INVESTIGATION OF THE IMPACT OF AGEING & CATARACTS ON VISUAL MOTION PERCEPTION ACROSS THE VISUAL FIELD

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Thesis Abstract

This thesis examines the effects of cataracts and optical degradation, particularly light scatter, on motion perception across multiple dimensions. By integrating online surveys and psychophysical motion behavioural experiments using random dot kinematograms (RDKs), this research explores how degraded visual input affects tasks involving speed estimation, direction discrimination, and motion coherence. The results provide novel insights into the mechanisms that contribute to motion perception deficits in individuals with age related cataracts.

The investigation specifically focuses on the impact of light scatter on the ability to detect and predict subtle variations in local and global motion patterns under simulated media transparency conditions. Key findings reveal from the simulated groups a significant variability in performance depending on the type of motion tested. For example, light scatter profoundly impairs radial speed discrimination and speed perception, while translational and spiral direction discrimination, as well as radial coherence, remain relatively unaffected. Conversely, a case study involving genuine age-related cataracts reveals marked deficits in speed and direction discrimination, although speed prediction remains intact. Despite limitations related to sample size, data on radial coherence data suggest increased just-noticeable differences (JNDs). These outcomes highlight the varying sensitivity of distinct motion-processing mechanisms to optical distortions.

Further analysis underscores the essential role of environmental contrast in shaping motion perception. The ability of observers to detect and interpret motion cues is highly dependent on contrast levels in their visual environment, indicating a complex interaction between sensory inputs and higher-order cognitive processes that guide decision-making, action planning, and behavioural responses. Degraded visual input disrupts not only perceptual accuracy but also the foundational sensory data essential for thoughts, choices, and memories.

Potential research directions include expanding sample sizes, incorporating binocular vision studies, and exploring the neural substrates of motion perception through advanced imaging techniques. Such investigations hold promise for advancing our understanding of the interaction between optical degradation, cortical reorganisation, and visual function. Ultimately, this thesis highlights the essential role of motion perception in daily life and accentuate the need for continued research to address the challenges faced by visually impaired populations. By bridging gaps in current knowledge, this study lays the groundwork for transformative interventions that enhance independence, safety, and overall knowledge for affected individuals.

Dedication

*To the memory of my late father, **Dr. Ibrahim Al-Rababaa**, whose unwavering support and guidance accompanied me throughout my educational and research journey until his passing. His wisdom and encouragement remain a constant source of inspiration in all that I do.*

*To my resilient and extraordinary grandmother, **Engr. Inna Walter Eichhorn**, and my dearest mother, **Engr. Elena Kunstantin Khurashvilli**, for their steadfast presence, love, and strength during both triumphant and challenging times. Their resilience has been a beacon of hope and motivation, shaping who I am today.*

To my siblings, near and far, whose bond transcends physical distances. Together, we stand united, supporting one another through every step of life's journey.

*To the musicians whose artistry uplifts the human spirit and soothes the soul. Special gratitude is extended to the exceptional **City Birmingham Symphony Orchestra (CBSO)** for their unparalleled performances, which have brought immense joy and solace to my life. Their dedication to creating beauty through music has been a profound source of inspiration during this challenging journey.*

Music possesses a unique power to convey emotions beyond words, weaving lyrics, melodies, rhythms, and harmonies into a tapestry of understanding and connection. It has been an indispensable companion on this path, offering spiritual sustenance when it was needed most. To all creators of music: recognise the transformative impact of your talent, continue using it wisely, and never cease to inspire.

Each of you—family, friends, and artists alike—has played an integral role in shaping this journey. You are my greatest inspiration, and for that, I am eternally grateful.

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Chapter 1 **Literature Review**

1.1 Introduction

In recent decades, advancements in medical science have led to an increased proportion of elderly individuals within the general population (Suzman et al., 2015, Lin et al., 2016, Gow and Gilhooly, 2003, Cheng et al., 2020). This demographic shift has resulted in a rising prevalence of age-related conditions, including cognitive decline and visual impairments such as cataracts (Gow and Gilhooly, 2003). These trends pose significant challenges for healthcare systems and society, necessitating substantial financial and personal resources to support the growing elderly population (Deary et al., 2009). Extensive research efforts have been dedicated to understanding the biological and cognitive functions that naturally diminish with age, particularly focusing on sensory and perceptual abilities like motion perception.

Motion perception forms a fundamental aspect of visual processing, enabling individuals to effectively navigate and interact with their environment. However, studies have consistently shown that motion perception declines with age (Anderson et al., 2000, Bennett et al., 2007a), beginning to deteriorate around middle age (30–50 years) and accelerating significantly after the age of 60 (Deary et al., 2009, Zimprich et al., 2008, Hänninen et al., 1996, Born and Bradley, 2005). This age-related decline in cognitive and visual processing may further complex the difficulties faced by older adults, particularly those with additional ocular conditions such as cataracts, which cloud the eye's lens, adversely impacting visual functions by scattering light and reducing contrast sensitivity, acuity, and overall image quality (Nita and Grzybowski, 2016). Although surgical procedures are effective in restoring visual acuity, they do not necessarily address all aspects of visual perception, such as motion processing, which are essential for safe and independent living.

The relationship between vision and cognition has also gained increasing attention in recent years. Research indicates that untreated visual impairments are associated with a higher risk of cognitive decline and dementia, with one study reporting a 12.6% increase in dementia prevalence among individuals with untreated vision loss (Livingston et al., 2024). Longitudinal studies further suggest that better visual acuity correlates with slower rates of cognitive decline in older adults (Runk et al., 2023). A systematic review highlighted that this association is particularly pronounced in cases of severe visual impairment, underscoring the potential role of simple vision tests as accessible screening tools for early indicators of dementia (Nagarajan et al., 2022). Evaluating visual functions such as acuity, contrast sensitivity, or motion perception—known to deteriorate with ageing and neurodegenerative diseases—could provide valuable insights into cognitive health. Given their non-invasive nature, cost-effectiveness, and widespread availability, these tests could facilitate earlier interventions aimed at modifying both visual impairment and its downstream effects on cognitive well-being.

Structural changes in the visual cortex also contribute to age-related declines in motion perception. Regions such as V3, V5/MT+, and frontoparietal areas exhibit reduced grey matter volume in older adults, correlating with diminished sensitivity to slow-motion stimuli (Newsome and Pare, 1988, Schenk and Zihl, 1997, Vaina et al., 2005, Hua et al., 2020). These findings suggest that age-related deficits in motion perception are not solely attributable to optical degradation caused by conditions like cataracts but also reflect underlying neurological changes.

The human eye converts incoming visible light (wavelengths ranging from 400 to 700 nm) into high-resolution images processed in the brain's visual cortex (Atchison, 2023). This process relies on the transparent cornea and lens, as well as the retina's photoreceptors and retinal pigmented epithelium (RPE) cells, which support photoreceptor function. Age-related conditions such as cataracts disrupt these mechanisms through the accumulation of proteins in the lens, leading to light scattering and impaired visual function (Bloemendal et al., 2004, Roskamp et al., 2020).

This study investigates the impact of age-related cataracts on motion perception by simulating cataract-like conditions in healthy young participants and comparing their performance to that of actual cataract patients. Using psychophysical experimental paradigms and simulation filters, the study separates the effects of optical degradation from those of age-related changes, providing insights into the specific perceptual deficits experienced by cataract patients. These findings aim to update the development of targeted interventions to improve the quality of life for individuals with cataracts, addressing both their visual and broader functional needs.

1.1.1 Ageing and Vision

As humans age, several changes occur in their visual perceptual processes. For example, contrast sensitivity threshold increases (Elliott et al., 1990) and visual acuity decreases (Weale, 1982, Kline and Scialfa, 1997). Simultaneously, a considerable number of individuals experience age-related conditions like cataracts. Despite the effective management of cataracts through surgical interventions (Fraser et al., 2013), limited research has been conducted to explore the perceptual impact on patients with cataracts. Consequently, it remains uncertain whether cataracts have a broader effect on the perceptual experience of individuals beyond the typical clinical assessments of vision and visual acuity.

Cataracts are known to increase blur and reduce contrast (Brown, 1993, Elliott et al., 1996), both of which have been associated with deficits in specific visual functions e.g. motion (Fraser et al., 2013). This thesis investigates the motion processing abilities of patients with cataract using healthy individuals with simulated cataract and attempt to quantify the effects on the overall visual experience by modelling motion perception abilities under altered environmental conditions.

1.1.2 The Effect of Healthy Ageing on Ocular Structures

The idea that declining systemic functions are linked to the process of ageing (Spear, 1993, Gow and Gilhooly, 2003, Hedden and Gabrieli, 2004) has been substantiated by numerous research studies examining the anatomical (Hedden and Gabrieli, 2004, Grossniklaus et al., 2013, Spear, 1993, Charman, 2008), physiological (Lin et al., 2016, Spear, 1993) and chemical processes in the eye (Salvi et al., 2006). It is important to understand changes associated with healthy ageing to frame clinically useful representations of visual perception in an older clinical population. To this end, the structure (anatomy) and function (physiology and chemistry) are important to consider, however, it is also important to assess the function of the visual system through psychophysical examinations, to determine the behavioural impact of any neural changes.

When considering cell biology and biochemical functions, research highlights a deterioration with age especially through a deficit in a mechanism called autophagy (Mizushima et al., 2008, Levine and Kroemer, 2008). Autophagy is a very important cellular biological function which relies on the removing of abnormal organelles and proteins through eukaryotic cells thus balancing cellular homeostasis. Moreover, autophagy is recognised as an adaptive procedure for various metabolic stress, for example: hypoxia, growth factor reduction and nutrient deficiency (Levine and Kroemer, 2008, Mizushima et al., 2008, Leib et al., 2009, Li et al., 2015). This stage of the natural ageing process results in the accumulation of the intercellular organelles and defective autophagic flux, and as a number of ocular diseases are related to the ageing process and oxidative stress, a lot of conditions are associated with this defective autophagic function, for example: cataract, glaucoma, optic nerve axotomy, age-related macular degeneration, and diabetic retinopathy (Leib et al., 2009, Li et al., 2015).

Physiologically, successful light perception relies primarily on the combined healthy function of corneal, lenticular and retinal structures and the transparency of the media between these structures e.g., tears, aqueous, vitreous. Importantly, for light rays to pass unobstructed through the ocular media and be focused appropriately on the retina, the ocular lens must be transparent. However, across the course of the life span, the crystalline cells continue to be produced and the old ones accumulate centrally inside the lens capsule, eventually leading to lens opacification (Charman, 2008, Augusteyn, 2010, Lin et al., 2016, Chader and Taylor, 2013, Chang et al., 2017, Liu et al., 2023). Similarly, the ageing lens is associated with other changes including the ratio of water to protein, as protein concentrations increase throughout the life span, and water concentrations drop (Augusteyn, 2010). These increased protein concentrations and its aggregation indicates that the water is lost from lenticular consistency most likely through central regions till at least the age of 60 years (Augusteyn, 2010, Chang et al., 2017). Also, it is necessary for the lenticular structure to be flexible to compensate the visual demands for near and far vision in order to keep the retinal image clear, although natural loss of its flexibility begins from ~10 years and continues to decline until the accommodative function reaches a dioptric power of 1 at the age of 40 years (Augusteyn, 2010). When the accommodative response reaches this level, it begins to affect near vision, which is a condition called presbyopia (Heys et al., 2004, Wolffsohn and Davies, 2019, Katz et al., 2021). The age of presbyopic onset differs according to many factors such as the visual demand, ethnicity and genetics of the individual (Lin et al., 2016, Chader and Taylor, 2013).

