020) and waves' simulation (Tavakkol and Lynett, 2020).

This is not the first time that image noise is used to add a sense of random appearance in simulated human body elements. To increase realism in surgery simulations, Xuemei, Huan, and Hui, 2010 showed how Perlin noise can be used to approximate the surface of specific human organs, while Elhelw et al., 2006, showed how it can be used to simulate tissues' surface specularity. Jakes et al., 2019 also presented an approach to obtain naturalistic patterns of fibrosis using Perlin noise. Another example can be found in Dustler et al., 2015, where noise was used to mimic the appearance of breast tissues to generate imaging phantoms.

For the development of the simulation, a novel technical approach was followed to generate HVS declines' simulation in a procedural manner (see Figure 6.2). First, initial parameters defining the appearance of the simulated effects are defined. That is, noise parameters and the minimum and maximum radii of the affected region can be adjusted through range sliders. Compute shaders take into account these parameters to generate the deficit maps accordingly. After that, dedicated custom shaders per deficit, fetch the corresponding maps and apply gaze-contingent effects based on additional parameters, like blurriness intensity, transparency etc. These parameters are explained later in this chapter.

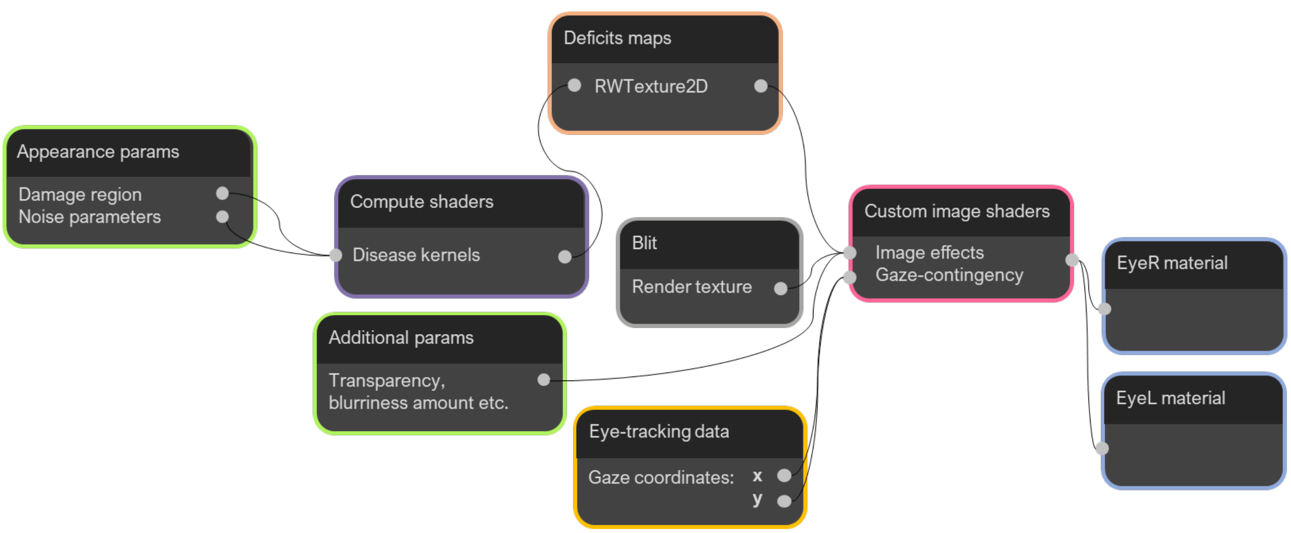

Figure 6.2 Visual representation of the technical approach followed to simulate gaze-contingent visual declines in a procedural manner

6.1.2 Blurred Vision

Blurred vision is one of the most (if not the most) common symptoms of several diseases, including glaucoma, cataract, AMD and DR. Depending on the disease, blurred vision can be manifested either in the entire VF or in specific parts of it.

Similarly to other studies (Krösl, Elvezio, Wimmer, et al., 2019), the simulation of blurred vision in the VE is obtained by convolving the image with a Gaussian function in both dimensions (Equation 6.2). In the present research, for the blurriness of the image, the dedicated shader considers the generated deficits maps. In cases where the whole VF is affected, the texture is ignored and Gaussian blur is applied to the entire image.

An additional parameter controlling the amount of blurriness allows to obtain different intensities of blurred vision (Figure 6.3).

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \tag{6.2}$$

6.1.3 Central Scotomas

The proposed simulation focuses on common symptoms of AMD, such as the relative scotomas (RS) and the absolute scotomas (AS) in the central and pericentral VF. RS do not completely block vision in affected regions, but cover it with a veil-like effect (Midena and Vujosevic, 2016), thus patients can still "see through them". Instead, AS completely mask vision in the corresponding region, which patients perceive as "missing parts" (Taylor et al., 2018). To simulate RS and AS in the VE, three parameters determining the effect are considered: the spreading of the scotoma, its shape and its translucency.

For the *spreading* of the central scotomas, it is assumed that the affected area is contained within a boundary circle, concentric with the circle defining central vision (r_c) (Figure 6.4). Given that the central point of vision corresponds to the center of the mask texture, w and h refer to the width and height of the mask texture, respectively, so that the coordinates

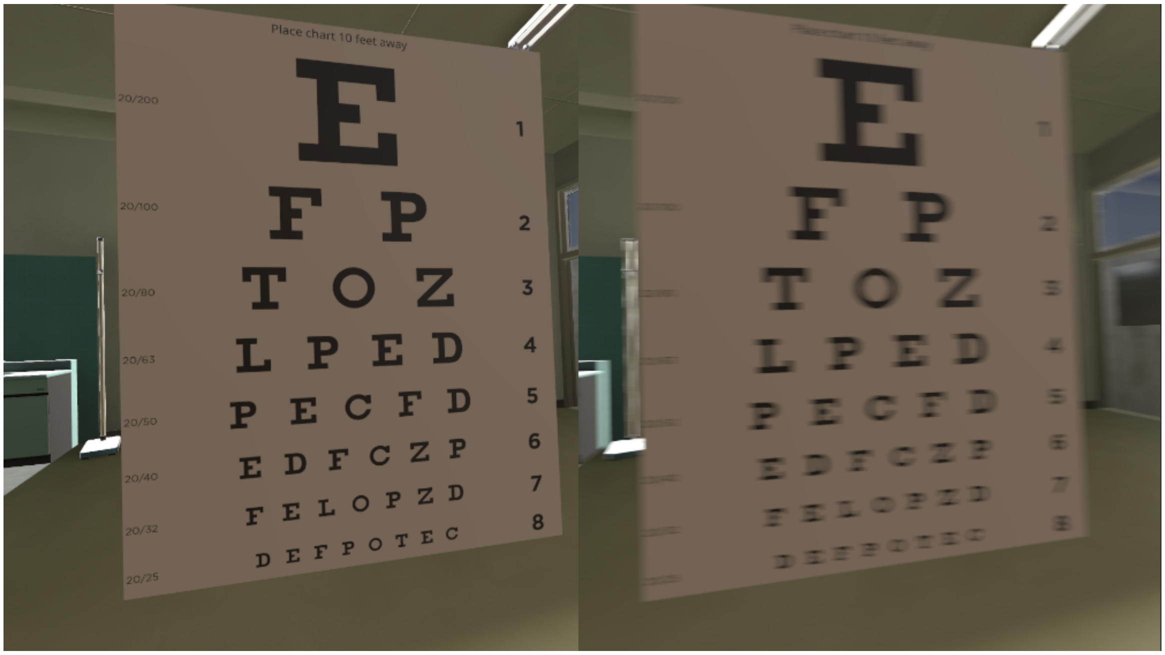

Figure 6.3 View of a Snellen chart in the VE. On the left, the image is clear, while on the right, Gaussian smoothing has been applied causing the blurriness of the image.

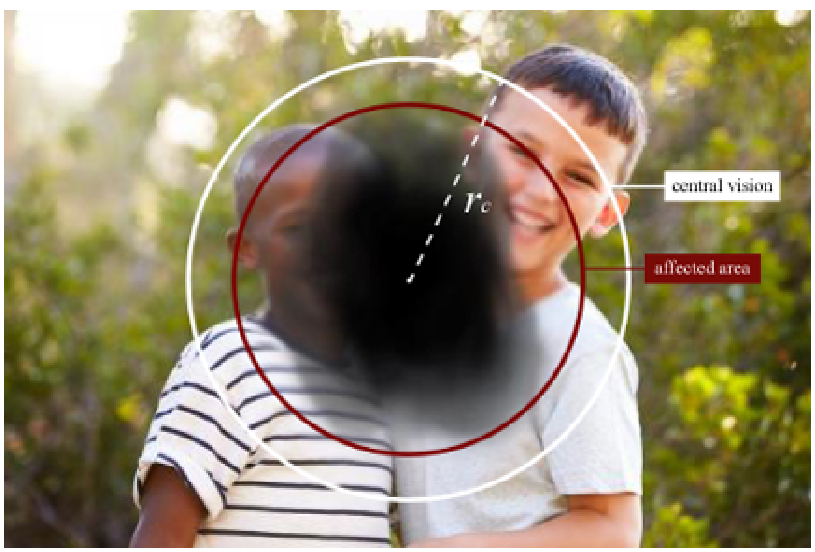

Figure 6.4 Boundary circle of the affected area of AMD vision in relation to the center of the VF. Original image: © National Eye Institute (NEI)

of the centre of the boundary circle are $(\frac{w}{2}, \frac{h}{2})$. Thus the dispersion of the deficit can be described through the radius of that boundary circle.

Using the canonical form of a circle, its inner surface, namely the affected area, is referred to as the set of points (x, y) that satisfy the condition of the Equation 6.3.

$$(x - \frac{w}{2})^2 + (y - \frac{h}{2})^2 < r_s^2 \tag{6.3}$$

Henceforth, when describing the central scotomas, we are referring to the set of points (x,y) of the Equation 6.3.

It is assumed that the center of the macular scotomas and the center of the VF coincide, as this is a common form of macular scotomas. However, this does not encompass the full diversity of the real condition, as macular scotomas can also appear in other parts of central VF (Midena and Vujosevic, 2016). This simplification is aimed at facilitating the evaluation of the appearance of the effects, as according to Midena and Vujosevic, 2016, the further the scotomas appear from the center, the more complicated it is to assess their form. We assume that for the needs of this research, this simplification suffices and does not affect the end result. Note that the case of paracentral scotomas can be easily achieved by adjusting the center of the circle in the Equation 6.3.

Let us now define the *shape* and the overall appearance of the scotomas in AMD. For the most part, macular scotomas have amorphous shapes with discontinuities. To simulate these "scallop-shaped" forms (Nazemi et al., 2005), procedural noise is applied to make their contour and inner surface, arbitrarily undulating. The result is produced by applying Perlin noise (Ebert et al., 2003); the two coefficients of Perlin noise, namely the *frequency* and the *amplitude* (Lagae et al., 2010) can be controlled to customize the appearance of the macular scotomas accordingly (Figure 6.5). Each texture pixel (texel) represents the amount of deviation from the intact condition of the eye. Additionally, to simulate decreasing intensity with eccentricity, the *normalized distance* of each point (x, y) from the center is used in the generation of the textures.

Finally, the *translucency* parameter controls the category of the scotomas. When the

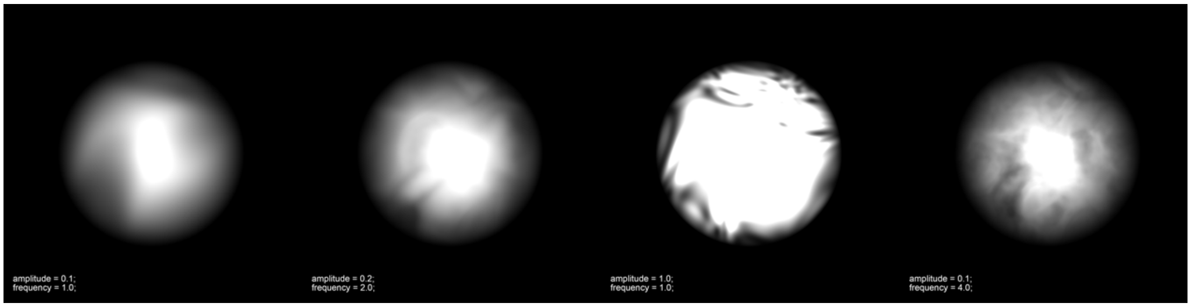

Figure 6.5 Mask textures obtained using different frequencies and amplitudes in Perlin noise kernel

variable of translucency is at zero, the simulated scotoma is considered absolute as it completely blocks vision. For values greater than zero, linear interpolation is used to blend the scotoma with the VE, producing this characteristic blurred, instead of "blind" spot (Figure 6.7).

6.1.4 Metamorphopsia

To approximate the distortion occuring in the VF, bump textures similar to the ones described for the case of the scotomas (Section 6.1.3) are generated procedurally using Perlin noise. Each pixel value of the bump texture indicates the spots where the distortion occurs. The distortion is then produced by shifting the UV coordinates of the image (Figure 6.6, bottom right); the intensity of the distortion can be further controlled through its corresponding parameter.