Operatively, the human eye functions in the following procedure: reflected light from objects enters the eye through the transparent cornea, then through the aqueous humour to the pupil, passing the lenticular lens through the vitreous humour before reaching the retina and then transduced by retinal photoreceptor cells (Figure 1.1). Once this happens, a complex neurological action takes place to convert the signal, form the image, and transmit it to higher cortical areas (Lin et al., 2016, Chader and Taylor, 2013, Petrash, 2013). However, if any of these structures become affected by the ageing process, then this could affect the visual capabilities of the individual.

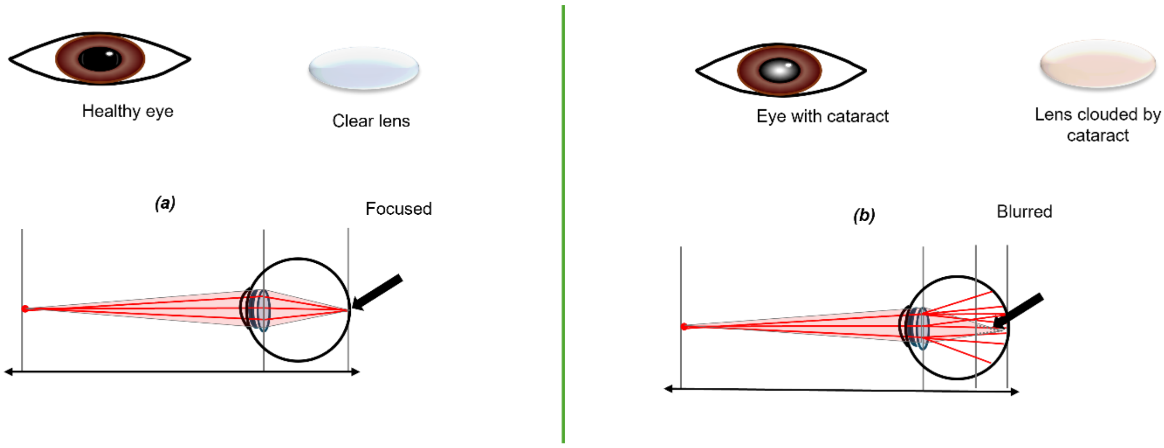


Figure 1.1. Schematic representation of the generation of focus cues using a light field within the human eye in healthy and cataract eyes. The shaded region denotes the entry of light from a singular source into the human eye, while the solid red lines represent the sampled light rays comprising the light field. When the eye is directed towards the focal point, the light rays converge at a specific location on the retina (a). Therefore, maintaining the health and transparency of the ocular lens is crucial for the production of a sharp image. Failure to do so may result in the image being focused on an unintended location, leading to the production of a blurred image (b).

Over the past three decades, there has been a growing interest in the perceptual and cognitive capabilities of older individuals, leading to numerous studies investigating the perceptual effects associated with ageing. As individuals age, there are functional and structural changes in the eyes, including cellular degradation and weakening of various ocular components, as described in the corresponding table (Table 1.1). These degenerative changes occur at both the anatomical and physiological levels, significantly impacting visual function. For instance, ageing leads to cell degradation and weakening in critical layers of the eye, such as the corneal endothelium and the retinal pigment epithelium (Friedman, 1968, Dorey et al., 1989, Edelhauser, 2006, Grossniklaus et al., 2013, Lin et al., 2016, Downie et al., 2021). The corneal endothelium, which plays a fundamental role in preserving corneal transparency, undergoes a gradual loss of endothelial cell density, thereby diminishing its capacity to regulate hydration and maintain optical clarity. In a parallel manner, the retinal pigment epithelium, which is essential for supporting photoreceptor functionality and facilitating the removal of metabolic waste, experiences thinning and a decrease in functional efficacy, ultimately leading to impaired visual acuity (Friedman, 1968, Grossniklaus et al., 2013, Petrash, 2013).

Table 1.1. A representation of several degenerative changes take place in the human eye:

Condition	Common signs	Common symptoms	Treatment
Refractive error (1)	Defocus of the formed retinal image	Blurry vision	Glasses, contact lenses refractive surgery
Age-related cataract (1)(2)	Opacification of the crystalline lens	Blur, glare, haze	Surgery when symptomatic
Primary open angle glaucoma (1) (2)	Optic nerve cupping, visual field changes	Asymptomatic initially, peripheral then central visual loss with progression	Pressure lowering treatments: medications, laser, surgery
Age related macular degeneration (1) (2)	Macular retinal changes	Early: asymptomatic Late: central vision loss (gradual or sudden)	Laser treatment, photodynamic therapy

(1) (Rowe et al., 2004) (2) (Zetterberg, 2016)

Other degenerative alterations include an increase in the viscosity of the vitreous humor, which may result in posterior vitreous detachment and the presence of floaters, thereby further impairing light transmission and visual acuity (Friedman, 1968, Grossniklaus et al., 2013, Petrash, 2013). Additionally, the development of drusen—small accumulations of cellular debris located beneath the retina—can disrupt nutrient exchange and contribute to the onset of conditions such as age-related macular degeneration (Grossniklaus et al., 2013). The ageing process also leads to a flattening of the cornea, which modifies its refractive power and may result in alterations in focus and clarity (Grossniklaus et al., 2013). This flattening is associated with a reduction in corneal sensitivity, potentially reducing the eye's capacity to respond effectively to environmental stimuli.

Evidence further shows that ageing process is associated with an increase in the density of trabecular meshwork cells, resulting in a transformation of the meshwork from an elongated, slice-like configuration to a more compact, rhomboidal form (McMenamin et al., 1986, Grossniklaus et al., 2013). This morphological alteration may prevent the outflow of aqueous humor, consequently elevating intraocular pressure and increasing the risk of developing glaucoma. Additionally, the systemic effects of ageing extend to the stromal layer of the ciliary processes within the ciliary body. A reduction in blood supply leads to an increase in density, collagenisation, and a decrease in length of this layer, which adversely affects the eye's capacity to accommodate for near vision, a condition referred to as presbyopia (McMenamin et al., 1986, Grossniklaus et al., 2013).

The cumulative effects of these degenerative alterations lead to a deterioration in visual function, which adversely impacts activities that necessitate precise visual discrimination, including reading, driving, and facial recognition. Understanding these age-related transformations is essential for developing interventions aimed at mitigating their impact on daily life and preserving visual health in older adults.

Studying the anterior eye, the process of ageing can result in various structural biological alterations. For instance, the corneal endothelial layer, which plays a crucial role in maintaining the structural integrity of the cornea, undergoes changes (Gipson, 2013, Grossniklaus et al., 2013, Lin et al., 2016). Some evidence suggests that endothelial cells are located in close proximity to the Schwalbe line within its regenerative zone, contributing to the maintenance of a paracentral reservoir of cells (Grossniklaus et al., 2013). Endothelial cells degenerate over time and loses many of its cells (Gipson, 2013, Grossniklaus et al., 2013, Lin et al., 2016). This can lead to corneal oedema and bullous keratopathy (Gipson, 2013). Also, due to long-term exposure of the outer ocular layer to the ultraviolet (UV) radiation from the sun, the corneal and conjunctival epithelium will be affected by oxidative stress and degenerate over time (Ibrahim et al., 2012). Moreover ocular ageing can lead to development of benign tumours called pterygium on the limbus, or development of conjunctival chalasis affecting the integrity of the conjunctival structure (Kato et al., 2007, Lin et al., 2016). Finally, the ageing process affects the ocular lacrimal and Meibomian glands causing tearing insufficiency and dry eye disorder (Gipson, 2013, Lin et al., 2016).

With regards to the retina, the ageing process is associated with reduction of neural cells and denseness of the internal limiting membrane, along with reduction in nuclear nuclei in the outer nuclear layer with migration of retinal pigment epithelium cells into the sensory retina, which can effect initial processing of the visual signal (Gartner and Henkind, 1981, Jackson et al., 2002, Grossniklaus et al., 2013). The ageing process is also linked with retinal vascular changes such as: loss of peripheral capillary cells, attachment of internal limiting membrane to the peripheral vascular arcades, reduction in foveal capillaries, and presence of arteriosclerotic changes in retinal vascularity (Gartner and Henkind, 1981, Kuwabara and Cogan, 1965, Dorey et al., 1989). These changes lead to a decreased blood supply to the choroid which forms choroidal atrophy. These changes can also affect the retinal pigment epithelium layer or other retinal layers, in which case peripheral chorioretinal atrophy can take place (Gartner and Henkind, 1981, Dorey et al., 1989, Curcio et al., 2001, Grossniklaus et al., 2013). Finally, lattice degeneration occurs as a result of vitreous liquefaction and retinal thinning forming retinal holes in those degenerated areas (Grossniklaus et al., 2013). Retinal degeneration can also result from age-related macular degeneration, a common disease and one of the leading causes of blindness in the elderly population (Wong et al., 2014). This presents in the central retina (macular) and can lead to loss of central vision which has a huge impact on the ability of the individual to see with high visual acuity. All these changes can be sight-threatening and so will be important to consider in the context of the data presented throughout this thesis.

Although most structures of the eye are affected by ageing, the key part of the eye relevant to this thesis is the crystalline lens. The natural ageing process significantly impacts the ocular lens, commencing in adolescence and resulting in a reduction of approximately half of the lenticular accommodative power by the mid-twenties (Anderson et al., 2008). On average, individuals tend to lose all accommodative ability after reaching their fifth decade of life (Krag and Andreassen, 2003), rendering the ocular lens the primary physiological organ affected by degenerative changes (Rich and Reilly, 2023). As the lens undergoes morphological changes, it takes a more oval shape, and by the age of 80 years, its mass nearly triples, increasing from 90 mg at birth to approximately 240 mg (Petrash, 2013, Grossniklaus et al., 2013). As well as, due to increased accumulation of lenticular proteins and its oxidation, the lens loses its transparency and the colour of the lens changes to become more yellowish (Lin et al., 2016, Truscott, 2005). Similarly, the lenticular fibres begin to turn inward from the equator and the lenticular epithelium becomes posteriorly displaced, with accumulation of these cells in the posterior capsule. As individuals age, the lens undergoes swelling, leading to an increase in both its sagittal and equatorial diameters. This process, as it progresses, can ultimately lead to the development of a posterior subcapsular cataract (Grossniklaus et al., 2013, Donaldson et al., 2023).