6.1.5 Glaucomatous damage

As described in Section 2.2.3, glaucoma is a set of visual disorders, caused by an increased pressure in the eye, which in turn damages the retinal ganglion cells (RGCs).
To imitate the "death" of RGCs in the glaucomatous damage and achieve a similar result to the one obtained from visual field tests (perimetry data), Voronoi noise was used (Aurenhammer, 1991). Based on the nearest-neighbor rule (Aurenhammer, 1991), the noise pattern

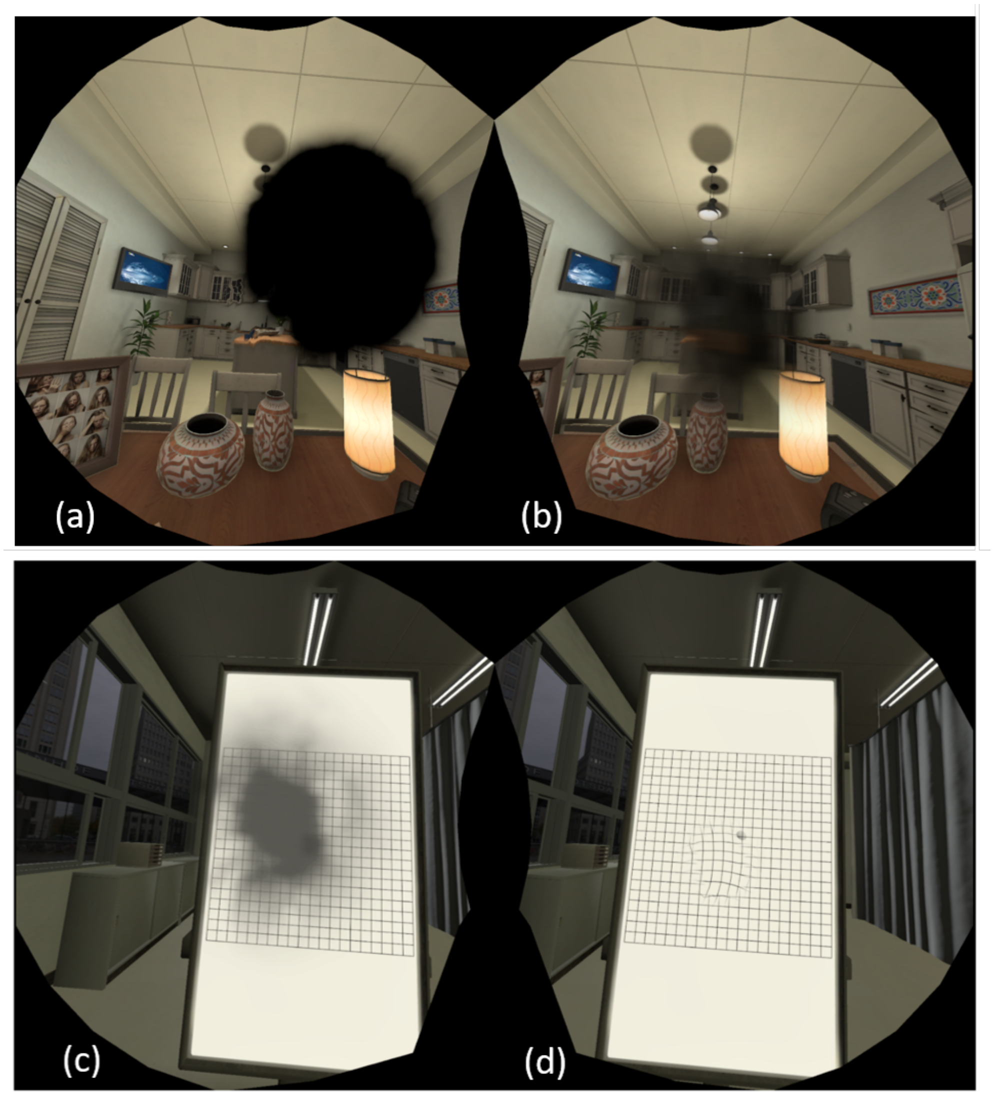

Figure 6.6 Screenshot taken from the VE showing the simulated: (a) absolute scotoma, (b,c) relative scotoma and (d) metamorphopsia

is generated, as each pixel gets a grayscale value according to its distance from the closest point of a set of randomly selected points (sites). In this case, the set of points considered correspond to the most affected RGCs.

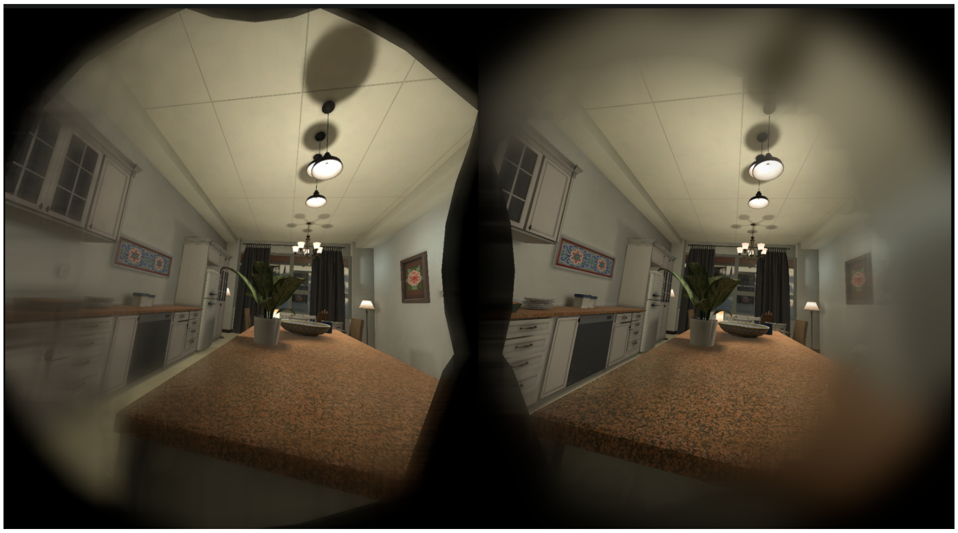

Figure 6.7 Two different intensities of the glaucomatous damage simulation in the VE

6.1.6 Other components

Previously, we described the case and presented the simulation of other symptoms manifested in the eyes of elderly adults and especially cataract patients (see Section 5.1.1). These are the decrease of contrast sensitivity (Allen and Vasavada, 2006) in nuclear cataracts; the xanthopsia (Blom, n.d.); and the decrease in the amount of light reaching the retina as a result of both the lens opacification in the cataract disease and the normal aging of the eyes (Allen and Vasavada, 2006; Gittings and Fozard, 1986).

While for the experimental needs of the first phase, these symptoms were adequately simulated using built-in effects, in this phase it was considered important to implement dedicated custom shaders for these effects, mainly to increase the flexibility and modularity of the simulation. For these symptoms, a sequence of operations is followed, described below.

Brightness-Saturation-Contrast

For the adjustment of the image's brightness, saturation and contrast, first the luminance of the image is obtained. That is, the dot product of the image with the coefficients of luminance is calculated (Equation 6.4) (Thorn et al., 2019). Through this, the RGB values of the image are translated to the CIE xyz color space. This tristimulus color space is widely used in research (Kerr, 2010) to mathematically represent the color of the light that the human eye perceives.

$$L = 0.2125R + 0.7154G + 0.0721B \tag{6.4}$$

For the simulation of the reduction of the light reaching the retina, an intensity coefficient can be set at runtime; the original image is multiplied by this intensity coefficient, achieving images of different brightness (Figure 6.8).

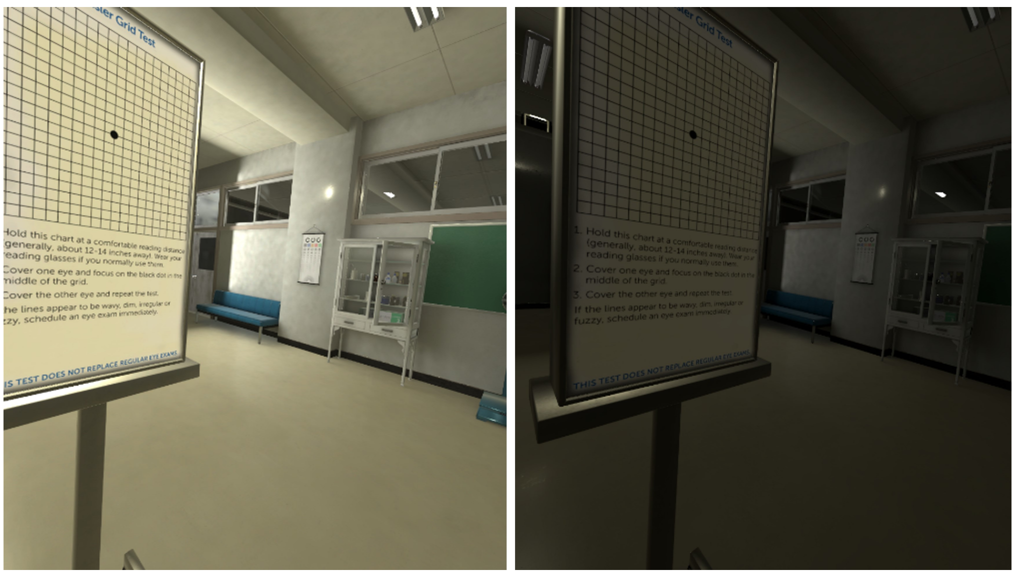

Figure 6.8 View of the VE from both displays. On the left one, no effect has been applied, while on the right one, the brightness reduction effect is active.

After this, the saturation operation is brought into play. This returns the result of a linear interpolation between the brightened image and a grayscale image obtained making use of the luminance function, by the user-defined input of the saturation parameter (Doran and Zucconi, 2018). The latter provides different saturation intensities (Figure 6.9).

Finally, for the contrast adjustment, linear interpolation is used between the average luminance color channels and the result of the saturation color of the previous operations.

Figure 6.9 View of the VE from both displays. On the left one, no effect has been applied, while on the right, the saturation reduction effect is active.

Tint

To obtain a more brunescent view in the VE similar to the case of xanthopsia, an additional fragment shader-based effect was included, that of image tinting (Figure 6.10). To obtain this effect, the image is multiplied by a color parameter, exposed to the user through a color palette.

Figure 6.10 View of the VE from both displays. On the left one, no effect has been applied, while on the right, the image tinting effect is active.

6.1.7 Testing extensibility

To test whether it is feasible to extend the principle of noise-based simulations to other eye diseases, we tested two additional effects, namely the dark sports and the floaters, symptoms that as seen in Section 2.2.4 can occur in DR[1] (Morello, 2007). Since DR is not directly related to aging (see Section 2.2.4), the simulation was limited to test this perspective for future work and its case was not studied at an experimental level. Below more information are provided on how we approached these symptoms of DR.

For both symptoms, curled Perlin noise was applied to the whole texture using different values of frequency and amplitude. Figure 6.11 presents some examples of the obtained deficit maps with different values on the curl function. The results seem to be consistent with the dark areas caused by microaneurysms as presented by other 2D simulations (see Figure 2.6). However, it is important to note that the generation of the noise texture is not adequate for the simulation, which necessitates the addition of other components, such as the appearance and disappearance of symptoms—a characteristic of this condition.

Figure 6.12 presents the floaters in the VF. In this case also, only the appearance of the condition was considered. Thus, for example, while the simulation provides gaze-contingent floaters, it does not include movement due to viscous drag (Milston, Madigan, and Sebag, 2016). Here, it is worth noting that floaters simulation was very positively evaluated by all three ophthalmologists (see Section 7.5).

6.1.8 Channel-packed effects

The symptoms of the visual declines do not always occur in a distinct way; for example, metamorphopsia can coincide with RS (Midena and Vujosevic, 2016). Even the conditions per se do not always appear separately. For instance, wet AMD and glaucoma can coexist in

[1]Floaters are caused by the changes in the consistency of the vitreous gel (Milston, Madigan, and Sebag, 2016) that commonly occur due to age, regardless of the presence of DR.

Figure 6.11 Obtained deficit maps with different parameter values, marking the dark spots in DR simulation

the same patient (Modjtahedi et al., 2020). For such cases, the option of generating packed textures was added, to avoid saving and loading different textures for each effect. These texture masks, which can be generated both offline and at run time, encoded information for each type of symptoms in a separate color channel (R: scotomas, G: metamorphopsia, B: glaucomatous damage) (Figure 7.8). As part of the simulation, individual channels are then extracted from the corresponding visual deficit shader.

6.2 Virtual elderly hands

The representation of the full body or even some parts of it in VEs, appear to increase the sense of being part of the latter. For example, studies have shown that the use of virtual hands in a VE can enhance immersion, body-ownership and the sense of presence (Slater

Figure 6.12 Noise-based simulation of floaters in the VE

et al., 2010). In a study by Argelaguet et al., 2016, two dimensions of embodiment in VEs were investigated: the sense of agency, which relates to the control of the avatar, and the sense of ownership, which relates to the sense that the avatar is the “source of experienced sensations”. These dimensions were examined through three different versions of virtual hands: an abstract, an iconic and a realistic hand. The results of this study revealed that the sense of agency is related to the control of the virtual hand and the performance on the task, while the sense of ownership is mainly related to the appearance of the virtual hand.

To address these two aspects, the present simulation incorporates elderly virtual hands that are controlled in an intuitive way. The 3D models of the hands used in this phase are photo-scanned hands of an elderly adult. Using an open-source software supporting 3D modeling and rigging, the hands were rigged and weights were painted appropriately for each finger, to render it compatible with the SteamVR real-time skeletal animation system (see Figure 6.14). This system was chosen for its compatibility with different VR controllers (ValveSoftware, 2022).

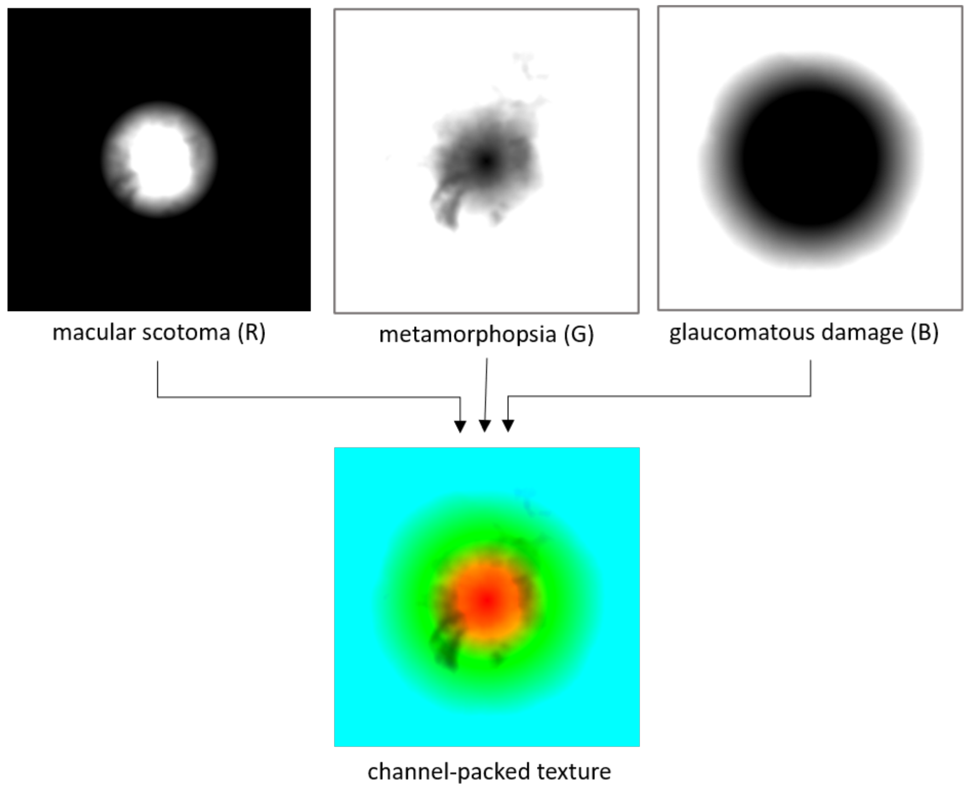

Figure 6.13 Example of a generated channel-packed texture containing information about a macular scotoma (red channel), metamorphopsia (green channel) and glaucomatous damage (blue channel)

In the VE, the hand and finger movements of the virtual hands are synchronized with the ones of the users, through the use of the VR controllers. The interaction with the virtual objects was achieved using the trigger button on the controller. Additionally, hand poses for specific interactive objects were created to render a more physical interaction in the VE. Finally, a shader supporting tessellation was used for the material of the virtual hands to accentuate specific characteristics of the aged hands, like wrinkles and prominent veins (Bains, Thorpe, and Southern, 2006).

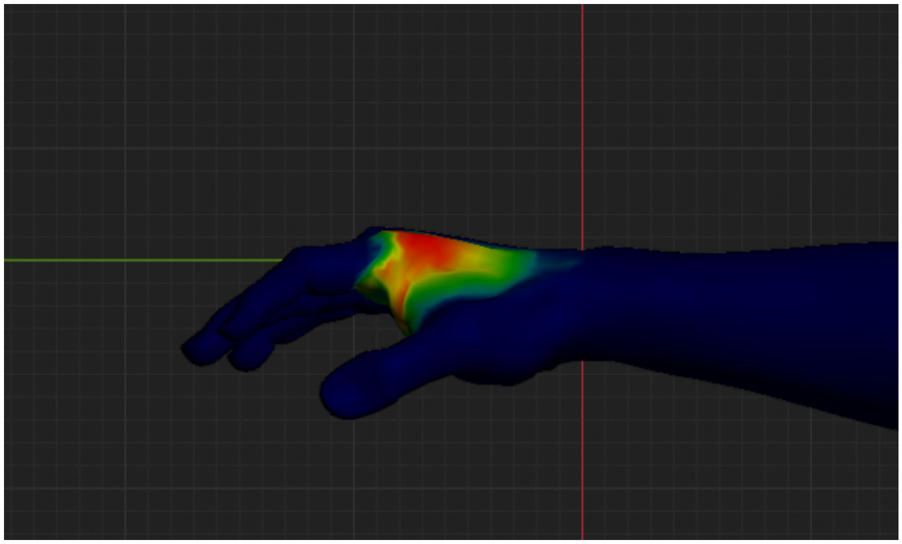

Figure 6.14 Painting skin weights on the 3D model of the photo-scanned elderly hands to define the affected areas of the finger movements in the open-source software Blender

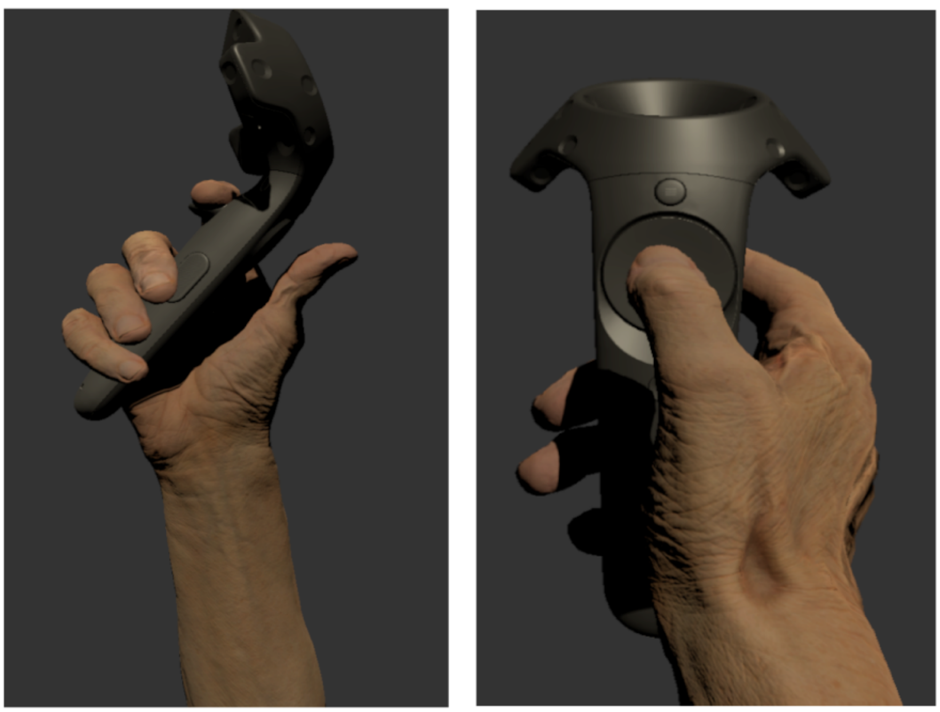

Figure 6.15 Right virtual aged hand, while interacting with the VR controller in the VE

6.3 Implementation

For the implementation of the simulation, the Unity3D game engine was used — long-term support version (2019.4), with the build-in render pipeline. The generation of textures detailed in Section 6.1 was achieved using compute shaders, implementing one kernel per disease.

For the visualization of the simulation in the VE, the HTC Vive Pro Eye headset was used with embedded eye-tracking technology by Tobii. The eye-tracking data were captured with a sampling rate of 120 Hz (Sipatchin, Wahl, and Rifai, 2020).

For the rigging and skin weights painting of the virtual hands, the open source 3D software Blender was used. The interaction with the virtual hands was achieved using the HTC Vive controllers (Figure 6.15).

6.4 Summary

In this chapter, we described the technical approach and methodology followed to simulate age-related declines in vision in a procedural manner. Additionally, the incorporation of aged hands in the VE was presented.

In the next chapter, we will see how the simulation was applied in three different tests within a study, to appraise the simulation's effectiveness in inducing similar difficulties to the actual visual deficits.

Chapter Seven

Phase 2: Validation

Towards establishing the validation of the simulation described in Chapter 6.1, its approximation to real problems was assessed, both in terms of their characteristics and the challenges they induce in specific tasks.

This approach was followed to check whether the proposed simulation could satisfy two a priori requirements that we have set regarding the accuracy of the simulated effects. We argue that the simulated effects represent as accurately as possible the actual deficits, if the simulated symptoms (perceptional correspondence) as well as the relative difficulty (functional correspondence) they induce in the virtual environments, correspond to the ones induced by the actual deficits in patients in real environments. For this, two hypotheses were propounded and examined within three different tests with healthy-vision adults and the results were interpreted with regard to available data from actual testing with patients.

In this chapter, the research hypotheses are presented and a detailed description of each test along with the experimental results are given. Additionally, an alternative proof-of-concept approach that could be used to validate simulations of visual problems using Machine Learning (ML) techniques, is proposed. Finally, the overall conclusions of the experimental evaluation of the second phase are provided.

7.1 Overview of the Experimental Design

As part of this phase of the research work, the first research question involved the appearance of the simulated deficits, and whether this approximates real experiences of patients. The hypothesis was whether the descriptions of subjects with healthy vision in the simulated VEs are congruent with self-reported descriptions of actual patients in real environments. For this, several open- and close-ended questions related to the simulated effects were posed to the subjects during their interaction with the simulated VEs. On the basis of manipulation check (Hoewe, 2017), this approach was adopted to also investigate whether subjects understand the simulated condition to which they are exposed.
The second research question concerned the impairments that these deficits can induce in daily tasks, such as in reading or transferring objects. The hypothesis here was that the simulation can produce similar impairments in visual functional performance tests to the ones observed in actual patients. For the investigation of the second hypothesis, two tests were implemented in the VE reproducing actual tests, namely the Minnesota Low-Vision Reading Test (MNRead) by Legge et al., 1989 and the reach-to-grasp and transport-to-place performance test by Pardhan et al., 2017. The performance of subjects with healthy vision experiencing an intact condition was compared with their corresponding performance in the simulated conditions in the VEs. The obtained results were investigated with regards to data of patients suffering from the actual visual deficits. Figure 7.1 shows a schematic of the validation process and how the two hypotheses were approached.

The order in which the three tests were carried out was the same for all subjects. Precisely, the experiment commenced with the reach-to-grasp and transport-to-place test described in Section 7.4.2. The order in which the simulated conditions were presented was random. Following this test, subjects proceeded with the MNRead test, as described in Section 7.3.2. In this case also, the conditions were presented in a random order. Finally, subjects completed the experiment with the self-reported descriptions (see Section 7.2). Figure 7.2 shows the

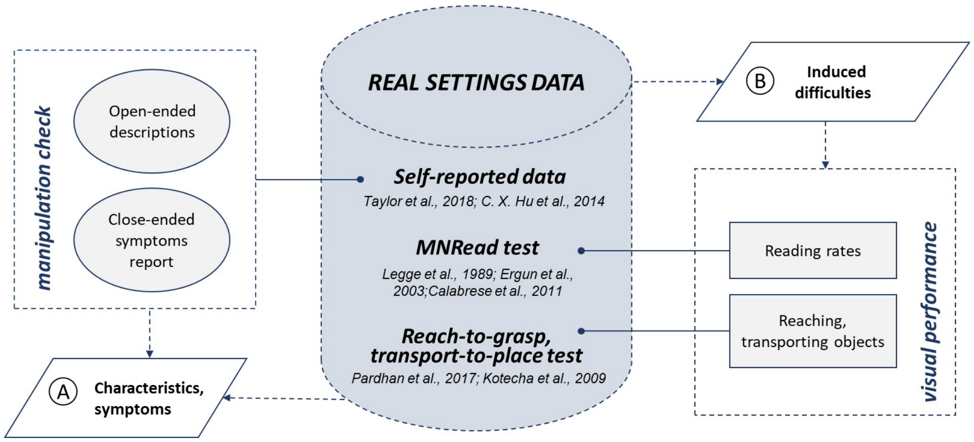

Figure 7.1 The experimental design followed for the validation of the simulation to compare: A) the characteristics of the simulated effects and B) the difficulties induced in specific tasks in the VE, with the corresponding information provided by actual patients.

tests in the order of presentation, indicating the virtually affected eyes in each case.

For all three tests, a within-subjects design approach was followed; that is, each subject tested all conditions. To enable comparisons, the same simulated effects both in the AMD and the glaucoma condition were used for all subjects.

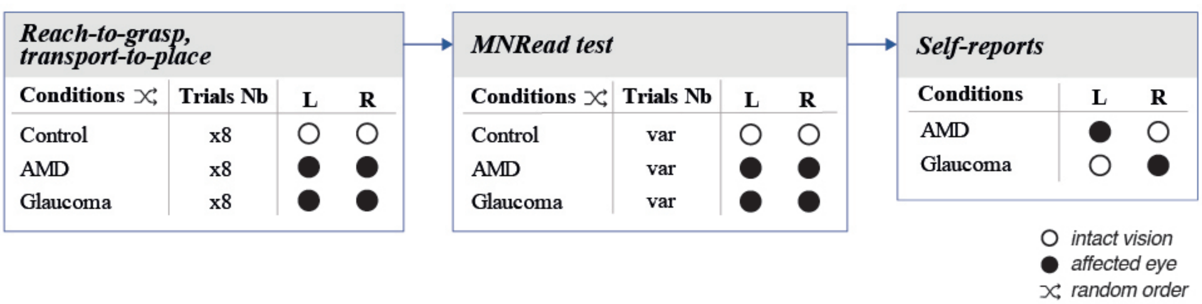

Figure 7.2 The experimental set-up of Phase 2 in the order of presentation (from left to right).

7.1.1 Participants

A pilot study was conducted with six volunteers. After ensuring experiment's feasibility, a main study was conducted with 24 participants (14 males) aged between 21 and 41 years old. The study was approved by the local ethics committee. No monetary compensation was provided to the volunteers who participated in the study. Inclusion criteria required subjects to have normal or corrected-to-normal vision and at least good level of English in reading. Prior to the experiment, subjects were informed about the purpose and the capturing of the data (eye-tracking, voice recording etc.), and written informed consent was obtained from the participants. No precise information about the measures was provided so that subjects' performance is not affected.

Below a detailed description of the experimental protocols followed for each test is provided together with the results obtained from the experimental evaluation. Later, overall conclusions are provided for the set of the three tests.

7.2 Test 1: Self-reports in the simulated VE

The observed indications of a condition (signs) are not always aligned with patients' perceived descriptions of a condition (symptoms) (K. K. Nichols, J. J. Nichols, and G. L. Mitchell, 2004). Thanks to data collected from patients with AMD (Taylor et al., 2018) and glaucoma (C. X. Hu et al., 2014), more specific descriptions are available on how these diseases are perceived by the patients themselves.

The first part of the simulation's validation process involved the comparison of these data with descriptions reported by subjects with healthy vision during the interaction of the latter with the simulated VEs. The two simulated conditions were the following:

1. AMD with central scotomas and metamorphopsia
2. glaucomatous damage with preserved central vision

To facilitate the comparison between the intact vision and the two simulated conditions, the simulation in the VE imitated unilateral visual loss. That is, subjects could judge comparing with the intact view by interchangeably closing one of the eyes.

7.2.1 Experimental Setup

For the purpose of this test, an everyday setting in an apartment was assembled in the VE (see Figure 7.3). Subjects sitting in a chair in front of a table and observing various elements around them, were asked to report how the effects affect their vision in the VE.

Initially, subjects could comment freely on how they perceive the condition by answering questions similar to the ones used in the real setting, such as *"When you are aware of your visual condition in the VE, can you describe how it looks?"* and *"How would you describe what it is wrong or different about your vision in the VE?"* (Taylor et al., 2018). After this, more specific yes/no questions, mostly drawn from the study by C. X. Hu et al., 2014 were posed, asking to indicate whether the questions corresponded or not to the simulated effects in the VE (see Table 7.2.2). These questions were the same for both conditions, but were posed in different order for each condition.

For the sake of facilitating the answering, specific cues were placed in the VE, like a table lamp and a picture of a person with various facial expressions (see Figure 7.3).

Figure 7.3 View of the virtual apartment, in which the self-reported descriptions were given. Specific objects were added to facilitate the reporting of the virtual symptoms.

The questions were posed orally to the subjects during their interaction with the VE and the examiner was indicating the answers on a questionnaire appearing on the interface of the application which was not visible to the subjects.

7.2.2 Results

As mentioned earlier, to provide descriptions on the simulated effects, subjects were asked to alternate the view by interchangeably close one of their eyes. It is important to note that two subjects were not able to fully keep one of their eyes closed, thus the comparison between intact and affected vision was approximate. In the future, switching views should be done automatically through the controllers, similar to the study of Krösl, Elvezio, Luidolt, et al., 2020.

Starting with the open-ended question, more descriptions were reported for the AMD than for the glaucoma condition. The specified descriptions were semantically categorized into 14 groups for the AMD condition. In the glaucoma condition, the descriptions were winnowed down to 9 categories. For example, in the AMD condition, “black”, “dark grey” etc were classified as “dark”. In the glaucoma condition keywords like “crying eyes” and “watery vision” were classified as “aqueous”. Contrarily to C. X. Hu et al., 2014, in this study, due to smaller sample size, descriptors like “cloudy” and “foggy” were categorized under the same category, named “overcast”. The categorized descriptions provided by the subjects for the simulated AMD and the glaucomatous damage, are presented in the word clouds of Figure 7.4.

In the AMD condition, subjects reported the existence of a moving, dark-colored spot hindering the clarity of vision and causing trouble in focusing. Among the secondary descriptions, of interest are those that present the scotomas as an insect-like shape/matter which obstructed the vision. In the glaucoma condition, the most frequently reported symptom ($n = 12$) was the “blurriness”, followed by the “aqueous” vision and the “overcast” effect.

Figure 7.4 Word clouds created based on the subjects' descriptions for the AMD condition (top) and the Glaucoma condition (bottom)

Interestingly, some subjects could not identify any problem in the glaucoma condition, at this first stage.

In the close-ended questions, to test the significance of the difference of yes-no proportions, the Chi-square test was used with Yates continuity correction for small samples. Table 7.2.2 presents the descriptive statistics of subjects' responses. According to the results, in the AMD condition, subjects at a significant level ($p<0.01$) reported that their vision was not normal (Q1). Instead, in the glaucoma condition, the answers were divided and no significant difference between yes-no answers was observed ($p>0.05$) for this question.

In the questions concerning the difficulty in understanding faces (Q6) and facial expressions (Q5), in the AMD condition, the positive answers were proportionally more than the negative ones. In the glaucoma condition, the number of subjects who reported that they experienced difficulty in perceiving faces, was not significantly different compared to the ones who did not report this symptom.