These changes could affect the visual capabilities of the individual because performance of daily activities and socialising rely heavily on vision and visual perception. The degenerative structural and physiological changes cause a decline in ocular functions, including visual acuity, contrast sensitivity and increased dark adaptation thresholds (Salvi et al., 2006). Moreover, the loss of overall systematic neuronal cells results in reduction of the number of ganglion and optic nerve axons cells and the number of photoreceptor cells, which altogether reduces the quality of a patient’s life (Salvi et al., 2006, Gartner and Henkind, 1981, Jackson et al., 2002, Grossniklaus et al., 2013).

Taken together, it is evident that the ageing process can significantly affect the structure and health of the eye, and potentially impact the quality of vision (Salvi et al., 2006, Gartner and Henkind, 1981, Jackson et al., 2002, Grossniklaus et al., 2013, Kuwabara and Cogan, 1965, Dorey et al., 1989). Therefore, it is imperative to include age-matched control subjects in studies examining the effects of cataracts in order to eliminate any potential influence of natural ageing (Salvi et al., 2006).

1.1.3 The Effect of Healthy Ageing on Ocular Functions

In relation to functional vision, it is typical for a healthy older individual to express two primary concerns regarding their visual capabilities: the ability to perceive objects in low light conditions and night vision. Their diminished visual acuity in dimly lit environments can impact their ability to carry out daily tasks and may result in a higher risk of accidents and falls. (Jackson et al., 1999).

Due to these known biological changes, studies have demonstrated that the normal ageing process can lead to a number of changes, such as: presbyopia (Katz et al., 2021), decreased contrast sensitivity (Spear, 1993, Owsley, 2011), reduction in visual acuity (Spear, 1993, Owsley, 2011), decreased colour discrimination (Shinomori, 2005), declining dark adaptation thresholds (Owsley, 2011), reduction in photopic and scotopic sensitivity (Shinomori, 2005) and changes in binocular vision (Spear, 1993, Ross et al., 1985, Sekuler et al., 2000).

Contrast refers to the quantifiable difference in luminance or colour between two adjacent areas, typically expressed as a ratio relative to either the lower or higher luminance value (Owsley, 2003, Simone et al., 2012, Stalin and Dalton, 2020, Tidbury et al., 2016). The minimum contrast necessary for an individual to detect a target is termed the contrast threshold, which is commonly expressed on a logarithmic scale to account for the wide range of detectable contrasts (Figure 1.2) (Kelly and Savoie, 1973, O'Carroll and Wiederman, 2014). Contrast thresholds can be assessed through various psychophysical tasks, including target detection, discrimination, recognition, and identification, each of which provides insights into different aspects of visual processing (Palmer et al., 2000, Schwartz, 2006). In research, contrast thresholds are often represented as contrast sensitivity (CS), defined as the reciprocal of the threshold, where higher sensitivity indicates a greater ability to detect subtle differences in contrast (Bertalmío, 2019).

When contrast sensitivity is assessed across different spatial frequencies—typically expressed in cycles per degree of visual angle—the resulting graphical representation is known as the contrast sensitivity function (CSF). In a standard CSF experiment, spatial frequency (SF) serves as the independent variable, with the experimenter systematically varying the SF of the stimulus. Observers are tasked with detecting a target presented at varying contrast levels, usually in a two-interval forced-choice paradigm (e.g., identifying which of two temporal intervals contains the target). The dependent variable is the contrast threshold, and the CSF is constructed by plotting the reciprocal of these thresholds as a function of SF (Schwartz, 2006, Bertalmío, 2019). This methodology highlights the variation in sensitivity to contrast across different spatial frequencies, independent of the physical size of the stimulus. For example, resizing a grating patch does not alter its spatial frequency, as the latter depends solely on the density of cycles within the stimulus. This distinction highlights the essential role of spatial frequency in understanding the relationship between contrast sensitivity and visual perception.

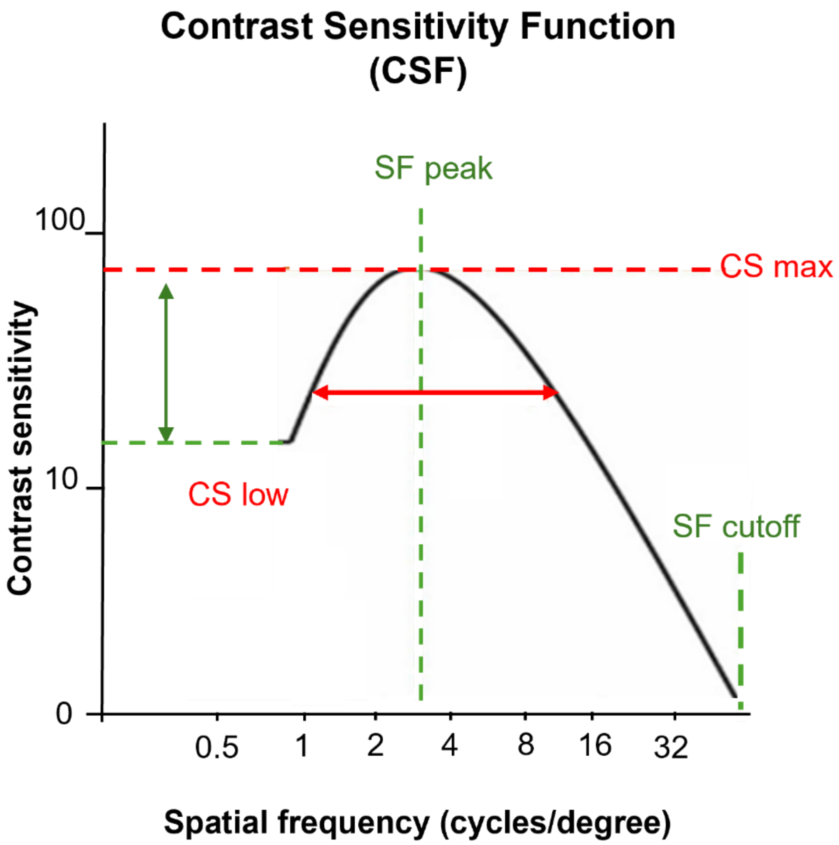


Figure 1.2. The contrast-sensitivity function (CSF) is illustrated as an inverted U-shaped curve. The x-axis shows spatial frequency (SF), which relates to the size of visual stimuli like letters or patterns, with higher frequencies representing smaller sizes. The y-axis indicates contrast sensitivity (CS), which declines as the stimulus contrast decreases. The truncated log CSF model, commonly used in vision research, is characterised by four key parameters: 1. **Peak Sensitivity** (CS max): The maximum contrast sensitivity achieved at the peak of the curve. 2. **Peak Spatial Frequency** (SF peak): The spatial frequency at which peak sensitivity occurs. 3. **Bandwidth**: The range of spatial frequencies over which the CSF remains above a certain threshold (often defined as half the peak sensitivity). This is indicated by the red double-ended arrow in the figure. 4. **Low Contrast Sensitivity** (CS low): The asymptotic level of contrast sensitivity at low spatial frequencies, where sensitivity plateaus. The green double-ended arrow in the figure indicates the truncation distance, which is the vertical measurement from the apex of the CSF curve (CS max) to the plateau region (CS low). This truncation reflects the practical limits of measuring contrast sensitivity in real-world conditions. This curve presents the boundary between visible and invisible gratings or letters, providing insights into human visual acuity across different spatial frequencies. Adapted from Schwartz (2006).

The assessment of contrast sensitivity is essential as it measures the capacity of both the optical system's to transmit information and the neural system's to process visual stimuli (Jackson and Bailey, 2004, Schwartz, 2006, Lord et al., 1991). Notably, even when a patient achieves optimal 6/6 visual acuity during a routine examination, this measure fails to account for approximately 90% of the actual visual experience due to the high contrast of the letters used in standard tests (Roark and Stringham, 2019). It is essential to acknowledge that the contrast sensitivity function (CSF) is influenced not only by the optical characteristics of the eye but also significantly by neural factors across both low and high spatial frequency ranges. For example, the low-frequency cutoff is determined by neural limitations, such as the integration of signals within the visual cortex, while the high-frequency cutoff is largely governed by optical factors, including the clarity of the ocular media and the diffraction limit of the eye

(Schwartz, 2006, Bertalmío, 2019). This distinction highlights the importance of considering both neural and optical contributions when interpreting contrast sensitivity data in clinical and research settings.

The optimal visual perception in our real world depends greatly on the individual's ability to discriminate between brightness levels among different areas of specific scenes, thus discriminating different details in the world depends on the ability to differentiate and distinguish between different luminance levels across the environment (Geisler, 2008).

Visual acuity (VA) is considered the most important test performed in many eye care clinics and is a requirement in all optometric and ophthalmic practices (Optometrists, 2023). Typically, older adults experience a gradual decline in their visual acuity as they age (Haegerstrom-Portnoy et al., 1999, Klaver et al., 1998), with the most severe loss occurring after the age of 70 years (Haegerstrom-Portnoy et al., 1999). Age-related VA deficiency can occur due to neurological or optical factors. Neurological issues are linked to the loss of retinal photoreceptors, bipolar cells, ganglion cells, or disruptions in the connections between these cells (Spear, 1993, Devaney and Johnson, 1980, Weale, 1975). This naturally occurring degeneration can lead to decreased visual resolution and VA, as the geniculostriate pathway in the cortex plays a critical role in high-quality vision. Optical factors also play a significant role in the age-related decrease in VA. One such factor is age-related miosis, or the gradual reduction in pupil size with age. Miosis limits the amount of light entering the eye, reducing retinal illumination, particularly in low-light situations (Weale, 1975, Spear, 1993). Additionally, the increase in lens thickness with age leads to more light scattering within the eye, which further reduces image quality and worsens defocus problems. These optical changes underscore the pupil's role in regulating light intensity and maintaining focus, although it is uncertain whether pupil size was specifically assessed in this context. Another measure of VA, "dynamic VA," refers to the ability to perceive fine details of moving objects (Ishigaki and Miyao, 1994) and also shows a decline in visual function with age. These findings indicate that older individuals are likely to exhibit reduced ability to distinguish fine spatial details in both static and moving scenes.

In terms of vision across the visual field, age tend to reduce visual acuity across the visual field, affecting both central and peripheral regions. However, this reduction is most often attributed to effects of glaucoma rather than natural ageing (Wood, 2002, Friström and Lundh, 2000, Owsley, 2011).