In the question regarding whether the effect is like looking through dirty glasses (Q13), a significant number of subjects ($n = 18$) reported a positive answer in the AMD condition ($p < 0.01$). In the glaucoma condition, more that half of the subjects ($n = 14$) positively reported this symptom ($p > 0.05$).

When answered whether the objects were appearing distorted (Q2), in the AMD condition, a significant number of subjects did not identify this symptom ($p < 0.01$). Instead, regarding the distorted vision in general (Q18), opinions were more divided with the differences between positive and negative responses not being significant. The same applied in the glaucoma condition.

In the AMD condition, subjects at a significant level ($p < 0.05$) agreed that the virtual world seemed darker with the virtually affected eye (Q7). This was not the case for the glaucoma condition. Half of the subjects ($n = 12$) in the AMD condition reported that the text appeared faded (Q15). In the glaucoma condition, six subjects responded positively to this symptom ($p > 0.05$).

Other symptoms included in the questionnaire, like intense light (Q11), difficulty in perceiving colours (Q14) and grainy vision (Q17) were not reported by a significant number of subjects both in the AMD and the glaucoma condition.

7.2.3 Discussion

In general, in the open-ended questions, subjects provided more detailed descriptions in the AMD than in the glaucoma condition. In the glaucoma condition, several subjects reported that there was nothing wrong with their vision in the VE. This result is not surprising given that glaucoma concerns peripheral vision, thus it is difficult to identify and describe problems affecting the latter; and is consistent with actual glaucoma cases. Instead, as AMD affects the central VF, any problems and inconveniences caused are evident. Below more details are

ID	Q	AMD					GL				
		yes	**no**	**h**	**p**	**chi**	**yes**	**no**	**h**	**p**	**chi**
Q1	Normal vision $^{-}$ $^{\circ}$	1	23	1	<0.001	36.750	9	15	0	0.1489	2.083
Q2	Objects distortion $^{-}$ $^{-}$	6	18	1	0.0015	10.083	7	17	1	0.0094	6.750
Q3	More intense light $^{-}$ $^{\circ}$	5	19	1	<0.001	14.083	9	15	0	0.1489	2.083
Q4	Objects' limits $^{\circ}$ $^{-}$	11	13	0	0.7728	0.083	6	18	1	0.0015	10.083
Q5	Facial expressions $^{+}$ $^{\circ}$	16	8	1	0.0433	4.083	12	12	0	0.7728	0.083
Q6	Faces $^{+}$ $^{\circ}$	21	3	1	<0.001	24.083	9	15	0	0.1489	2.083
Q7	Darker world $^{+}$ $^{-}$	16	8	1	0.0433	4.083	8	16	1	0.0433	4.083
Q8	Veil-like $^{\circ}$ $^{\circ}$	13	11	0	0.7728	0.083	11	13	0	0.7728	0.083
Q9	Need for more light $^{\circ}$ $^{-}$	11	13	0	0.7728	0.083	3	21	1	<0.001	24.083
Q10	Clouds $^{\circ}$ $^{\circ}$	9	15	0	0.1489	2.083	10	14	0	0.3865	0.750
Q11	Too much light $^{-}$ $^{-}$	3	21	1	<0.001	24.083	3	21	1	<0.001	24.083
Q12	Regions difficult to see $^{+}$ $^{+}$	22	2	1	<0.001	30.083	18	6	1	0.0015	10.833
Q13	Dirty glasses $^{+}$ $^{\circ}$	18	6	1	0.0015	10.083	14	10	0	0.3865	0.750
Q14	Colours $^{-}$ $^{-}$	5	19	1	<0.001	14.083	5	19	1	<0.001	14.083
Q15	Faded text $^{\circ}$ $^{-}$	12	12	0	0.7728	0.083	6	18	1	0.0015	10.083
Q16	Darker/missing regions $^{+}$ $^{\circ}$	21	3	1	<0.001	24.083	14	10	0	0.3865	0.750
Q17	Grainy vision $^{-}$ $^{-}$	8	16	1	0.0433	4.083	5	19	1	<0.001	14.083
Q18	Distorted vision $^{\circ}$ $^{-}$	10	14	0	0.3865	0.750	7	17	1	0.0094	6.750

$^{+}$ significantly positively reported

$^{-}$ significantly negatively reported

$^{\circ}$ not significantly reported

Table 7.1 Descriptive statistics of the responses in the close-ended questions.

given about the self-reported descriptions in the VE for each condition.

AMD condition

Regarding the AMD condition, subjects reported the existence of a dark spot hindering the clarity of vision, which corresponds to the delineation of scotomas. Here, it is pertinent to note that sometimes clinical features are subject to conflicting views in the literature. For example, according to D. C. Fletcher, Schuchard, and Renninger, 2012, scotomas are a “well-documented” symptom of AMD, while in the study by Taylor et al., 2018, this symptom was reported by some patients in the late stage of AMD. The problem can be that patients cannot always identify the condition due to *perceptual filling-in* (Zur and Ullman, 2003). For example in the study by D. C. Fletcher, Schuchard, and Renninger, 2012, more than half of the patients with binocular scotomas were totally unaware of them. In any case, as part of the present simulation, an advanced form of AMD with dark blurring spots were presented to the subjects, thus the main descriptions correspond to the simulated effect.

In the AMD condition, the most reported symptom in the VE was the difficulty in seeing specific parts in the VF, which is among frequently reported symptoms of actual AMD patients (Taylor et al., 2018).

A significant number of subjects reported difficulty in understanding faces and facial expressions. This is in line with the literature about the actual problems that AMD patients have in face perception (Bullimore, Bailey, and Wacker, 1991), an important problem that affects their interpersonal relationships and the overall QoL (Lane et al., 2018). Additionally, in the AMD condition, half of the subjects reported faded text; text appearing faded is among the symptoms of AMD according to Karimi, 2012.

As mentioned earlier, for the AMD condition, in addition to the macular scotomas, the effect of metamorphopsia was included. However, subjects did not perceive at a significant level the simulated distortion in the VE. This can be due to the fact that the effect was overlapping with the scotoma and that the distortion affected the pericentral VF in the VE.

As Midena and Vujosevic, 2016 mentioned, the further a problem appears from the centre, the more difficult it is to perceive its characteristics.

One-third of the subjects reported a sense of darker world in the VE, while this is not a frequently reported symptom in AMD patients. This could have been explained by potentially poor lighting conditions in the VE, as there is evidence that the latter can increase AMD challenges (Alexander et al., 2014). However, this reported symptom may be more related to the dark spot itself, as when subjects were asked about needing more light, the majority replied negatively.

Finally, the majority of subjects reported that AMD produced a “dirty glasses” effect, but this finding though could not be verified due to lack of reports regarding such subjective descriptions for AMD.

Glaucoma condition

Regarding the glaucoma condition, the prevailing descriptor in the VE, that is blurry vision, corresponds to the main symptom of actual glaucoma patients according to C. X. Hu et al., 2014.

On the same study (C. X. Hu et al., 2014), among the most reported symptoms is the need for extra light. This is a symptom that was reported by only three subjects in the VE. For this, the brightness decrease effect needs to be accentuated to provide a darker image.

It is interesting that several subjects described the glaucomatous damage in the VE, as if a watery element was covering the lenses. This is a description already reported by an actual glaucoma patient in the study by C. X. Hu et al., 2014.

In the question regarding whether the effect is like looking through dirty glasses, more than half subjects responded positively. In the study by C. X. Hu et al., 2014, this symptom was more relevant for patients with a more pronounced VF loss due to glaucomatous damage.

In the glaucoma condition, 6 subjects responded positively to faded text effect, a finding consistent with the study by C. X. Hu et al., 2014, in which 30% of the respondents complained for this symptom.

Problems in perceiving faces was also reported in this study but not at a significant level. This kind of problem is reported by patients with glaucoma, especially with increased VF defects (Glen et al., 2012). Similar to the study by C. X. Hu et al., 2014, few subjects reported difficulty in recognizing objects' limits and perceiving colours.

Concluding, an unexpected, yet interesting general finding revealing from this test is that although all subjects experienced the same simulation, their answers varied, sometimes significantly. This highlights the need for additional objective measurements.

7.3 Test 2: MNRead Test in the VE

MNRead is a standardized test, through which significant results can be obtained about how reading rates are affected by different visual disorders (Legge et al., 1989; Ergun et al., 2003; Calabrese et al., 2011). Thus, to investigate how the simulated eye-diseases effects affect the performance in virtual tasks, the MNRead test was appropriately transferred to the VE.

7.3.1 Experimental Setup

As part of the MNRead test in the VE, subjects were seated in front of a 3D model of a display with a self-illuminated material in a dimmed-lighting room at a viewing distance of 20 cm (Figure 7.5). As no chin rest was provided, to make sure that the display was always at the same distance and aligned with subject's eye level, real-time interpolation in the position of the display in all three axes was applied based on the subject's head position. In addition, subjects were instructed not to move their head, but use their eyes' movement only, to perform the test.

Following the protocol of the actual MNRead test (Legge et al., 1989), several sentences containing simple words in English were presented on the display, one after the other for specific timed periods. The sentences did not necessarily make sense and were formed based on a list of words with three to six characters. The sentences were organized in four lines and were randomized, both in terms of words and order of lines; keeping though the arrangement 3-4-4, 3-4-4, 3-3-5, and 5-6 per line (Figure 7.5).

At the beginning of the test, three example sentences were presented to the subject to ensure understanding of the task. When the first actual sentence appeared, the time to read the sentence was recorded. Every time the subject was reading successfully a sentence and there was time remaining, the exposure time was reduced by 25%—the percentage change recommended by the researchers who carried out the experiment in the physical space (Legge et al., 1989).

The subjects were asked to read the sentences aloud as fast as possible without going back to correct themselves in case of misreading some words. They were instructed to read more and more quickly each time until they were starting to make mistakes. The test was terminated when the subject failed to complete a sentence within the given time.

The sentence, the timed exposures and the number of missed words for each trial were recorded and used for the data analysis. Additionally, the system was recording the audio for each trial. The recordings were used for cross verifying the validity of the measurements registered during the experimental process. The options to reduce the exposure time could be manipulated by the examiner through an interface on the screen, invisible to the subject. Additionally, through the interface, the number of missed words for each sentence were recorded by the examiner (Figure 7.5).

After the test was completed for one condition, a button was enabled to indicate that the examiner could pass to the next condition. The same process as described above was followed for the other conditions, indicating a new exposure time that was used as a reference for the rest of the sentences.

For the MNRead test, three conditions were created and tested in the VE:

1. The control condition, in which no effects were applied.

2. The bilateral AMD condition, with AS on the left eye and RS coexisting with metamorphopsia on the right eye.

3. The bilateral glaucomatous condition, with peripheral VF loss in both eyes.

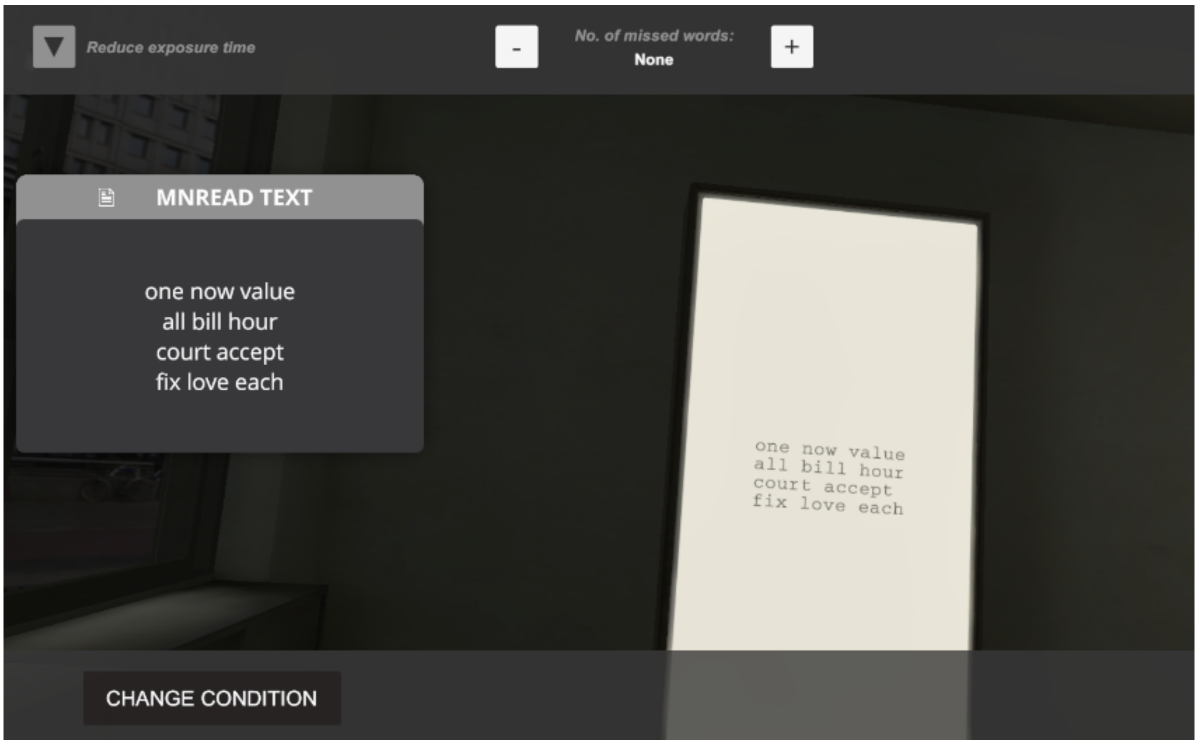

Figure 7.5 Examiner interface and subject's view of the MNRead environment in VR

7.3.2 Results

As mentioned earlier, in the MNRead test two measures were considered, that is eye-tracking data during the pilot study and reading rates during the main study. The results are provided in the next subsections.

Eye-tracking Data

To get an indication of subjects' visual behaviour in the VEs and whether this may be affected by the simulation, during the pilot study, eye-tracking data were extracted and differences in fixations between the three conditions were measured. Figure 7.6 shows heat maps obtained from the eye-tracking data in the pilot study.

Based on the results, fixations in the AMD condition fit the pattern of preferred retina locus (PRL). That is, similar to real AMD patients, subjects in the VE showed a preference to fixate to a position "superior" to the scotoma (Sunness and Applegate, 2005) to compensate for the blind spot. Instead, as expected, fixations in the control condition were centrally concentrated. These initial results demonstrate that central scotomas' simulation can produce a similar difficulty to that experienced by real patients when trying to read a text.

In contrast to AMD, in glaucoma patients, fixations are mainly central (Kameda et al., 2009). However the eccentric fixation that subjects adopted during the glaucoma simulation is not surprising, as such cases may also occur (Kameda et al., 2009).