The ageing process also has consequences for the performance of the ocular binocularity functions and motility as it can affect saccades, pursuit, vergence, and fixation (Sekuler et al., 2000). The importance of binocular vision that it allows us to see the surrounding environment uniformly and binocularly by facilitating both eyes to work together both suppressively and facilitatively (Blake and Wilson, 2011, Yan et al., 2021). As well the effect of ageing process on binocular functions, it also affects tasks such as: hand-eye coordination, stereoscopic vision, and reading (Yan et al., 2021). Within saccadic tests, evidence shows that older individuals usually have weaknesses in suppressing reflexive saccades along with increased saccade latency, meaning it takes them longer to make the movement

(Pelak, 2010). There is an indication that older individuals may have reduced effectiveness in accurately tracking moving objects in smooth pursuit tasks, although the extent of this impairment depends on the properties of the object, such as its speed (Paquette and Fung, 2011, Dowiasch et al., 2015). It is important to note that older individuals tend to rely more on convergence function than divergence in their daily activities, although this function is often found to be deficient in this population (Vidailhet et al., 1994, Pelak, 2010). This deficiency is likely due to accommodation dysfunction and the presence of presbyopia, which limits the individual's ability to use vergence to track moving objects (Lockhart and Shi, 2010). Additionally, older individuals commonly experience intrusive or reflexive saccades during stable fixation, which should be taken into consideration when designing and interpreting behavioural experiments related to visual function (Pelak, 2010).

Colour vision is another feature of vision that deteriorates as age advances; in the study represented in Figure 1.3 the experimenters tried to simulate the decline in ocular lens transmission for different wavelengths using specific filters for each age group (Arden and Wolf, 2004). Older people typically show deficiencies in colour discrimination with particularly poor performance in the blue green and red-light spectra (Helve and Krause, 1972, Sekuler et al., 2000). Despite the deteriorated ability of the retinal cones to process wavelengths of light with increasing age, their functional perception remains comparatively constant because it depends on the function of three different cones that have a moderately stable function (Sekuler et al., 2000). Even though the overall colour discrimination does not change significantly in older individuals, under certain condition the colour discrimination can be shown to have deteriorated considerably (Shinomori, 2005). It is thought that cataract formation, pupillary miosis, retinal illumination, and macular degeneration are the main factors for reduced colour discrimination with ageing that may reduce the spectral radiance of stimuli on the retina (Helve and Krause, 1972, Arden and Wolf, 2004, Friström and Lundh, 2000, Shinomori, 2005). The reduced lenticular transparency and increased brunescence that usually occurs due to an increased density (e.g. cataracts) acts similarly to a filter for the light transmitted through it, especially for shorter wavelengths, so colour discrimination will be affected accordingly (Arden and Wolf, 2004, Shinomori, 2005).

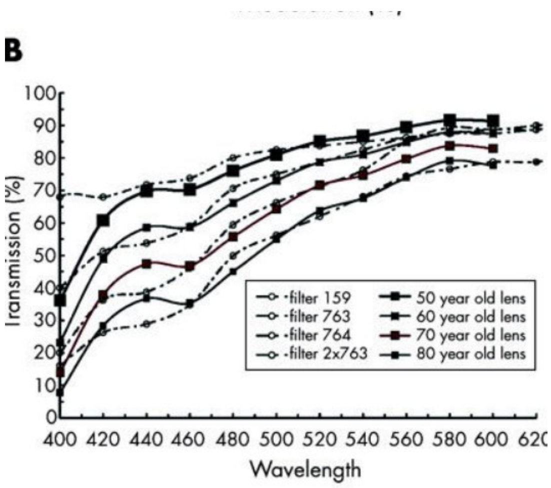


Figure 1.3. Ageing ocular lens light transmission (Arden and Wolf, 2004).

Arden and Wolf (2004) conducted a study to investigate the impact of screening using a modified method of colour and CS testing on elderly individuals. Sixteen observers were initially recruited, then three were subsequently excluded due to early signs of age-related maculopathy (ARM), abnormal colour vision, and abnormal alcohol responses in the electrooculogram (EOG). The remaining observers had no systemic or ocular diseases that could affect their vision, normal fundi, and normal corrected visual acuity. The average age of the observers was 71.75 years, with a range from 57 to 82 years. The mean visual acuity was 0.93, ranging from 0.7 to 1.5. The contrast thresholds for protan and tritan were determined to be 6.63% (SD 1.22%) and 26.8% (SD 5.5%), respectively. The gender distribution consisted of seven female and nine male observers. The authors conducted multiple revised experiments to simulate deteriorated colour discrimination caused by ageing ocular lens in middle-aged individuals (Arden and Wolf, 2004). The simulation involved the use of plastic filters provided by Lee Filters, Ltd, UK, with specific filters assigned to different age groups. The results indicated that individuals aged 70 and 80 years had an increased threshold in smaller tritan letters and filters. Specifically, female thresholds were 6.9% for protan and 28.0% for tritan, while male thresholds were 6.4% for protan and 26.0% for tritan. The contrast thresholds for the 65–74-year-old group were found to be insignificantly different from those of the 75–84-year-old group, with mean values of 7.0% and 6.4% for protan, and 28.0% and 27.7% for tritan, respectively.

Subsequently, the researchers repeated the previous experiment, examining the impact of simulated yellow filters on colour perception through the ocular lens in individuals aged 20 years, as shown in Figure 1.4 (Arden and Wolf, 2004). It is noteworthy that the tritan values in Figure 1.4 shows that colour contrast threshold increases with increasing equivalent age, which aligns with data showing reductions in wavelength transmission through an ageing lens (refer to Figure 1.3).

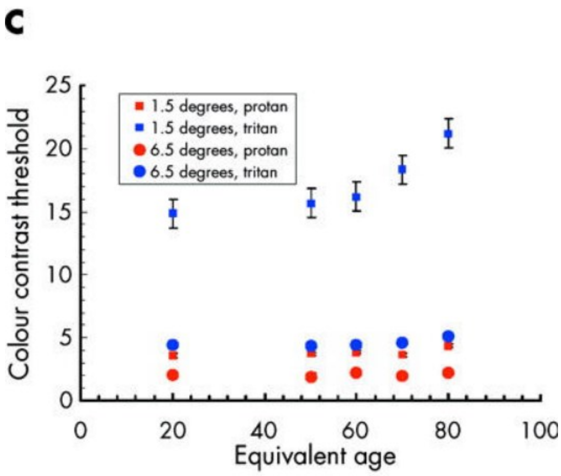


Figure 1.4. The figure illustrates how colour contrast thresholds change for 20-year-old individuals when yellow filters are used. It assessed colour contrast sensitivity, focusing on protan and tritan defects, at two different stimulus sizes (1.5 degrees and 6.5 degrees) across various equivalent ages. The x-axis represents "Equivalent Age," which mimics age-related visual changes by modifying stimulus parameters, while the y-axis indicates "Colour Contrast Threshold," the minimum contrast level needed for detection. The data points show average thresholds, with vertical error bars representing ±1 standard deviation (SD). Red circles indicate thresholds for protan defects, and blue circles represent thresholds for tritan defects. Generally, smaller stimuli (1.5 degrees) led to higher thresholds than larger stimuli (6.5 degrees), highlighting the effect of stimulus size on colour contrast sensitivity. Furthermore, the figure reveals that thresholds rise with increasing equivalent age, indicating a decrease in colour contrast sensitivity as simulated ageing occurs. This analysis emphasises the relationship between stimulus size, age-related changes, and colour contrast sensitivity, offering insights into how visual performance is influenced under these circumstances. Data adapted from Arden and Wolf (2004).

The retina receives light that travels through the eye's media and enters through the pupil. It's important to note that the size of the pupillary diameter plays a significant role in controlling the amount of light that reaches the retinal surface, which affects retinal adaptation. Vision specialists describe visual stimuli based on the illumination of the retina, which is influenced by the pupil's diameter (Schwartz, 2006). Retinal illumination is measured in trolands, a unit that combines the brightness of the stimulus with the pupil's area, ensuring that the light reaching the retina is consistent for everyone, regardless of their pupil size (Schwartz, 2006).

The amount of light reaching the retina significantly affects temporal acuity at both low and high frequencies. Low frequencies are essential for preserving contrast in stationary images, however, it is well understood that most organisms in their natural environments are usually in a dynamic motion rather than stationary (Kelly, 1961). Age-related miosis of the pupil can reduce retinal illumination by as much as two-thirds of its typical levels, similar to using a neutral filter with a density of 0.50 (Schwartz, 2006). In older adults, decreased retinal illumination is clinically associated with pupillary miosis and cataract development (Owsley, 2011). Furthermore, advanced cataracts, which cause the ocular lens to appear yellowish, can lead to reduced retinal illumination and impaired colour discrimination in the tritan (blue-yellow) spectrum (Haegerstrom-Portnoy et al., 1999, Friström and Lundh, 2000).

Age-related miosis can be described as the consistency and stability of an older individual’s pupil to remain constricted despite the decreased light levels. This happens due to deterioration in the pupillary light reflex associated with the ageing process, caused by losing the automatic flexibility of the pupillary muscles to constrict and relax with the changing light levels (Mathôt, 2018, Winn et al., 1994). This may result in difficulties in low light environments, while maintaining normal function in well-lit conditions due to the individuals' pupils remaining constricted to regulate the amount of light entering the eye (Sloane et al., 1988, Owsley, 2011, Owsley, 2016). Consistent with this concept, the age-related miosis results in elevated thresholds for scotopic vision (Owsley, 2011, Owsley, 2016). As a result, the increased severity of cataracts and age-related miosis leads to an obvious decline in the level of retinal illumination experienced by these individuals (Haegerstrom-Portnoy et al., 1999, Owsley, 2011). Furthermore, the regulation of pupillary diameter is crucial not only for managing contrast sensitivity but also for preserving optimal visual acuity by adjusting the pupil size to minimise light distortion (glare) within the eye. In normally functioning eyes of younger individuals, the pupils typically have a larger average diameter, and they can adapt their diameter to restrict excessive light entry and regulate the levels of light focused onto the retina (Sloane et al., 1988, Owsley, 2011, Owsley, 2016). However, the decrease in pupil size is linked to certain beneficial effects on vision, such as enhanced depth of field and reduced optical distortion (Sloane et al., 1988, Owsley, 2011, Owsley, 2016).

At a higher processing level, ‘perception’ refers to the cognitive process of extracting, organising and interpreting sensory information. To achieve an optimal level of perception, the visual system must integrate these sensory signals with higher-order functions, such as motor skills (Wang et al., 2022b, Qiong, 2017). The unique configuration of retinal cells, in combination with cortical function, plays a significant role in the sophisticated perceptual processing of the entire visual field (Turano et al., 2005). In essence, the functionality of the retina can be categorised into central and peripheral regions (Turano et al., 2005, Long et al., 1990). The central retina exhibits a heightened sensitivity to image contrast and displacement (Szlyk et al., 1998), while the peripheral retina, covering a larger portion of the visual field, plays a more significant role in orientation and motion perception (Turano et al., 2005, Geruschat et al., 1998, Long et al., 1990). Accordingly, impairments in the central retinal areas are linked to difficulties in detection and alterations in evaluation, whereas impairments in the peripheral retinal areas are associated with collisions with objects in the environment and a sense of disorientation (Turano et al., 2005, Geruschat et al., 1998, Szlyk et al., 1998). As a result, the resulting duality in retinal perception enables the processing of various types of visual information for the purpose of walking, or to support locomotion (Turano et al., 2005, Geruschat et al., 1998, Szlyk et al., 1998).