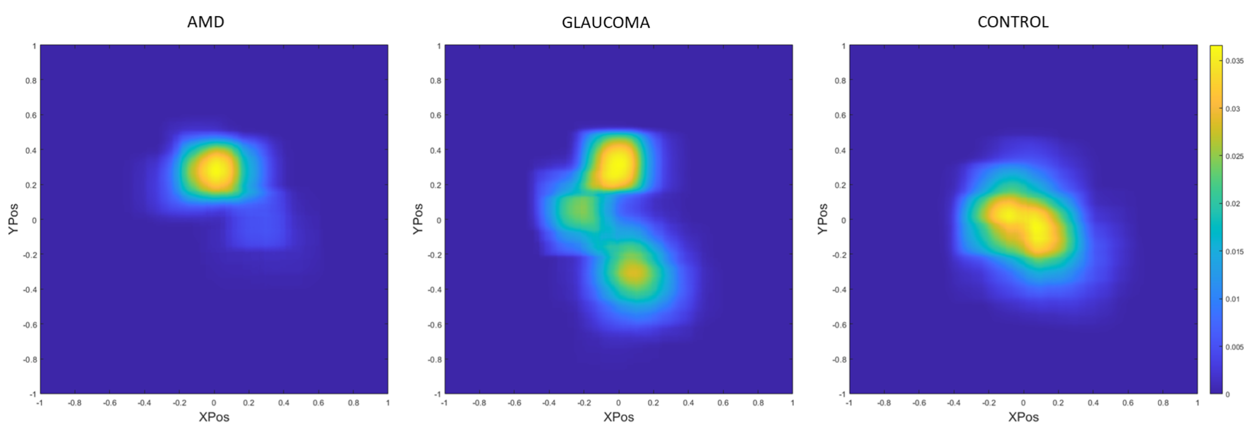

Figure 7.6 Eye-tracking heat maps during the AMD (left), the Glaucoma simulation (middle) and the control condition (right) in the pilot study.

Reading Rates

Reading rates are the main measure of the MNRead test and provide evidence on whether certain eye conditions affect visual performance. As such, reading rates were assessed during the main study with all 24 subjects. For the reading rates, variance was tested using repeated measures ANOVA, with corrections for sphericity. According to the results of the reading rates in words per minute (wpm), in descending order, subjects read in average 181.2 ± 59.5 wpm in the control condition, 168.4 ± 60.4 wpm in the glaucoma condition and 129.3 ± 58.5 wpm in the AMD condition. Table 7.2 presents the summary statistics of the MNRead test per condition and Figure 7.7 summarizes the data in boxplots for the three conditions.
The difference in the average reading speed between the AMD and the control condition was ≈ 52 wpm. Post hoc analysis (Table 7.3) indicated that this difference was significant ($p < 0.001$). Reading performance in the AMD condition was also significantly lower (by 39 wpm) than the glaucoma condition ($p < 0.05$). Although lower reading rates were demonstrated in the glaucoma compared to the control condition, these were not significantly different.

Table 7.2 Descriptive Statistics of the MNRead test

	WPM		
	AMD	CTRL	GL
Mean	129.272	181.230	168.370
Std. Deviation	58.525	59.468	60.399
Minimum	55.021	68.226	62.417
Maximum	258.456	278.862	261.158

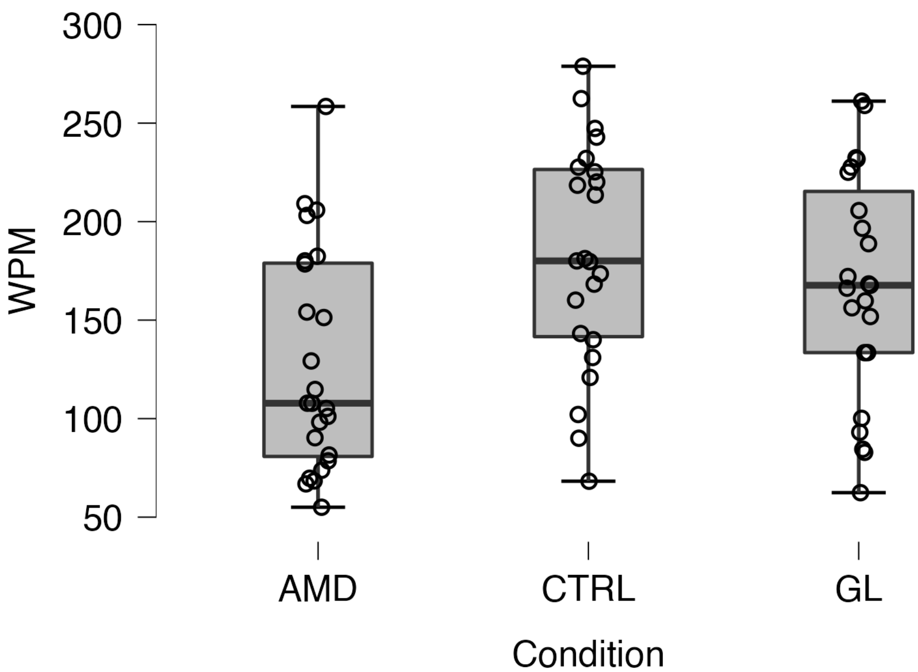

Figure 7.7 Reading rates in words per minute (WPM) per condition

Table 7.3 MNRead Post Hoc Comparisons - Condition

		Mean Difference	SE	t	p_{bonf}
AMD	CTRL	−49.520	12.490	−3.965	< .001
	GL	−37.960	12.490	−3.039	0.013
CTRL	GL	11.561	12.490	0.926	1.000

7.3.3 Discussion

The eye-tracking data revealed the different visual behaviour of the subjects in the simulated conditions compared to the control condition. Although additional data are required to draw more reliable conclusions, these initial results demonstrated the potential of the simulation to induce difficulties that are congruent with the ones experienced by real patients.

The results of the MNRead test showed that reading rates in the AMD condition were significantly lower than in the control condition. These findings corroborate previous studies which showed that AMD significantly affects reading performance, with people suffering from AMD reading 46 wpm less than people with healthy vision (Varadaraj et al., 2018). Although slower reading rates were demonstrated in the glaucoma compared to the control condition, these were not significantly different, in contrast to the study by Ikeda et al., 2021. In general, the results from the MNRead test in the VEs approximate real data. Admittedly, a direct comparison between the actual patient data and the ones obtained from the simulation would not be appropriate, as in real settings different cases of patients were considered, while in this study, all subjects experienced the same manifestation of the deficits. Also, contrarily to real data, in this study, each subject tested all three conditions.

Finally, it is important to note that although the protocol of the MNRead test was carefully followed to transfer the test to the VE, a validation of the VR-based version of the test is necessary, before more firm conclusions can be drawn. Similar to other researchers who digitalized the MNRead test (Calabrèse et al., 2018) a validation is necessary to measure any performance differences between the test in the real and the virtual environment, both for healthy and low vision people; a topic included in the future research agenda (Section 8.5).

7.4 Reach-to-grasp and Transport-to-place Task in the VE

Evidence exist that specific visual deficits, like AMD can affect the "reach-to-grasp" and "transport-to-place" components that are related to every day activities like reaching and moving objects (Pardhan et al., 2017; Kotecha et al., 2009). To examine whether the simulation could induce similar difficulties as the ones that real patients experience, the test described in Pardhan et al., 2017 was appropriately transferred to the VE.

7.4.1 Experimental Setup

Following the description of the test by Pardhan et al., 2017, a 3D model of a table was used covered with a black diffuse material plane, for contrast purposes. In this test, the subject was seated in front of the table and was asked to move a white cylindrical object of two different sizes, from an initial position (near/far) to a final position on the table (near/far), which was marked with a white cross (2 x 2 cm). The system was detecting any accidental fall of the cylinder and in this case the trial was automatically ended so that the subject could not go back to retry transferring it correctly.

Each trial was randomized in terms of:

- the two sizes of the cylindrical objects, the small (diameter = 3 cm, height = 10 cm) and the large (diameter= 8 cm, height = 10 cm)
- the start position (near = 36 cm and far = 56 cm) and
- the end position (near = 15 cm and far = 35 cm away from the start position)

In the actual test, three repetitions of each combination were performed, that is 24 trials in total (Pardhan et al., 2017). Instead, in the present study, only one repetition per combination was performed, that is 8 trials per condition, or 24 trials in total per subject. This change was effectuated after the pilot study, to reduce the overall duration of the task, as each subject had to test all three conditions, which would mean 72 trials (24 trials x 3 conditions). Such an excessive test duration could potentially trigger wrong results due to subjects' fatigue.

Along the lines of the actual procedure, prior to each trial, the initial and target positions were not visible to the subject and a black screen was presented to them.

For the analysis of the data, the position, orientation and velocity of the virtual cylinders, and the hands movements were recorded every 15 ms. Also, the duration of the movement was captured and event triggers were automatically marking the different phases (grabbing/releasing cylinder).

In contrast to the actual setup, components related to gripping, such as the grip precision were not considered. The reason being that as the VR controllers were used for the interaction with the virtual objects, the real grabbing conditions could not be approximated. The choice to conduct the experiment in a purely virtual environment was determined for the sake of ease of the experimental procedure, as we considered that the complexity of the setup outweighed the importance of the additional data in our case. That is, had we approached the test as a mixed reality experience, using for example real cylinders attached to VR trackers and/or hand tracking (through front cameras, VR gloves, etc.) the test would require a person tasked with correctly positioning the cylinders at the exact points between the different trials. This configuration would add extra cost, time and a generally more complex setup. The fact that in our case the setup was virtual, therefore automatically determined by the system, also helped to avoid potential errors.

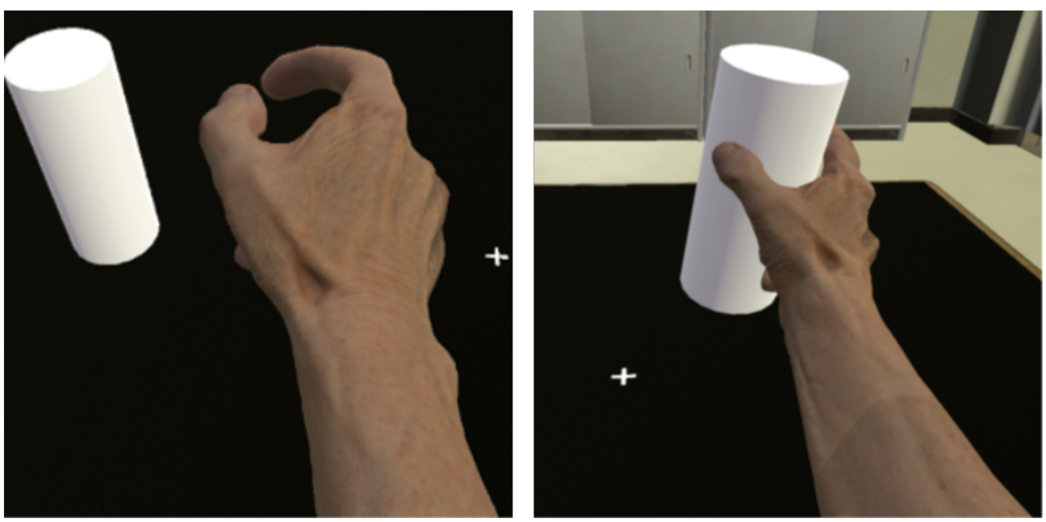

Figure 7.8 Virtual environment, during the test reach-to-grasp (left) and transport-to-place (right) in a trial with the big cylinder and the near end position (white cross)

The three conditions created were the same as in the case of the MNRead test: the control condition, the simulated condition of the bilateral central visual field loss (CFL) caused by

AMD and the bilateral peripheral visual field loss (PFL) due to glaucomatous damage.

Figure 7.9 Subject interacting with the VR simulation during the reach-to-grasp and transport-to-place test

7.4.2 Results

For the performance test proposed by Pardhan et al., 2017, the following data were analysed during the two separate phases of the process, namely the *reach-to-grasp* (R2G) and the *transport-to-place* (T2P) phase: movement duration, deceleration time, peak velocity and velocity corrections. Additionally, the reaction time was measured, that is the time taken before starting the movement to reach the object and the object placement errors which corresponds to the distance between the final position/placement of the cylinder and the cross-marked target position. An analysis of variance with repeated measures ANOVA design was performed. More details are given below, for each phase individually.

Reach-to-grasp Phase

The null hypothesis that there was no significant variation in reaction times between the three conditions was rejected at the 95% default level ($p < 0.001$). Similar to Pardhan et al., 2017, confidence intervals were corrected using the Bonferroni method. Post hoc analysis revealed that the reaction times both in the AMD and the glaucoma conditions were significantly higher than the corresponding ones in the control condition, with probability values $p_{bonf}<0.001$ and $p_{bonf}=0.043$, respectively. No significant difference was observed between the AMD and the glaucoma condition in the reaction times ($p_{bonf} > 0.05$).

Regarding the movement time (MT), there was a significant variation between the three conditions ($p = 0.003$). The results from the post hoc analysis were as follows: AMD differed significantly from the control condition ($p_{bonf} < 0.001$) but not from the glaucoma condition ($p_{bonf} > 0.05$). Additionally, no significance was found between the glaucoma and the control condition ($p_{bonf} > 0.05$).

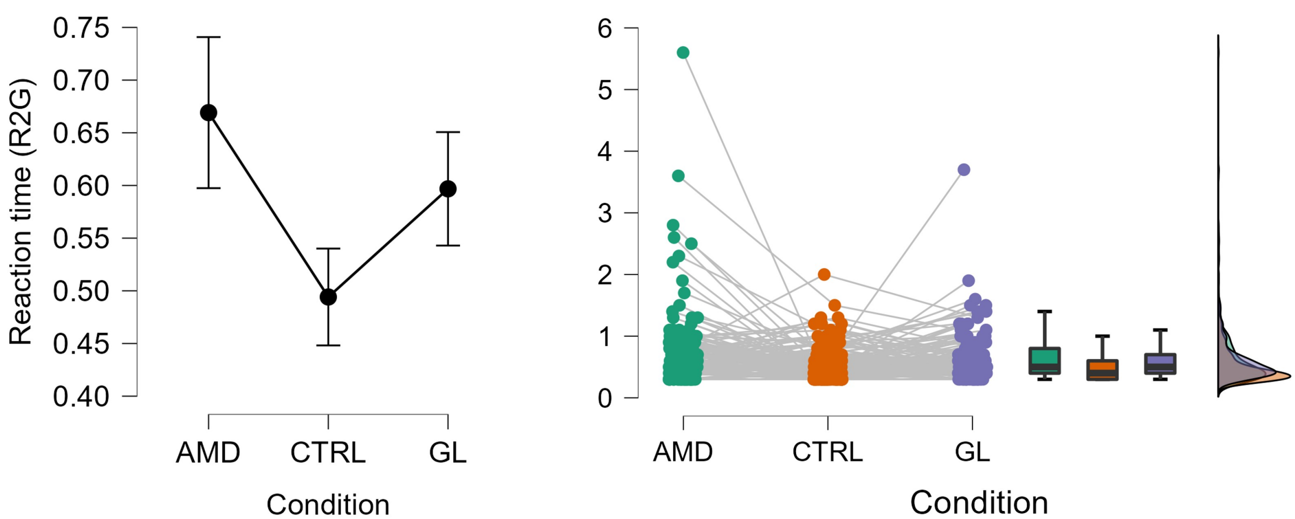

Figure 7.10 Reaction time by condition

Regarding the velocity corrections, a highly significant difference was found between the three conditions in the repeated measures ANOVA tests of variance with applied tests for sphericity ($p < 0.001$). Post hoc tests revealed that in the AMD condition, the number of