The context of objects existing in our visual space across different locations provides essential information to support the walker, as moving securely through the environment requires the brain to understand the spatial relationship between an object and the walker and a constant update of this relationship as the situation changes (Turano et al., 2005). Approximately 40% of motion functions are attributed to visual field and contrast sensitivity (Warren and Rushton, 2008, Long et al., 1990).

Therefore, navigation through the surrounding environment is achieved through two strategies: optic flow and egocentric direction. The processing of optic flow information helps to direct walking and has many phases, the first phase occurs when the retinal image is converted into a radial pattern, using the principle focus of expansion to help lead the walker to move to a specific point in the environment. Additional phases involve the flow of equalisation strategy and strategies dependent on local signs like differential displacement, parallax and inward motion (Warren and Rushton, 2008, Turano et al., 2005). The egocentric direction strategy counts on the detected direction of the target, walking toward such a goal under this scheme does not require the presence of visual context for that target, instead the target direction is perceived in relation to oneself (egocentric) in respect to the location of the reflected image on the retina and the eyes and head position (Turano et al., 2005). Ocular associated degenerative changes (Friedman, 1968, Dorey et al., 1989, Edelhauser, 2006, Grossniklaus et al., 2013, Lin et al., 2016, Downie et al., 2021), theoretically should not significantly affect motion perception as long as the peripheral area is not affected (Turano et al., 2005, Schwartz, 2006, Long et al., 1990, Geruschat et al., 1998).

Understanding the subjective perception of visual task difficulties and the sensitive implications of these challenges among patients is essential for gaining insight into the impact of eye conditions and ageing on daily functioning. Reduced retinal illumination in older individuals and the presence of cataracts can affect the ability to perform daily activities, highlighting the significance of adequate light illumination for optimising visual capabilities (Giménez et al., 2014, Daneault et al., 2018). However, older individuals with cataracts may also experience glare due to increased lenticular density if light levels are too high (Daneault et al., 2018). Therefore, for the purpose of this study, it is important to focus on the impact of ageing and cataracts on the visual processing of moving objects.

1.2 Cataracts

In order to systematically examine the potential influence of cataracts on motion perception, it is essential to explain the nature of cataracts, their various classifications, and their implications for visual function. This understanding will provide a foundation for linking cataracts to perceptual deficits, particularly in dynamic visual tasks, which are explored in subsequent chapters through behavioural experiments Chapter 5 Chapter 8), surveys (Chapter 3), and age related cataract case study **Error! Reference source not found.**).

1.2.1 Types of Cataracts

Age-related cataracts affects vision according to its severity and commonly presents in early stages as the need for minus spectacles and can progress to more severe degrees of visual impairment close to blindness (Panchapakesan et al., 2003, Nizami et al., 2021). The most typical symptoms for cataracts are deteriorated vision, seeing coloured haloes, monocular diplopia, variation in colour discrimination, deficiency of stereopsis and light sensitivity (Brown, 1993, Nizami et al., 2021, He et al., 2020a). For the purpose of clinical studies, age-related cataracts are divided into three main types: nuclear, cortical and posterior subcapsular (Brown, 1993, Chew et al., 2012). Additionally, there is a fourth rare type: the Christmas tree cataract (Natung et al., 2016). It is also important to consider that many patients may have more than one type of cataract at one time (Natung et al., 2016, Chew et al., 2012).

1.2.1.1 Nuclear Cataract (NC)

This typically presents in patients older than 50 years, with central opacification in the nucleus of the lenticular lens that increases the level of scattered light within the eye (Figure 1.5) (Chang et al., 2011, Salmon, 2019, Truscott, 2005). This condition is marked by yellow pigmentation of the lens due to the deposition of urochrome pigment (Salmon, 2019, Truscott, 2005).

In its early stages, nuclear cataract formation, it increases the central refractive index of the lens causing a myopic shift (lenticular myopia), and patients' distance visual acuity becomes more affected than near acuity. In its early stages it can decrease an individuals' presbyopia levels, permitting them to read without spectacles (Salmon, 2019, Wong et al., 2001, Hassan et al., 2011). As the cataract progresses and the lens matures, a refractive error might develop which can be hyperopic or astigmatic in nature (Pesudovs and Elliott, 2003). Also, the associated variations in the refractive index increase significantly between the cortex and nucleus in the lens, causing monocular diplopia in advanced stages (Nizami et al., 2021). The alterations in visual function are relevant to the behavioural experiments that will be addressed subsequently, which will investigate the effects of cataracts on motion perception and contrast sensitivity.

Figure 1.5. Nuclear cataract (Course, 2024).

1.2.1.2 Cortical Cataract (CC)

Similar to nuclear cataract, cortical cataract could occur bilaterally but usually presents asymmetrically. The disorder arises due to local disruption of the structure of the mature lens fibre cells, cortical cataract fibres are seen in Figure 1.6. The disrupted fibres cause comprehensive protein oxidation and cortical precipitation. The progression of the deficit differs among individuals as some cortical cataracts remain stable for a long time and others progress relatively quickly. Importantly, the effect of this type of cataract on visual task performance differs significantly across individuals, depending on the location of the opacity in relation to the visual axis. The majority of patients suffer from glare when subjected to powerful central light sources but in other cases diplopia (double vision) might also occur (Salmon, 2019, Nizami et al., 2021, Pesudovs and Elliott, 2003).

If left untreated, this type of cataract can cause angle closure glaucoma; in advanced stages of this type of cataract when it is said to be mature, once the whole cortex from the capsule to the nucleus becomes white and opaque, the lens absorbs water, becoming swollen and enlarged (Chen et al., 2011, Richardson et al., 2020).

Figure 1.6. Cortical cataract (Webeye.ophth, 2019).

1.2.1.3 Posterior Subcapsular Cataract (PSCs*)*

PSCs make up around 10% of cataracts that are related to ageing (Giuffrè et al., 1994). Individuals with this type of cataract usually present at younger ages than those with nuclear or cortical cataracts. Indeed, ageing is not a fundamental factor for development of PSCs, instead they might be associated with other conditions such as trauma, alcohol abuse, consumption of steroids (either systemic, topical or intraocular), inflammation, and exposure to ionising radiation (Richardson et al., 2020, Brown and Akaichi, 2015, Vasavada et al., 2004). Several risk factors can accelerate the progression of PSC in younger individuals. A study involving elderly female twins with an average age of 62 years revealed a significant genetic influence on the development of NC (48%) and CC (53% to 58%). In contrast, age was found to account for only 38% and 11 to 16% of the variability in cataract development, respectively (Hammond et al., 2001, Hammond et al., 2000).

Commonly, PSCs typically develop in the posterior cortical layer and only impact visual acuity when they coalesce within the visual axis (see Figure 1.7) (Giuffrè et al., 1994, Chang et al., 2011). The most prevalent symptoms associated with PSCs include glare (Tan et al., 1998, Adamsons et al., 1992) and diminished vision in bright light conditions, attributable to the light scattering caused by the cataract (Adamsons et al., 1992, Vasavada et al., 2004). Additionally, there is the complication that pupils constrict (miosis) in bright light, and pupils generally decrease in size with age (Guillon et al., 2016), making it more challenging for patients to see if they have central cataracts. Furthermore, accommodation occurs during near tasks, thus allowing the opacity to intersect within the visual axis (Salmon, 2019).

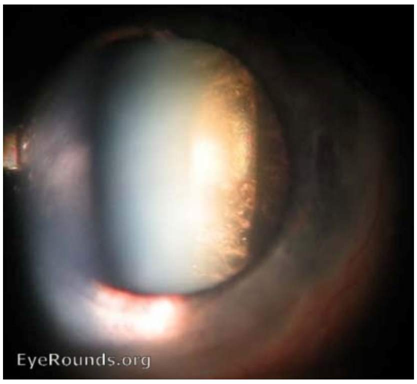


Figure 1.7. Posterior subcapsular cataract (Eyerounds.org, 2019).

1.2.1.4 Christmas Tree Cataract (CTC*)*

An infrequent type of cataract presents with the presence of polychromatic needle-like formation in the bottom of the cortex and nucleus of the lens (Salmon, 2019). It differs from other types of cataracts in showing different colours inside the crystalline lens, and when the light passes through the lens these needles glitters like Christmas tree (Figure 1.8) (Natung et al., 2016). The precise cause for this type of cataract is unknown but it is believed that typically is caused by accelerated breakdown of proteins induced by elevated calcium levels (Natung et al., 2016, Salmon, 2019).

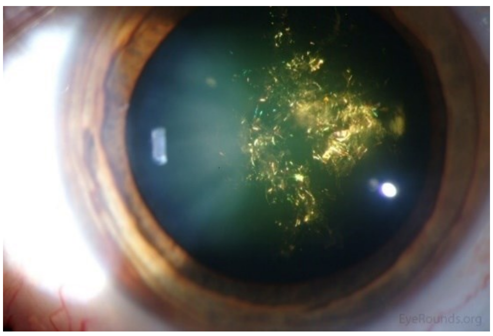


Figure 1.8. Christmas tree cataract (Eyerounds.org, 2015).

Despite presenting in different locations and varieties, age-related cataracts altogether share a mutual sign which is light scattering of the ocular lens which leads gradually to various ocular and functional complications (Brown, 1993), including reduced contrast sensitivity, photophobia, and increased blur.

1.2.2 Grading of Cataract Severity

In order to decide the degree of lens opacification, type and severity in cataracts, two scaling systems are most frequently used in eye clinics: (1) the LOCS III that bases its grading on slit lamp examination, and (2) the Wisconsin cataract grading method that uses fundus imaging in grading the degree of cataract (Cao et al., 2020). Cataract grading is considered important as it aims to provide a standardised strategy of grading cataracts and permits the physician and ocular clinicians to assess cataract progression by following it over time. It also carries the advantage that it makes it easier to share records if required with other physicians. Moreover, scaling provides an organised way to compare many cataract outcomes across different studies (West et al., 1988, Gali et al., 2019).

1.2.2.1 The LOCS III Grading System

The LOCS III scaling system was developed three decades ago when clinicians and scientists combined the Oxford Clinical Grading System with early iterations of the Lens Opacities Classification System (LOCS) to establish a standard way to grade and evaluate cataracts (West and Taylor, 1986). This became the LOCS III system that is still used in clinics today. This system was produced with the goal of offering a reliable and reproducible grading structure that will be simple for physicians to use while still managing the importance of cataract features (Gali et al., 2019). This system is practical and easily applicable in clinical applications for all age-related cataract types (Freeman and Pesudovs, 2005). To grade the cataract using the LOCS III, physicians need to use a slit lamp during the clinical examination procedure and compare findings to the grading system, shown in Figure 1.9 below (Cao et al., 2020, Chew et al., 2012, Tan et al., 2011). This system could reduce the cost of clinical studies comparing to photographic gradings, however it requires from a clinician to be well trained and experienced using slit lamp examination (Karbassi et al., 1993, Cao et al., 2020).

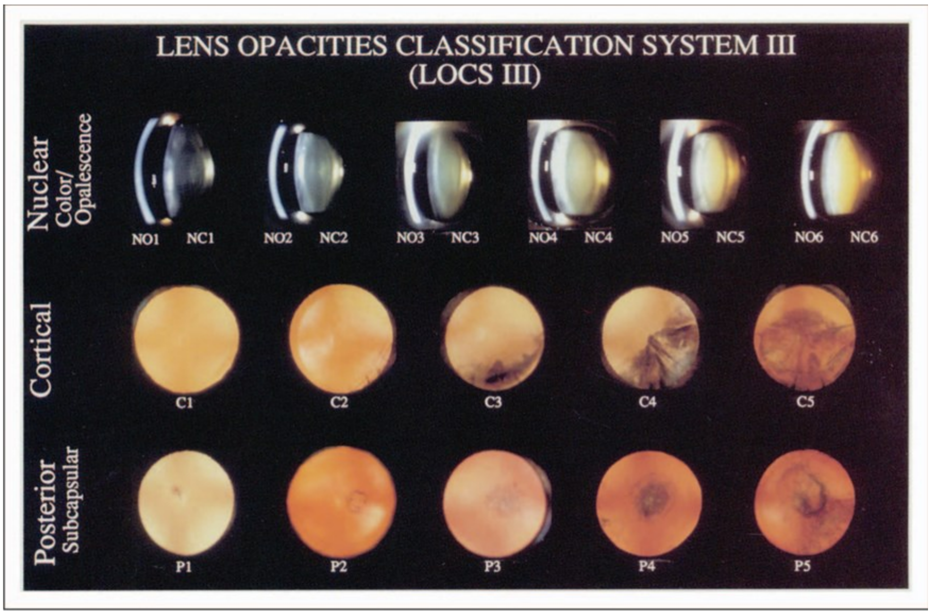


Figure 1.9. The Lens Opacities Classification System III (LOCS III) Standards introduced in 1993 from (Gali et al., 2019).

1.2.2.2 The Wisconsin Cataract Grading System

The Wisconsin cataract grading method is a simple method that relies on fundus imaging to grade the severity of cataract by estimating the blurriness of retinal images (West et al., 1988, Cao et al., 2020, Tan et al., 2011). For example, in Figure 1.10 you can see that 2d is evidencing a much more severe cataract than in 2a as it is blocking almost all light from reaching the retina to take the photograph.

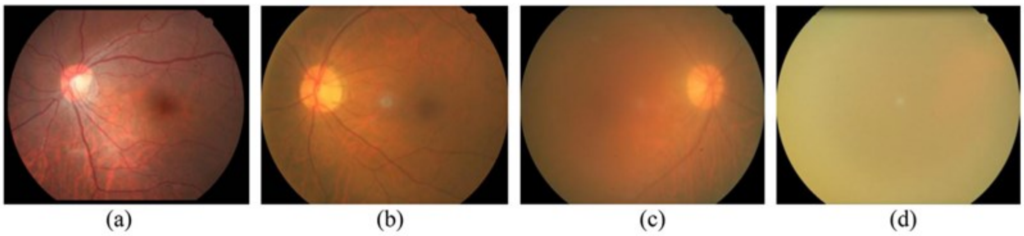


Figure 1.10. Retinal images showing varying levels according to the Wisconsin scale: (a) non-cataract, (b) mild cataract, (c) moderate cataract, and (d) severe cataract from (Cao et al., 2020).

Though this system is one of the system that is most widely used (Tan et al., 2011) based on photographic grading through requires to be performed within a well skilled ophthalmologist (Tan et al., 2011, Cao et al., 2020).

1.2.3 Causes and Treatment

Cataracts represent the second leading cause of vision impairment globally and are the leading cause of blindness in developing nations (Rao et al., 2011, Truscott and Zhu, 2010). Various risk factors contribute to the development of cataracts, including advanced age, tobacco use, excessive ultraviolet radiation exposure, diabetes, and long-term corticosteroid use (see Table 1.2). The symptoms associated with cataracts, such as glare, diminished contrast sensitivity, and difficulty recognising colours significantly impact quality of life (Lamoureux et al., 2011, Chew et al., 2012).

Table 1.2. The frequency of different types of cataracts in relation to various risk factors, categorised as highly influential (++), moderately influential (+) or mildly to no influence (0).

Risk factors	**Cataract type**			References
	NC	**CC**	**PSC**	
Ageing	++	++	+	*(Giuffrè et al., 1994)* *(Chang et al., 2011)*
Diabetes	0	++	++	*(Li et al., 2014)* *(Becker et al., 2018)*
Ionising radiation, which includes radiation encountered in space environments.	+	+	++	*(Cucinotta et al., 2001)* *(Minamoto et al., 2004)* *(Worgul et al., 2007)* *(Jacob et al., 2012)* *(Smith et al., 2012)* *(Azizova et al., 2018)*
Myopia	++	0	+	*(Brown and Hill, 1987)* *(Lim et al., 1999)* *(Younan et al., 2002)*
Ocular inflammation (e.g. Uveitis)	+	+	++	*(Hooper et al., 1990)* *(Chen et al., 2008)*
Solar UV radiation	++	++	+	*(Modenese and Gobba, 2018)*
Steroids (glucocorticoids)	0	0	++	*(James, 2007)*

The predominant treatment for cataracts involves the surgical excision of the affected lens, followed by the implantation of an intraocular lens (IOL) (Donthineni et al., 2023, Cicinelli et al., 2023). Nevertheless, there are frequent delays in both diagnosis and treatment, particularly in low-resource settings (Zhu et al., 2016, Xu et al., 2018). These delays highlight the necessity of examining the impact of cataracts on motion perception and daily activities, as investigated through behavioural experiments and a case study.

The clinical information presented in this section serves as a basis for understanding the impact of cataracts on visual function. The survey will collect subjective data regarding patients' experiences with cataracts. The behavioural experiments will focus on the influence of cataracts on motion perception, which is essential for effective navigation and interaction with one's surroundings, while the case study will offer a comprehensive examination of individual responses to the progression of cataracts. Collectively, these elements seek to connect clinical findings with real-world perceptual challenges faced by cataract patients.

1.3 Motion Perception

Successful performance of several tasks in our daily life relies on our ability to accurately perceive diverse types of motion (Arena et al., 2012). This necessitates multiple, simultaneous computations across a few different levels in the visual pathway. The visual system achieves this by analysing rapidly changing visual information that falls on the retina and compares that signal to knowledge about eye movements and motion of the self (Hutchinson et al., 2012).

In general terms, moving objects and figures in our world are thought to largely be processed by specialised cells in the retina contributing to the magnocellular (M) pathway (Ward et al., 2018). These cells can prioritise dynamic (moving) information, in order to process speed, direction and other characteristics of moving objects independently to spatial information such as form (Snowden and Kavanagh, 2006, Ward et al., 2018). The signal is then passed on to specialised areas in the brain, such as V5/MT+ (Ajina et al., 2015, Rees et al., 2000), V3A (Tootell et al., 1997, Koyama et al., 2005), V6 (Helfrich et al., 2013) and STS (Braddick et al., 2000). However, as discussed above, some of this processing ability will decline as part of the normal ageing process (Bennett et al., 2007b, Yang et al., 2009a), and research suggests that deficits in motion detection associated with ageing are likely related to degenerative changes in the visual pathway rather than to optical changes in the anterior segment of the eye like cataract and corneal opacity (Andersen, 2012).

As this thesis aims to quantify the extent of any motion deficits in cataract patients, it is important to first look at these potential deficits associated with ageing for specific aspects of motion processing e.g., direction, speed, visual field location, local and global motion, and complexity.

1.3.1 Direction and Speed Discrimination

One of the most fundamental elements of successful motion perception is the ability to identify and discriminate the direction and speed of a moving stimulus. Research indicates that motion-sensitive regions of the brain in non-human primates exhibit a phenomenon known as "tuning," wherein individual neurons demonstrate a preference for specific directions and speeds (Maunsell and Van Essen, 1983, Priebe et al., 2003). This tuning is believed to be analogous in humans. However, empirical evidence suggests that the abilities to discriminate direction and speed are subject to various perceptual biases. For instance, individuals tend to exhibit heightened sensitivity to direction when stimuli are presented monocularly in two-dimensional contexts, as opposed to binocularly in three-dimensional settings, irrespective of the speed of the stimuli (Cooper et al., 2016). Additionally, humans are generally more sensitive to horizontal motion compared to vertical motion (Fahle and Wehrhahn, 1991). Importantly, behavioural studies indicate that individuals are more attuned to planar (local) directions in comparison to more complex global directions (Beardsley and Vaina, 2005).

At the cortical level, humans demonstrate a preference for foveofugal motion (motion away from the point of fixation) in comparison to foveopetal motion (motion toward the point of fixation). This preference is believed to be linked to perceptual mechanisms that are necessary for understanding self-motion within one's environment (Fahle and Wehrhahn, 1991, Holliday and Meese, 2008). Nevertheless, behavioural studies indicate that within the range of 5° to 12° eccentricity along the horizontal meridian, individuals show marginally lower motion coherence thresholds for foveopetal motion, suggesting an enhanced sensitivity to motion directed toward fixation in this specific range (Raymond, 1994). Similarly, humans display an increased sensitivity to speed gradients (Grzywacz and Merwine, 2003); however, the cortical processing of speed, along with the associated perceptual experience, may be influenced by factors such as spatial frequency (Chen et al., 1998, Vintch and Gardner, 2014) and the contrast of the visual stimulus (Thompson et al., 2006, Vintch and Gardner, 2014).

Research has established a significant correlation between neuronal activity in the V5/MT + region and speed discrimination in macaques, an animal model closely resembling humans (Yang et al., 2009b). This evidence implies that analogous mechanisms may be involved in speed processing in humans. For example, investigations using functional magnetic resonance imaging (fMRI) in adult human subjects have revealed increased activation in the MT subdivision of V5/MT+ during speed discrimination tasks, in contrast to other visual tasks such as contrast discrimination (Huk and Heeger, 2000). Additionally, positron emission tomography (PET) studies have indicated heightened neural activity in the mid-temporal region when attention is directed towards speed as opposed to shape or colour (Corbetta et al., 1991). Collectively, these findings reinforce the notion that the V5/MT+ region is integral to the processing of speed-related information.