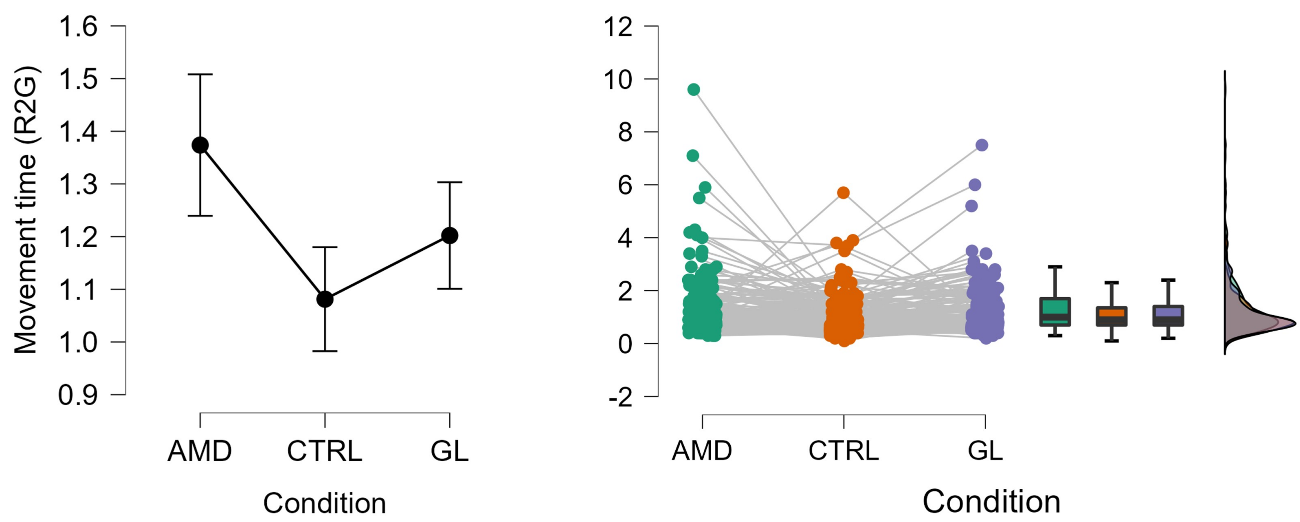

Figure 7.11 Movement time per condition in the reach-to-grasp phase

velocity corrections was significantly higher compared to the control condition ($p_{bonf} < 0.01$) but not compared to the glaucoma condition ($p_{bonf} > 0.05$). Borderline significant variation was found between the glaucoma and the control condition ($p_{bonf} = 0.044$).

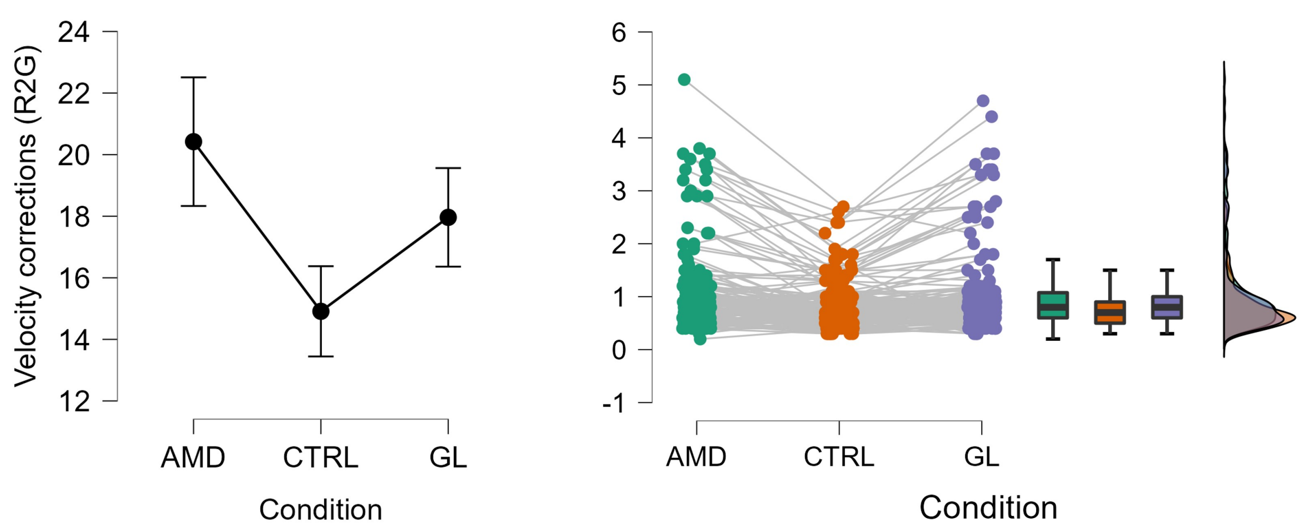

Figure 7.12 Velocity corrections by condition in the reach-to-grasp phase

The results registered a significant variation between the three conditions in peak velocity values ($p = 0.004$). More precisely, peak velocity was significantly decreased in the AMD condition compared to the control condition ($p_{bonf} = 0.003$). There was no significant variation between the AMD and the glaucoma condition; and between the glaucoma and the control condition.

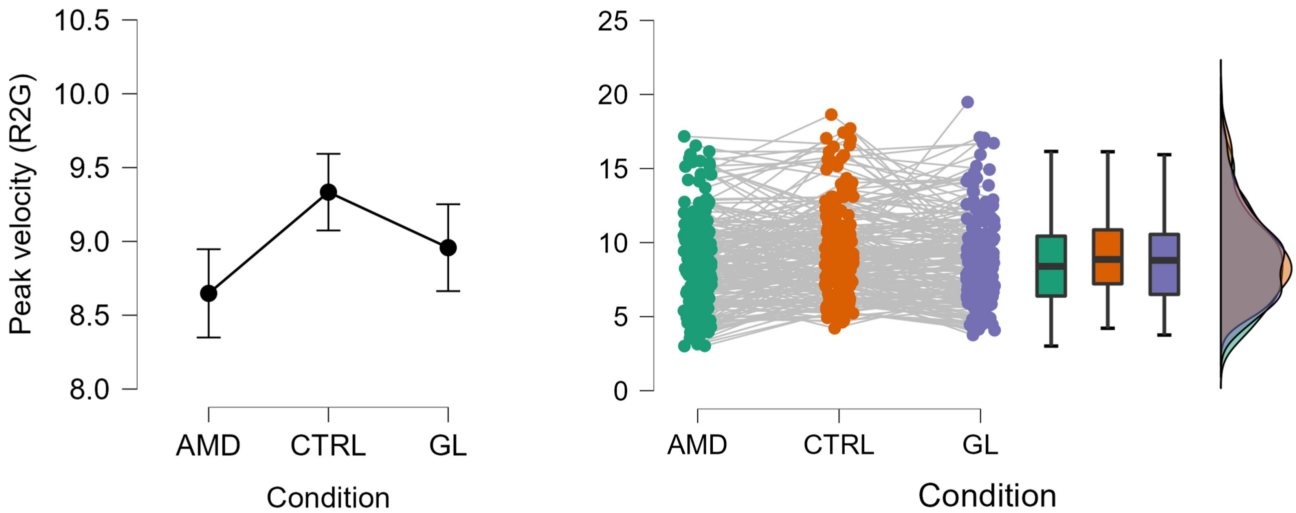

Figure 7.13 Peak velocity by condition in the reach-to-grasp phase

The null hypothesis that there was no significant variation in deceleration times between the three conditions was rejected at the 95% default level ($p = 0.03$). The post hoc analysis showed that the deceleration time in the AMD condition was significantly higher than in the control condition ($p_{bonf} = 0.021$). However, the deceleration time between the AMD and the glaucoma condition did not differ significantly ($p_{bonf} > 0.05$). Same applied between the glaucoma and the control condition.

Transport-to-place Phase

In the Transport-to-place phase, no significant variation was found between the three conditions on the final placement of the cylinder ($p > 0.05$). Although no cylinder fell down during the transport to place phase, cylinders fell down several times after placing them in the target position.

Significant variation was found in the duration of the movement in the transport-to-place phase between the three conditions ($p < 0.001$). ANOVA post hoc tests indicated

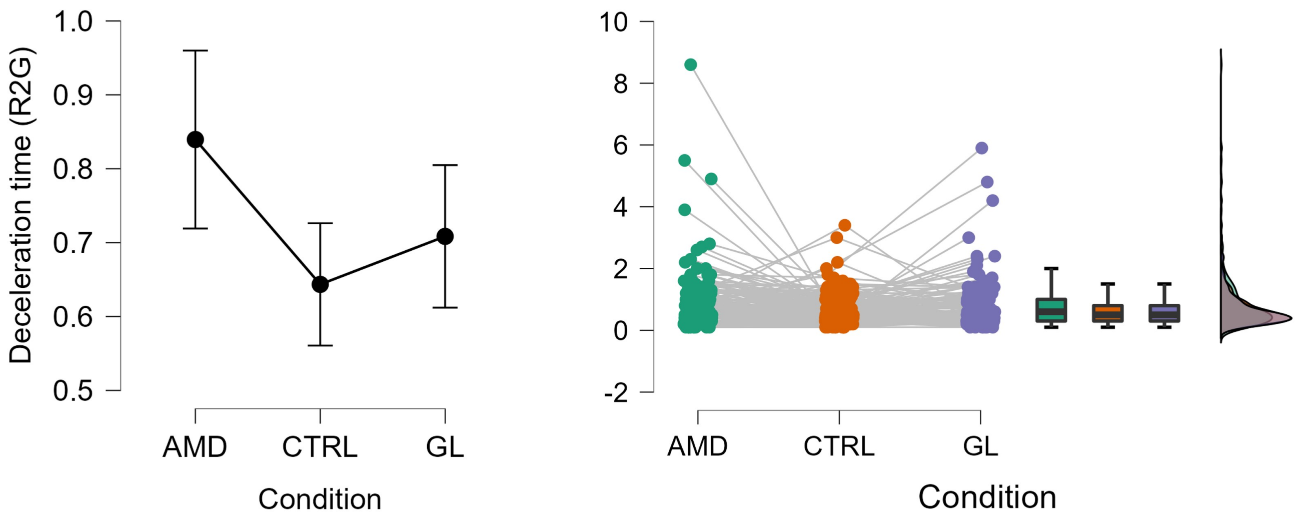

Figure 7.14 Deceleration times by condition in the reach-to-grasp phase

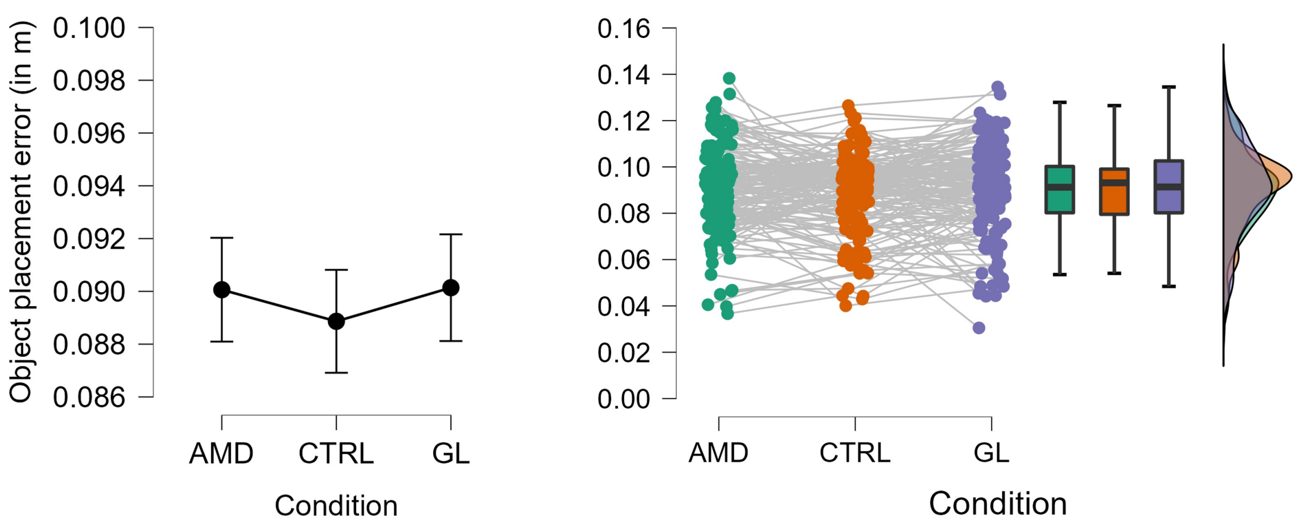

Figure 7.15 Cylinder placement by condition

that transport duration was significantly longer in the AMD condition compared to the control condition ($p_{bonf} < 0.01$). The AMD and the glaucoma condition however were not significantly different in terms of transport duration ($p_{bonf} > 0.05$).

Finally, the number of velocity corrections were found to be significantly different in the AMD, compared to the control condition ($p_{bonf} < 0.01$), but not compared to the glaucoma condition ($p_{bonf} > 0.05$). Significant variation was also found between the glaucoma and the