Nonetheless, despite the prevailing consistency of these findings, there exist significant discrepancies within the literature concerning the specific characteristics of speed processing in the human brain. For example:

1. **Variability in Experimental Conditions:** Research indicates that perceptual biases in speed discrimination demonstrate considerable variability influenced by several factors, including the type of stimulus (e.g., planar versus global motion), eccentricity (the distance from the fovea), and the degree of attention given to the task (Cooper et al., 2016, Grzywacz and Merwine, 2003). These variations emphasise the complexity nature of motion perception and underscore the necessity for meticulous experimental design to adequately address these variables.
2. **Influence of Contrast and Spatial Frequency on Cortical Processing of Speed:** Experimental studies have demonstrated that the cortical processing of speed is affected by both the spatial frequency and contrast of visual stimuli (Chen et al., 1998, Vintch and Gardner, 2014, Thompson et al., 2006). Specifically, stimuli with lower contrast may result in an underestimation of speed, whereas higher spatial frequencies can lead to unpredictable biases

in speed perception. If these variables are not properly controlled, they may contribute to variability in experimental outcomes.

3. **Variability in Neural Responses Among Individuals:** The V5/MT+ region is extensively recognised for its role in the processing of speed; however, individual differences in neural responses—such as variations in baseline activity or connectivity within this region—may account for the inconsistent results observed across various studies. For example, older adults and individuals with visual impairments, including those with cataracts, may demonstrate modified activity patterns in the V5/MT+ area, which could subsequently influence their capacity to accurately process speed (Huk and Heeger, 2000).

These inconsistencies highlight the critical need for careful experimental design in studies of motion perception, particularly in populations with visual impairments such as cataracts. For example, if cataracts reduce retinal illumination or contrast sensitivity, this may distort speed discrimination performance and complicate the interpretation of the results. To achieve reliable outcomes, it is essential for researchers to consider variables such as stimulus contrast, spatial frequency, and attentional capacity. By addressing these factors, researchers can ascertain that any observed deficits in motion perception are authentically associated with the condition being studied (e.g., cataracts) rather than being confounded by extraneous influences.

Motion perception is a fundamental component of visual processing, and understanding how it evolves with age is essential for evaluating the impact of visual impairments like cataracts. Several studies have demonstrated that ageing exerts a significant influence on motion perception. For example, research indicates that as individuals age, the thresholds for motion direction coherence tend to increase (Trick and Silverman, 1991, Gilmore et al., 1992, Andersen and Atchley, 1995, Bennett et al., 2007b, Conlon and Herkes, 2008, Billino et al., 2008, Bower and Andersen, 2012) (see Figure 1.11). Additionally, sensitivity to speed discrimination reduces (Snowden and Kavanagh, 2006), and there is a noted decrease in the preferred speed of neurons within the brain, which subsequently reduces sensitivity to higher speeds (Yang et al., 2009a). Trick and Silverman (1991) estimated a decline in motion direction sensitivity of approximately 1.4% per decade, suggesting that an individual in their 80s may show a 1.4% greater deficit in directional discrimination compared to a person a decade younger. Furthermore, evidence suggests that ageing adversely affects the capacity to differentiate between two similar directions, although training interventions may alleviate some of these age-related effects (Ball and Sekuler, 1986).

In a key study, Arena et al. (2012) examined the effects of ageing on motion coherence thresholds under varying speed conditions. Their results, illustrated in Figure 1.11, indicate that motion coherence thresholds tend to increase with age, especially at higher speeds. This age-related reduction in motion sensitivity serves as a reference point for evaluating the performance of individuals with cataracts, who may experience further impairments in motion perception due to reduced retinal illumination and contrast sensitivity (Arena et al., 2012). By assessing motion coherence thresholds in healthy individuals across different age cohorts, Arena et al. (2012) established a foundation for understanding the impact of normal ageing on motion perception. This is particularly significant to the current research, which aims to determine whether cataracts worsen these age-related declines, specifically in dynamic visual tasks.

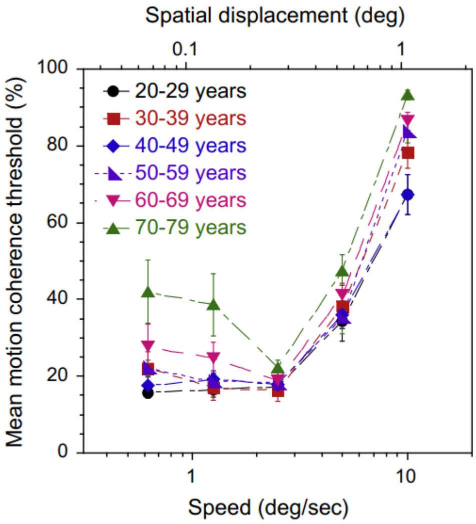


Figure 1.11. The figure presents the mean motion coherence thresholds for various age groups in relation to stimulus speed. Specifically, it explains the correlation between mean motion coherence thresholds and stimulus speed across distinct age categories, namely 20–29 years, 30–39 years, 40–49 years, 50–59 years, 60–69 years, and 70–79 years. The data indicate a progressive increase in motion coherence thresholds with advancing age, which is influenced by the speed of the stimulus. A comprehensive understanding of these baseline trends is essential for assessing the potential exacerbation of motion perception deficits in older adults due to visual impairments, such as cataracts. Adapted from Arena et al. (2012).

Nevertheless, not all research findings demonstrate uniform effects of ageing on motion perception. Some studies indicate that older adults maintain sensitivity to low spatial and temporal frequencies, as well as to movement coherence thresholds at medium and high velocities (He et al., 2020b, Snowden and Kavanagh, 2006). For example, older individuals typically exhibit poorer performance primarily at slow speeds (less than 1°/s) (Snowden and Kavanagh, 2006), suggesting that higher velocities may be necessary for the reliable identification of the direction of moving objects (Allen et al., 2010). These inconsistencies highlight the necessity of standardising methodologies across research to ensure the reliability and comparability of findings (Brown and Bowman, 1987, Mapstone et al., 2008, Kavcic et al., 2011).

Importantly, in addition to the impact of healthy ageing on veridical motion perception, there have been mixed reports showing that features such as contrast sensitivity and blur can affect speed perception (Thompson, 1982, Stone and Thompson, 1992, Ascher and Grzywacz, 2000, Anstis, 2004, Thompson et al., 2006, Pretto et al., 2012, Leibowitz et al., 1972). For example, when contrast is reduced across the entire visual field, speed of external objects appears to be increased, making them appear to be moving faster than they are (Anstis, 2004, Thompson et al., 2006). Similarly, studies simulating the ‘reduced distance contrast’ perceived during foggy weather conditions found that this led to overestimation of personal speed, leading to slower driving speed (Pretto et al., 2012), clearly demonstrating that perception of speed can lead to behavioural modifications. In addition to this, blurring of a stimulus/object has been shown to decrease motion sensitivity, particularly in the peripheral visual field (Leibowitz et al., 1972). Taken together, these data suggest that an individual with either reduced contrast sensitivity or increased blur would potentially perceive motion inaccurately, and that it could lead to behavioural compensation (e.g., modified driving speed). A population of people who fit these criteria are those who have acquired age-related cataracts, so if indeed a reduction in contrast and an increase in blur can affect motion perception, then it will be important to measure the extent of this across the different types of cataracts.

1.3.2 Central (foveal) vs Peripheral Motion Processing

Motion processing ability varies depending on where the presented stimulus falls in the visual field, and its corresponding retinal location, more specifically, whether it is formed on the central or peripheral retina. For example, the central retina (fovea) has a much lower lever of neural convergence (one summation of cones to ganglion cells), leading to low sensitivity to stimuli, however very high detail vision (Masland, 2017). On the other hand, the peripheral retina involves much more retinal space and shows high neural convergence (many photoreceptors feed into one ganglion cell) which leads to high sensitivity but lower density of ganglion cells, which results in poor detail vision (Solomon et al., 2002, Sinha et al., 2017). This means that although it is difficult to do tasks requiring high spatial resolution (e.g., reading) in the peripheral visual field, it is still possible to detect and discriminate motion directions and speeds (Masland, 2017, Solomon et al., 2002).

In a typical observer, contrast sensitivity can be measured by plotting a contrast sensitivity function (CSF) where contrast threshold is plotted for various spatial frequencies. There is a plethora of evidence suggesting that if tested peripherally, the shape of the CSF will appear identical to that of centrally presented stimuli, but the entire function will be shifted towards lower spatial frequencies (Koenderink et al., 1978, Kelly, 1984, Johnston, 1987), providing the stimulus is scaled to account for the reduced acuity and larger receptive fields in the peripheral retina. A research by Thibos et al. (1996) has suggested the potential presence of a subtle alteration in the shape of the function at the higher range of spatial frequencies (Thibos et al., 1996). While there are variations in the precise configuration of the function, there is agreement that presenting stimuli peripherally results in a decrease in contrast sensitivity, as illustrated in Figure 1.12.

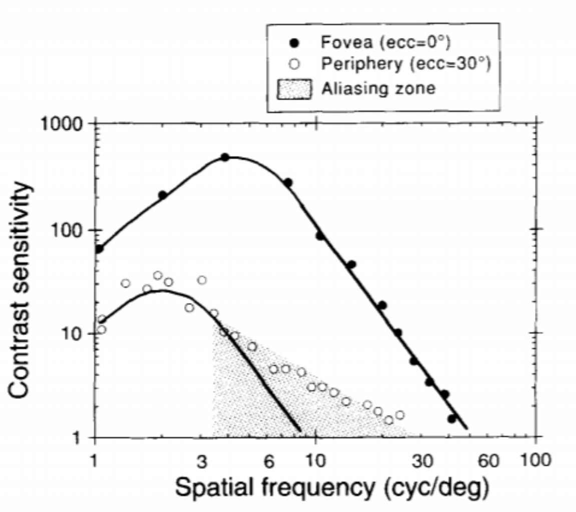


Figure 1.12. Comparison of CSFs for grating detection in central (closed symbols) and peripheral (open symbols) visual fields. The shaded area shows the portion of the peripheral CSF not accounted for by the shape of the central CSF from (Thibos et al., 1996).

It has also been suggested that motion detection is greater in the temporal visual field than the nasal visual field (Fahle and Wehrhahn, 1991) consistent across the left and right hemifields, however the stimuli used for this experiment were considered to be low-level and therefore the same cannot necessarily be assumed for higher-order stimuli.