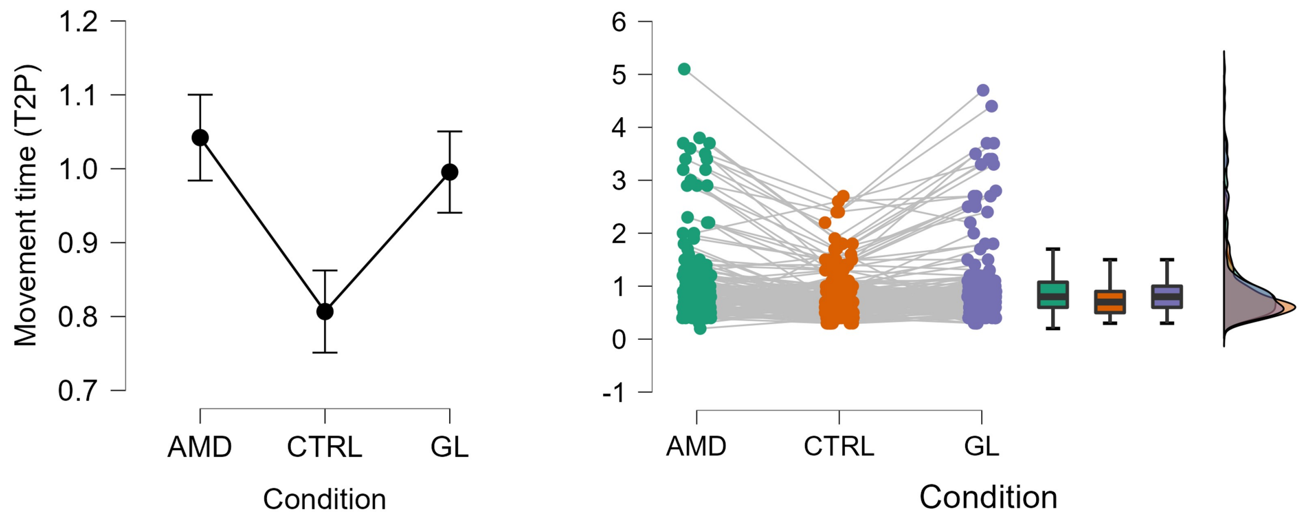

Figure 7.16 Transport duration by condition

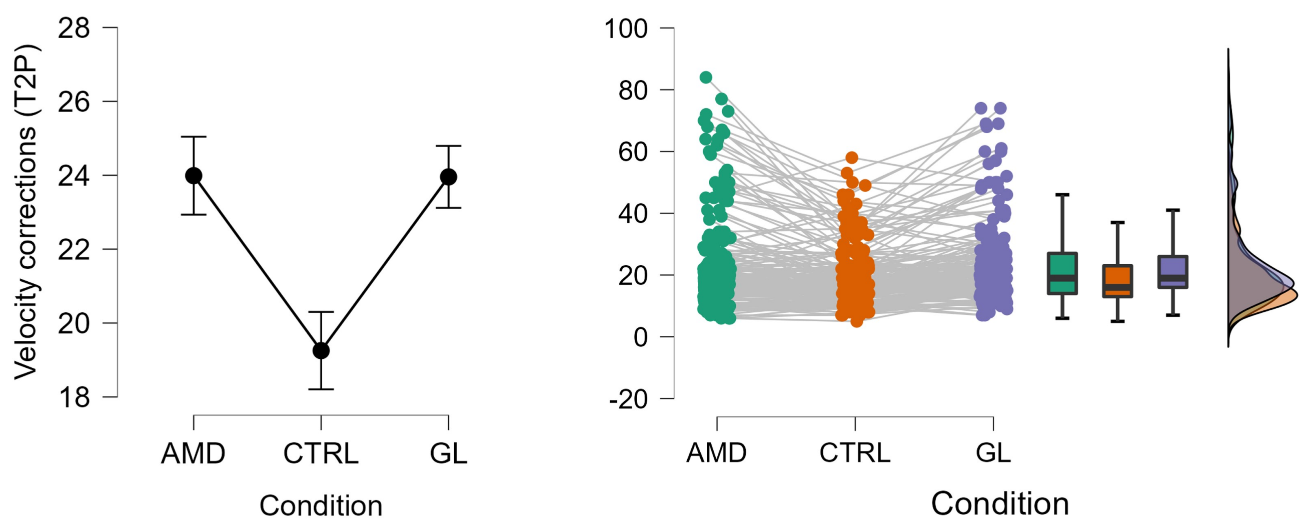

Figure 7.17 Velocity corrections by condition in the transport-to-place phase

control condition ($p_{bonf} < 0.001$).

7.4.3 Discussion

An important result of the reach-to-grasp and transport-to-place test is that the reaction time, the overall movement time, the deceleration time and the velocity corrections were significantly different in the AMD condition than in the control condition, which is consistent

		AMD (mean ± SD)	CTRL (mean ± SD)	GL (mean ± SD)
R2G	Movement time	1.374 ± 1.173	1.081 ± 0.735	1.202 ± 0.929
	Peak velocity	8.648 ± 3.113	9.334 ± 3.038	8.958 ± 3.029
	Deceleration time	0.840 ± 0.961	0.644 ± 0.481	0.708 ± 0.748
	Velocity corrections	20.421 ± 18.396	14.911 ± 10.518	17.963 ± 13.697
	Reaction time	0.669 ± 0.598	0.494 ± 0.263	0.597 ± 0.364
T2P	Movement time	1.042 ± 0.817	0.807 ± 0.460	0.996 ± 0.805
	Peak velocity	6.373 ± 2.277	6.893 ± 2.477	6.948 ± 2.777
	Deceleration time	1.170 ± 0.817	0.952 ± 0.522	1.271 ± 0.807
	Velocity corrections	23.989 ± 16.171	19.254 ± 10.074	23.956 ± 13.886
	Object placement	0.090 ± 0.018	0.089 ± 0.017	0.090 ± 0.019

Table 7.4 Descriptive statistics for the reach-to-grasp (R2G) and transport-to-place (T2P) phases

with the study by Pardhan et al., 2017. Interestingly, in contrast to Pardhan et al., 2017, the results of the test in the VE register a significant variation between the three conditions in peak velocity values.

Although in almost all cases, the measurements were more affected in the AMD than the glaucoma condition following the trend of the findings by Pardhan et al., 2017, the AMD condition did not differ significantly from the glaucoma condition.

Based on the results and the observation during the experiment, the main reason that could account for this lack of significance between the AMD and the glaucoma condition is the loss of accuracy in the eye-tracking data, due to the so-called *slippage*. Slippage is a documented effect of the eye-trackers placed in head-mounted displays, such as the HTC Vive Pro Eye and is caused by the movement of users' head (Sipatchin, Wahl, and Rifai, 2020). In the MNRead task, slippage did not seem to affect the results, as subjects were instructed to

keep their head stable. However, in the reach-to-grasp and transport-to-place task, subjects' movements to reach and transport the cylinders affected the quality of the eye-tracking data, with the glaucomatous damage often placed incorrectly and the scotoma not appropriately centered in the field of view. This shift caused the glaucomatous damage to pose difficulties to subjects similar to the ones experienced in the AMD condition and vice versa. This is an important aspect that should be taken into account for similar VR-based simulations.
Another factor that could account for this is that the simulation of glaucoma condition could correspond to intense VF loss. This is indicated by the results from the self-reported descriptions, but not the results of the MNRead test.
Contrarily to Pardhan et al., 2017, no significant variation was found between the three conditions on the final placement of the cylinder. This is not surprising as the object placement can be significantly affected by the manipulation of the virtual cylinders, given that the interaction in the VE was fully virtual, thus quite different than the actual physical interaction in the real environment. A solution using mixed-reality objects would be preferable to better approximate the real conditions of the experiment. However, as explained earlier, the latter would require a manual approach of setting up the trials. As part of this initial work, an automatic solution was selected over a more accurate testing.

Although a novel version of the test that can be performed in a more automated, yet intuitive way in the VEs was developed and tested yielding interesting results, a number of caveats should be mentioned. First, a difference between the test in VR and the actual test is the number of trials performed (see Section 7.4). This reduced number of trials which was selected to shorten the duration of the overall testing could affect results significance. Second, to register differences between the three conditions, the study was carried out in a within-subject design and the same simulated conditions were presented to all subjects. These do not represent the actual test conditions and therefore the comparisons between real and virtual environments are approximate. Finally, as in the case of the MNRead test, the protocol of the reach-to-grasp and transport-to-place test needs to be validated in the

VE.

7.5 A proof-of-concept validation approach using ML

Throughout the second phase of the present research work and especially during the validation of the procedurally-generated effects, three important challenges emerged. Below we present these challenges and explain how they could be addressed using an alternative approach based on Machine Learning (ML).

Sample size. To test the different variations of the simulated effects, one would need a very large sample size or a prohibitive amount of time for one or more experts to evaluate the simulations. ML can be particularly useful to deal with the variability and heterogeneity of the symptoms, which can challenge the feasibility of time- and resources-consuming experiments.

COVID-19. Amid a global pandemic crisis, the experimental procedures have admittedly been affected and this is evidenced in relevant studies (Krösl, Elvezio, Luidolt, et al., 2020). For this purpose, an ML-based approach could contribute to the validation of the simulation, without the need to involve users.

Subjectivity. At an initial stage of Phase 2 of this research, to obtain an external review and assess the quality of the proposed simulation, an evaluation was conducted with three external ophthalmologists, using chain referral sampling. Through an online anonymous questionnaire, the ophthalmologists were asked to evaluate, according to their expertise, rendered videos of the simulated effects from a first-person view. The evaluation was focused on the aspect of representativity—the extent to which the simulated effects correspond to the actual ones—, and the realism of the simulation. To ensure that the experts would focus on the effects rather than the 3D environment, the latter was replaced with high-dynamic-range imaging skyboxes of real environments. Prior to the evaluation of the simulation, the ophthalmologists were asked to self-evaluate their expertise on the specific eye disorders.

Despite the same level of expertise, the ratings showed a large variability (Table 7.5) even inverse agreement - Krippendorff's alpha = -0.1727 (Hayes and Krippendorff, 2007), thus a consensus on the evaluation was not reached. This was also reflected to their responses to additional close-ended questions, in which the first rater stated that the effects were representative, the second one stated that the effects were less pronounced than the actual conditions, and the third one that the effect was more pronounced. An ML-based approach could be used for cross-validating evaluation results obtained through traditional volunteer-based performance evaluation. In this case, the expected benefit of ML-based evaluation is the mitigation of subjective judgments, often implied in volunteer-based evaluations.

	Rater 1	Rater 2	Rater 3
Metamorphopsia (realism)	6/7	2/7	5/7
Metamorphopsia (representativity)	6/7	1/7	5/7
Macular scotomas (realism)	7/7	1/7	4/7
Macular scotomas (representativity)	7/7	1/7	4/7
Glaucomatous damage (realism)	7/7	2/7	2/7
Glaucomatous damage (representativity)	7/7	1/7	4/7
Floaters (realism)	6/7	7/7	6/7
Floaters (representativity)	6/7	7/7	6/7

Table 7.5 Ophthalmologists' evaluation of the simulated effects based on rendered videos

ML-based evaluation approach followed in this research, involved the training of dedicated deep learning networks (LeCun, Bengio, and Hinton, 2015) that can distinguish images showing a variety of visual defects. The trained networks can then be used for testing the fidelity of simulated age-related eye conditions' renderings produced using the simulation methodology as presented in Section 6.1. The proposed method for ML-based evaluation involves generating a training set, tuning an existing deep network using transfer learning, and the classification process of VR-based renderings of different eye conditions. These aspects are analysed in the following subsections.

7.5.1 Training set

To train a machine learning algorithm, a training set is required with images depicting optical views of patients with eye conditions considered in this work (i.e., glaucomatous damage and macular scotomas in combination with metamorphopsia). The training set was constituted by considering images and videos showing optical views of patients with eye conditions found on medical websites such as in the National Eye Institute's media library (*National Eye Institute* n.d.) and in Ligue Braille (*Ligue Braille* n.d.). In addition, images showing views seen by observers with intact vision, are used to create a training set for normal vision. It should be noted that the background scenes of the videos used for creating the intact set of images are similar to the ones encountered in the training images depicting eye deficits. In total, three classes were considered in this experiment ("Glaucoma", "AMD", and "Normal") and for each class about 200 training samples were used. Furthermore, data augmentation techniques were adopted (Perez and Wang, 2017), which involve the transformation of a given image by changing the image scale, rotating the image, and creating mirror reflections along the x and y symmetry axes.

Training a Deep Neural Network

Training a deep network to classify image objects requires large amounts of training data. However, in cases where there is limited availability of training data, existing trained deep networks can be tuned to a specific classification problem using transfer learning (Shin et al., 2016). For this work, a pretrained version of the GoogLeNet (Szegedy et al., 2015) deep network is used. GoogLeNet is a 22-layer deep convolutional neural network trained on more than a million images from the ImageNet database (Russakovsky et al., 2015) to perform the process of object recognition among 1000 object classes. Typical classes encountered in the ImageNet database include different plants, natural objects, sports-related objects, different animals, and objects depicting humans. Given the large and diverse variety of objects encountered in the ImageNet database, it is expected that the initial layers of the GoogLeNet trained using the ImageNet database, highlight image features that suit most object recognition tasks.

As part of our work, a pretrained version of GoogLeNet, available in the MATLAB deep learning toolbox was tuned for classifying images showing different eye deficits. The process involved the initialization of the convolutional layers with the pretrained weights and the replacement of the final fully connected, SoftMax and output classification layer with corresponding layers adjusted based on the training data described in Section 7.5.1. For the network training, the Adam optimization method (Kingma and Ba, 2014) was used with 6 epochs, mini batch size of 20 and 0.0001 learning rate. During the training process, 70% of the images from the training set were used for training the network, and the remaining 30% constituted the validation set. After the network was trained, 100% of the images in the training set were classified correctly, while the correct recognition rate on the validation set was 99%.

Classification of VR-based Renderings of Visual deficits

During the performance evaluation phase, rendered VR views from frames of videos showing simulated eye conditions were normalized to a standard resolution of images input to a GoogLeNet (224x224) pixels, and used as inputs to the tuned GoogLeNet, to classify the given frame into one of the three classes considered. As a result of the classification process, the trained network returns the probability that a certain video frame belongs to one of the three classes considered. However, as rather than assessing individual frames, we are mainly interested to determine whether a particular video depicts a certain eye condition, all probability scores from each video frame are accumulated to produce the overall score that shows the likelihood that a particular video depicts a certain eye condition. As a result, based on the probability scores for each frame, the overall probability that a certain video shows one of the three classes is formulated.

Test Set

The test set was comprised of 15 videos with about 1600 frames in each video. The 15 videos show 4 different scenes rendered in a virtual environment. For each scene, a video was rendered with and without the simulated effects to produce four videos with normal vision, four videos depicting glaucomatous damage and seven videos depicting AMD. The latter show different types of the condition (RS only, AS only, RS and metamorphopsia coexisting).

Results of Performance Evaluation Using Machine Learning

According to the results (Table 7.6), 61% of all frames, from all 15 test videos, were classified correctly. When considering the overall probabilities accumulated among all video frames, 12 out of 15 videos (80%) were classified to the correct class. Based on the results, the network seems to perform well with the recognition of the glaucomatous damage. The results indicate that the tuned network was suitable for extracting features used for distinguishing between the classes.

Most classification errors include videos with "Normal" vision classified as "AMD" and vice versa. Figure 7.18 shows examples of misclassified video frames. In the case of glaucomatous damage (Figure 7.18, left), the misclassification is attributed to the appearance of a dark image structure that resembles the appearance of macular scotomas, causing the classification of the frame as "AMD". In the case of macular scotomas (Figure 7.18, right), the failure is attributed to the alignment of the scotoma with trees appearing in the scene, causing the interpretation of the scotoma as a tree rather than being associated with a macular scotoma. As a result, this frame was classified as "Normal".

Table 7.6 Results of performance evaluation obtained from the Machine Learning algorithm

Video	Ground truth	% of frames classified correctly	Video classified as
1	Glaucoma	61%	Glaucoma
2	Glaucoma	51%	Glaucoma
3	Glaucoma	67%	Glaucoma
4	Glaucoma	49%	Glaucoma
5	AMD	40%	Normal
6	AMD	68%	AMD
7	AMD	76%	AMD
8	AMD	86%	AMD
9	AMD	91%	AMD
10	AMD	75%	AMD
11	AMD	81%	AMD
12	Normal	65%	Normal
13	Normal	14%	AMD
14	Normal	45%	AMD
15	Normal	39%	Normal

Figure 7.18 Typical images depicting glaucomatous damage (left) and macular scotomas (right) not recognized correctly, due to interferences with the VE

7.5.2 Discussion

These preliminary results indicate that using an ML-based performance evaluation method is promising and could benefit from better training data both in terms of quality and quantity.

It is important to note that this approach was used using 2D simulations based on subjective views. However, in the future, more objective data can be included for the training of the ML algorithm, such as data from perimetry tests.

7.5.3 Conclusions

In this chapter, a comprehensive analysis of the three different tests performed to validate the soundness of the proposed simulation was provided. Overall, interesting results were obtained from the manipulation check and the performance tests.

More precisely, the self-reported descriptions given in the structured and unstructured questions were similar to self-reports of actual patients, with some exceptions. These could be addressed by a simple parameterisation of the simulation. The second test, which concerned a reading task, showed that both in terms of performance and visual behaviour, the results were congruent with that of similar tests with actual patients in real environments. Finally, the third test evaluating subjects' performance on a reaching-transferring objects task, also showed that the evoked challenges were in line with real-life challenges of actual patients with VFL and PFL compared to people with healthy vision. Unexpected, non-significant discrepancies occurred between the two simulated conditions, which merit further study. An explanation for these may relate to the limitations of the technology used, namely the sensitivity of eye-tracking technology to movement. An additional explanation could be the intensity of the effects; in this case, this problem can be easily remedied by adjusting the parameters of the simulation in future setups.

Additionally, an innovative approach was proposed using ML techniques. The use of ML to validate these simulations appears as a promising approach, when considering the diversity of the possible clinical presentations which would require a prohibitive sample size for testing. Additionally, the ML approach could be particularly useful in cases where other traditional methods of experimentation are not feasible, for example during the current COVID-19 crisis. The reported work on using ML-based evaluation presents a pilot investigation that highlighted the potential of this approach. Future work could concentrate on enhancing the objectivity of the ML-based approach, using for example real patient data (i.e., data acquired from visual field tests) to generate the training set, exploring the possibility of developing dedicated deep network architectures, and considering additional types of eye diseases.

In the next and final chapter of this research work, general conclusions are given with regards to the research questions, including the limitations related to the findings. Finally, the implications and contributions of the present research are discussed and future perspectives are proposed.

Chapter Eight

Conclusions

To recapitulate, the present research work investigated the VR-based simulation of common age-related declines, focusing mainly on vision, to be harnessed as a perspective-taking experience. To address the primary research questions, a two-phased approach was followed.

In the first phase, a prototype simulation was developed and tested within three studies. The first study was exploratory and aimed to examine whether the simulation could give the sense of being older. It also investigated whether the simulation could have any impact on possible stereotypical views against the elderly and other age-related opinions. Additionally, through the interaction with young designers, the potential of using the proposed simulation as a design-for-all tool was considered.

The second and third study focused on the design aspect and the aim was to investigate any potential effectiveness of the simulation in supporting elderly-friendly design, especially in the evaluation stage. In addition, the third study concerned a comparison, in practice, of the VR-based simulation with the personas and the aging suits which are used in the design of elderly-friendly products.

In the second phase, the research recurred to the development, this time focusing on vision. For this, an effort was expended to involve expert opinion and render the simulation more representative of the actual deficits. To study whether self-reports of healthy subjects during the simulation were similar to those of real patients, a manipulation check was conducted. In addition, an experimental approach based on two real test protocols was proposed and tested, to assess whether such simulations can emulate actual eye conditions validly, by inducing similar impaired performance to specific tasks. Finally, the use of ML to validate such simulations appeared as a promising approach, when considering the diversity of the possible deficits' manifestations.

8.1 Key Research Findings

As part of this research, the results of two different studies suggested that the proposed simulation induced to subjects the sense of being an elderly adult in the VE. Also, a trend towards raising awareness of the age-related problems simulated in the VE was observed. However, this altered perspective did not demonstrate a significant effect on changing negative views against the elderly and the aging in general.

From a design perspective, several significant outcomes were yielded.

- First, the discussions with design students confirmed the interest in using the proposed VR-based simulation in representing real design scenarios, to understand problems and identify needs of impaired elderly.

- Second, in another study, the simulation significantly affected reading and in some cases even locating important information on pharmaceutical products, a result which is consistent with real cases. The results implied the importance of elderly-friendly design and how this can be achieved, harnessing VR technologies.

- Third, when the proposed VR-simulation was compared to the user personas and the goggles of the aging suit, it prevailed over the former and was tantamount to the latter, underperforming in terms of ease of use, but outperforming in terms of role-taking and helpfulness.

Regarding the validation of the simulation in the VE, the descriptions of the simulated effects approached the actual problems. Additionally, the effects induced difficulties in a similar trend to the real deficits. Discrepancies from actual patient data seem to be related to limitations imposed by the technology per se. These limitations are documented and need to be considered in future studies.

Taken together, with regard to the research questions, the results demonstrated the following points.

RQ1 *Can the proposed simulation effectively induce the sense of being an elderly adult?*

The proposed simulation did induce to young adults the sense of being elderly. In two different studies, subjects indicated a significantly increased age during their interaction with the simulated condition compared to their actual age.

RQ2 *To what extent the proposed simulation can be useful in elderly-friendly design?*

The proposed simulation was effective in elderly-friendly product design. In two experimental studies, it helped visualize and evaluate virtual copies of designs in question, through the eyes of elderly adults with specific visual deficits. It even outperformed in certain aspects in a comparison of methods used for this purpose (user personas and simulation goggles).

RQ3 *Do simulated effects in the VE represent the actual deficits of impaired elderly adults?*

For the most part, the simulated effects did represent the actual deficits. The main features of the diseases in the way they were presented in the simulated environments to subjects with healthy vision, were aptly reported and approximated descriptions of patients with real problems. For the rest of the cases, a simple configuration of simulation's intensity is sufficient.

RQ4 *Can the proposed simulation effectively induce similar difficulties in VEs to the ones experienced by actual elderly patients?*

The proposed simulation did induce, to a certain extent, to young adults with healthy vision, similar difficulties to the ones experienced by elderly adults with specific visual deficits. Two main attributed reasons for the differences are identified. First, as expected, it is inherently difficult to accurately compare between cases of patients with different manifestations of the problems on one side, and healthy subjects under the same simulated conditions on the other side. Second, to the head-mounted eye-tracking technology and its sensitivity to user movements, which affected the accuracy of effects' placement in the VF.

RQ5 *To what extent the proposed simulation can help in changing negative views against aging and the elderly?*

The proposed simulation did increase the understanding of age-related problems, but did not have a significant effect on changing views towards elderly people and aging. This may be due to the administered questionnaire that measured the change in young people's views, which contained mostly explicit questions; for this case, implicit measures may be more appropriate. In any case, this was a secondary question considered only in an exploratory study, thus more thorough investigation is required.

8.2 Limitations

Despite the positive outcomes, the present research has a number of limitations. The primary limitation relates to the sample, both in terms of its limited size and the fact that it included exclusively healthy young population. To draw safer conclusions, it is necessary to test the simulation with a larger sample. Additionally, elderly impaired adults should be included to compare their performance in visual tests in the VE and consolidate the research around the validity of the simulation.

Another limitation relates to the fact that as part of the validation process of the simulation, real visual tests were transferred to VEs. For safer comparisons, their digital form needs to be validated with healthy and low vision people similar to Calabrèse et al., 2018.

Finally, in this research, the use of ML as an alternative or additional way of validating such simulations was considered. However, this approach is exploratory and to establish its soundness, a thorough investigation is required, using for instance real data, like visual field tests.

8.3 Contributions

From a methodological and technical point of view, the contribution of the present research work lies in the introduction of a novel approach to provide a diverse assortment of visual effects, simulating common age-related deficits. The most sophisticated method that we have distinguished in the relevant literature is the one by P. R. Jones and Ometto, 2018, which includes many of the features of our proposed simulation. They, too, use the idea of "reference textures" to define the region of the problem, however their method of implementing the simulated effects differs, in that it relies on the use of mathematical models, in a similar fashion to previous computer-generated simulations (Thompson et al., 2017). Our work introduces the idea of procedural noise to generate these textures, to simulate realistic effects that can be manipulated at run time; to our knowledge this aspect has not been approached before. We believe that this noise-based approach amplifies the flexibility and variability of the effects' appearance without affecting the simulation's consistency.

An additional technical contribution related to the aforementioned textures, is the concept of channel-packed effects. These are textures that contain information for each symptom in separate color channels. This option that to our knowledge has never suggested before, can be useful for cases of comorbidity or combination of symptoms.

Finally, another technical input of the present work that contributed significantly to the virtual experience is the incorporation of aged hands in the VE, synchronised with users' hand movement while holding the VR controllers (see Section 6.2). This option allows the easy generation of hand poses for realistic interaction with virtual objects, without requiring any rigging knowledge. The poses are compatible with the most common VR controllers, thus this option can be easily integrated in many different setups.

From an experimental point of view, the present research work addressed pivotal research questions on the soundness of the VR-based simulation with regards to its intended purpose. This was achieved through a mixed method approach combining both subjective and objective measurements, and considering data from actual patients, improving its confidence level. In other relevant studies, simulations' validation is assessed from a single perspective. For example, an extensive assessment of the challenges induced by simulated visual impairments was carried out by P. R. Jones, Somoskeöy, et al., 2020 using quantitative data during the interaction of healthy-vision subjects with the simulation. Another notable effort to validate such simulations is the study by Krösl, Elvezio, Luidolt, et al., 2020 in which people with unilateral visual problems were asked to evaluate the simulation in the VE. In our case, a trilateral assessment was obtained. First, an evaluation was conducted by external experts. Second, qualitative data through self-reports in the simulated VE were considered and compared to actual patient data. Third, quantitative data were examined on the reduced performance caused by the simulated effects in the VE. This last point was achieved through actual tests that are validated in real-world conditions, thus are more reliable indicators of the induced difficulties, than the everyday tasks examined by P. R. Jones, Somoskeöy, et al., 2020.

Finally, another contribution of this research is that through different studies, it assessed and demonstrated the effectiveness of the proposed simulation in the design process and for the first time, this was carried out in comparison with other methods employed for the purpose of user understanding.

8.4 Implications

Being able to provide many instances of a specific visual problem, the proposed simulation offers the possibility to test different simulated conditions in a setting that approximates reality in the sense of diversity between individuals, in an otherwise healthy sample. This is particularly useful in isolating experimental variables which would be difficult to be achieved with an aging sample. As aptly noted by Cornelissen, Bruin, and Kooijman, 2005, *"By using normal observers with an artificial simulated impairment, we can more easily look at the effect of a parameter without confounding its effect with that of others"*. To provide an example, the simulation could examine the effect of visual problems, but not declined hand dexterity in an object transferring task.

The ability of the simulation to control a behaviour from the perspective of an individual with specific, mainly visual, problems, whether this is for medical, design or other purposes, should in no way imply that the simulation is valid. An implication emerged from the review of the related work is that the success of many similar simulations vis-à-vis their intended purpose is taken for granted and therefore only their effectiveness in different cases is examined (Krösl, Bauer, et al., 2018; Zavlanou and Lanitis, 2016). In the second phase of the present research work, a novel method based on mixed methods is proposed, explained and tested to examine whether the simulation does represent actual deficits. A similar practice is recommended for future simulations.

Concluding this section, it is important to highlight a general ambiguity concerning the manifestation of the visual deficits which is deduced both from the review of the literature and the present research. For example, in the literature, patient self-reported symptoms are not always consistent with medical descriptions (C. X. Hu et al., 2014; D. C. Fletcher, Schuchard, and Renninger, 2012). As discussed in Section 7.2.3, this may be explained by the perceptual filling-in phenomenon (Zur and Ullman, 2003). Another explanation could be the differences in tolerance/discomfort thresholds, and the subjectivity of what one considers a “problem”. For example, some people disregard floaters, while for others this symptom is a source of psychological stress (Y.-K. Kim et al., 2017).

This general ambiguity was also observed in this research in two cases. First, in the external review during the development process, in which experts’ feedback was not always in agreement. Second, by the variations in the reported virtual effects that subjects provided for the exact same simulation. For this, the present research stresses the importance of considering different perspectives and employing various methods to validate such simulations.

8.5 Future perspectives

Given the absence of direct comparison between the real and the simulated conditions during the Phase 2 of the present research work (see Chapter 7), among the next plans for further research should be the validation of the tests used in the visual performance tasks in the VEs, and the test with real patients. This way, the performance of the latter can then be compared with that of young healthy-vision adults in the simulated environments and enhance the robustness of the results.

In a more general context, perspective-taking approaches such as the proposed simulation are quite powerful tools for studying specific situations first-hand and this opens up various directions for future research.

With *metaverse* recently coming to the forefront, the first steps towards its integration into various aspects of our lives have already begun and the word “meta” started to be used as a first compound of various terms, to indicate this new era, with one of the most known being the meta-education (Mystakidis, 2022). Various factors such as the development of the metaverse world itself with big investments in its content and research (Bosworth and Clegg, n.d.), combined with other factors such as the development of technology (5G, XR-reality), the cryptocurrency and the non-fungible tokens that have encouraged transactions between the real and the virtual world, and the global pandemic crisis and the self-isolation that it entailed, to name a few, seem to contribute to an increasing shift towards virtuality (Mystakidis, 2022; Park and Y.-G. Kim, 2022). This shift has already stressed a need for accessibility to welcome people of different ages, disabilities etc. (Sarabipour, 2020). In the future, simulations like the one proposed in this research work could be used to visualize, adapt or even dynamically change the content, towards inclusive virtual spaces—one of the main characteristics of this metaverse ecosystem according to Bosworth and Clegg, n.d. Although, as part of this research, the effectiveness of the simulation was examined solely in design cases, it could be tested in other cases and topics such in the design of AAL and rehabilitation applications, in providing experiential knowledge to medical students or in testing scenarios, like elderly pedestrian behaviour and car driving in a safe and controlled environment.

Simulating deficits in VEs is a topic involving many aspects. Although a lot of work has been carried out both through the present research and other related studies, there are several aspects that are yet to be studied and could be explored using techniques and approaches presented here. For example, the present research did not address problems that are not associated with aging, as this was outside of its scope. Also, it did not exhaust the age-related problems, but focused on the common ones. Thus, in the future, the present methodological approach could be followed for simulating other deficits and assess simulation's validity. As an example, a similar noise-based approach could be used to simulate retinitis pigmentosa and optic neuritis.

Finally, as part of the present research, an innovative approach was proposed harnessing ML techniques. The reported work on using ML-based evaluation presents a pilot investigation that highlighted the potential of this approach. Future work could concentrate on enhancing the objectivity of the ML-based approach, using for example real patient data (i.e., data acquired from visual field tests) to generate the training set, exploring the possibility of developing dedicated deep network architectures, and considering additional types of eye diseases. Also, by training the model with data obtained during visual performance tasks in the VEs with healthy-vision adults and visually-impaired elderly, an ML approach could be used for purposes of diagnostics and early detection of eye conditions.

8.6 Epilogue

Much work on the potential of XR-based approaches to simulate age-related and other declines, and especially visual deficits has been carried out over the last years, with simulations evolving from using ready-made effects to integrating real data and mathematical modeling, towards more sophisticated and comprehensive simulations. This shows the strong interest and supports the potential of XR to yield valuable knowledge on the topic. The present research contributed to this work by providing a simulation tool that tried to approximate as accurately as possible the actual problems, incorporating the aspect of controlled randomness for heterogeneous effects, hoping that this will pave the way for more realistic and accurate simulations. Of course, this has a long way to go and much more experimental investigation is needed. For this, as a future perspective, we plan to make this simulation tool accessible and open to the academic community, with a view to understanding first-hand the difficulties that many people face and addressing their needs, towards a better quality of life.

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