In terms of the impact of ageing, Wojciechowski, Trick and Steinman (1995) investigated motion coherence thresholds for fast (28°/s) random dot kinematograms (RDKs) moving in one of the four cardinal directions (up, down, left, right) at five positions across the visual field (central, 18° superior, 18° inferior, 18° nasal, 18° temporal). They found that ageing significantly impacts the thresholds at all five locations, with the greatest elevation when stimuli are presented centrally, and least elevation when stimuli are presented superiorly. Importantly, they also compared their results to that of perimetry at the same retinal locations and concluded that global motion tests (e.g., RDKs) may be more sensitive at detecting deficiencies than standard perimetry measures. Other research looking into the impact of field loss on optic-flow stimuli associated with moving through space, found that loss in either the central or peripheral visual field will have an effect on the patient's ability to safely navigate and move throughout the world (Turano et al., 2005). There is also evidence to suggest that older individuals have a deteriorated ability to localise moving objects in the peripheral field (Blake et al., 2008, Andersen and Ni, 2008, Allen et al., 2010).

It is therefore clear that healthy ageing can impact vision throughout the entire visual field, up to a visual angle of at least 18°. The extent of impairment may differ based on the nature and position of the stimulus. Additionally, the level of blurriness and the ability to perceive contrast decrease as a stimulus moves away from the fovea, which can also impact motion perception. Furthermore, as will be investigated in a subsequent section, cataracts can potentially influence various regions within the visual field, underscoring the significance of assessing motion perception capabilities across the entire visual field.

1.3.3 Local vs Global Motion Processing

Local motion can be defined as the motion signal at a specific location in the visual field. For a stimulus to be considered a "local" motion stimulus, the motion signal must be discriminable from any single point of the stimulus. In contrast, global motion can be defined as a collection of different local motion elements from a stimulus that can only be accurately perceived when the entire stimulus, such as a flock of birds, is detected (Hutchinson et al., 2012, Furlan and Smith, 2016a). In research laboratories, global motion is often artificially generated using RDKs (Hutchinson et al., 2012).

Figure 1.13 illustrates the distinction between local and global motion. The left panel shows uni-directional motion over a limited distance, with each individual dot reveals the direction of the stimulus (e.g., upwards). Such type of motion is characteristic of local motion, as the direction can be detected from a single point. Conversely, the right panel shows global pattern motion across the entire display, wherein the overall radial direction cannot be detected from a single dot, rather requires integration of the entire stimulus. This serves as an example of global motion, which arises from the collective movement of numerous local elements.

It is important to note that the left panel demonstrates uni-directional local motion, whereas the right panel illustrates the emergence of global motion through the interaction of various local components. Additionally, both panels incorporate variations in vector lengths to signify differences in speed, which may affect the perception of motion coherence and sensitivity. These variations are intentional and reflect the complexity of real-world motion stimuli, where speed changes can occur naturally.

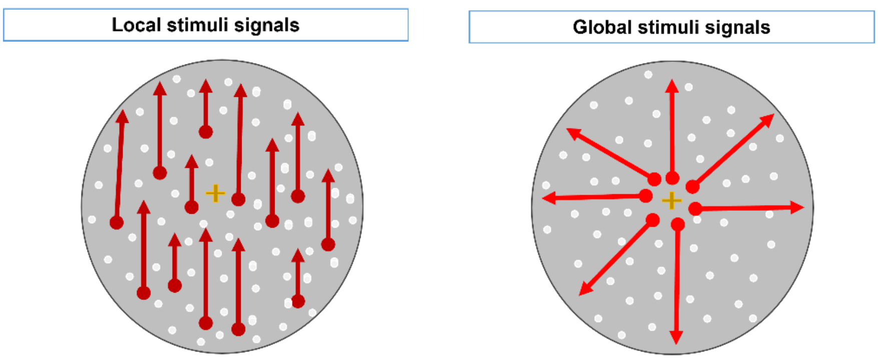


Figure 1.13. Distinction between local and global motion. This figure illustrates the difference between local and global motion by comparing two types of stimuli. The left panel shows **uni-directional motion over a small distance**, where each individual dot reveals the direction of the stimulus (e.g., upwards). This represents **local motion**, as the direction can be discerned from a single point. The right panel shows **global pattern motion across the entire display**, where the overall radial direction cannot be interpreted from a single dot but requires integration of the entire stimulus. This demonstrates **global motion**, which emerges from the collective movement of multiple local elements. Vector lengths in both panels vary to represent differences in speed, reflecting the complexity of real-world motion stimuli.

In general terms, humans and primates are thought to be very sensitive to global motion signals, as it only requires the occurrence of less than 5% of local motion elements to move in a specific direction to detect the presence of the global motion (Hutchinson et al., 2012). This increased sensitivity is likely due to the neural processing mechanisms within the human brain, which demonstrate increasing specialisation for global motion in higher cortical areas. For example, the medial superior temporal area (MST), a subdivision of V5/MT+, is particularly tuned for global motion processing (Duffy and Wurtz, 1991, Grossberg et al., 1999, Smith et al., 2006, Furlan and Smith, 2016b). However, the simultaneous occurrence of local and global motion in natural environments presents a significant challenge for the brain to differentiate between these signals. Consequently, the ability to flexibly shift attention between local and global motion is considered a critical component of effective motion processing (Bulakowski et al., 2007).

This attentional flexibility can be analytically assessed through psychophysical experiments, such as RDKs, in which participants observe moving dots that include both coherent (global) and random (local) motion elements. By manipulating the ratio of coherently moving dots, researchers can determine thresholds for global motion detection and evaluate the impact of attention on performance (Newsome and Pare, 1988, Braddick et al., 2000). Additionally, attentional cueing paradigms can be employed, where participants are instructed to focus either on local motion details or on the overall global motion pattern. Cues prompting shifts in attention allow researchers to evaluate the efficiency of attentional switching (Bulakowski et al., 2007, Pascolini and Mariotti, 2012). Dual-task designs, which require simultaneous processing of local and global motion, further elucidate how cognitive resources are allocated (Greenwood et al., 2017). Neuroimaging techniques, including functional magnetic resonance imaging (fMRI) and electroencephalography (EEG), can also be employed to investigate brain activity in regions such as V5/MT+ and MST during these tasks, thereby enhancing the understanding of the neural mechanisms that underpin attentional flexibility (Smith et al., 2006, Furlan and Smith, 2016b). These research methodologies not only elucidate the motion processing capabilities of healthy individuals but also establish a framework for exploring potential deficits in populations with visual impairments, such as those affected by cataracts (Hutchinson et al., 2012, Snowden and Kavanagh, 2006).

The effect of age on the processing of global movements has been studied in detail using RDK patterns. For example, Hutchinson and colleagues (2012) conducted a comprehensive examination of psychophysical data relating to age-related declines in global movements. Their findings suggest that impairments in global movements are prevalent in specific stimulus contexts. Specifically, ageing seems to impair the processing of translational movements (Ball and Sekuler, 1986, Trick and Silverman, 1991, Wojciechowski et al., 1995, Billino et al., 2008), with the extent of this deficit varying between 2% and 13.5% based on reported values. There also appears to be an additional deficit in observers with Alzheimer’s disease (Trick and Silverman, 1991), demonstrating that cognitive decline can affect global movement processing. However, Snowden and Kavanagh (2006) report that the speed of the dots presented appears to play a role in the results, with slow dot speeds (< 1°/s) highlighting an age-related deficit, but no evidence of a deficit was found at speeds of 1-4°/s. However, at high point velocities (between 6-22°/s), the evidence seems more convincing that an age-related deficit occurs (Atchley and Andersen, 1998b, Ball and Sekuler, 1986, Trick and Silverman, 1991, Wojciechowski et al., 1995, Billino et al., 2008), suggesting that velocity tuning may become narrower with age. Allen et al., (2010) also found that visibility and contrast can influence the detectability of a deficit, with high-contrast, fast-moving dots resulting in equivalent performance between young and older observers, yet, older observers exhibited higher movement thresholds when contrast was reduced.

Interestingly, the relationship between age and motion perception has been found to show notable gender differences. For example, Gilmore et al. (1992) observed that older women experienced a more significant increase in motion coherence thresholds than their male counterparts, suggesting that gender may play a significantly influence the impact of ageing on visual processing. A thorough understanding of the interactions between age, gender, and visual impairments like cataracts is vital for the development of targeted interventions aimed at improving outcomes for diverse patient groups.

Overall, the deterioration of ocular structures and functions, alongside the development of ocular pathologies such as presbyopia, senile miosis, and cataract, can collectively lead to a reduced quality of the focused retinal image and degradation of the optical signal, however the effect of these changes are not sufficient to explain the full extent of the global motion deficits (Hutchinson et al., 2012, Allen et al., 2010).

1.3.4 Other Factors Affecting Perception

Whilst it is true that the sensory input is required for perception to take place, there are several 'top-down' processes that also influence perceptual experience. Some of these are outlined below.

1.3.4.1 Attention and Memory

To clearly notice a stimulus, individuals need to focus their attention on it; otherwise, they might miss or ignore significant details (Mack, 2003). This requires the ability to maintain attention for long durations, such as during reading, as well as the skill to quickly redirect attention when a new stimulus appears. Research shows that as people age, the range of their attention may decrease, possibly due to a decline in working memory capacity (Lawrence et al., 2018). This reduction could result in less efficient processing of visual information and an increase in perceptual mistakes. Although these observations have mainly been made in controlled lab settings (Hedden and Gabrieli, 2004, Mattay et al., 2006), it is suggested that they may have implications for individuals' experiences in real-world settings.

In 1950, no nation had a population exceeding 11% of individuals aged 65 years and above (Norman, 2020). By contrast, in the year 2000, the maximum proportion reached 18%. Nevertheless, projections indicate a substantial escalation in this demographic trend by 2050, with estimates suggesting that it may surge to 38% (Norman, 2020). It is expected that by the year 2050, the global population is expected to exceed the population of adolescents with estimates indicating that there will be 2.1 billion older individuals aged 60 years and above compared to 2.0 billion adolescents aged 10 to 24 years (Rudnicka et al., 2020). This significant increase in the ageing demographic raises concerns about their cognitive abilities, as research indicates that around half of individuals aged 85 years and older are likely to develop Alzheimer's disease (Hebert et al., 2003). This underscores the decline in behavioural and cognitive functions associated with ageing, which has been linked to various structural changes in the brain (Park and Reuter-Lorenz, 2009, Park and Schwarz, 2001). These changes include a reduction in dopaminergic cell count (Li et al., 2001), diminished brain volume (Raz et al., 2005), decreased white matter density (Resnick et al., 2003, Good et al., 2001) and an increase in neurofibrillary plaques and masses (Park and Reuter-Lorenz, 2009). Nevertheless, the brain is a dynamic organ and can adapt to some extent by using a process known as 'scaffolding', which involves modifying cortical functions through strengthening existing connections, forming new connections, and discontinuing use of old or weak connections (Park and Reuter-Lorenz, 2009). These alterations in brain function may have implications for individuals' perceptual experiences.

In general, the ageing process has been linked to a decrease in various cognitive functions such as processing speed (Salthouse, 2000), working memory processing and capacity, inhibition, and long-term memory, as shown in Figure 1.14 (Park and Reuter-Lorenz, 2009).

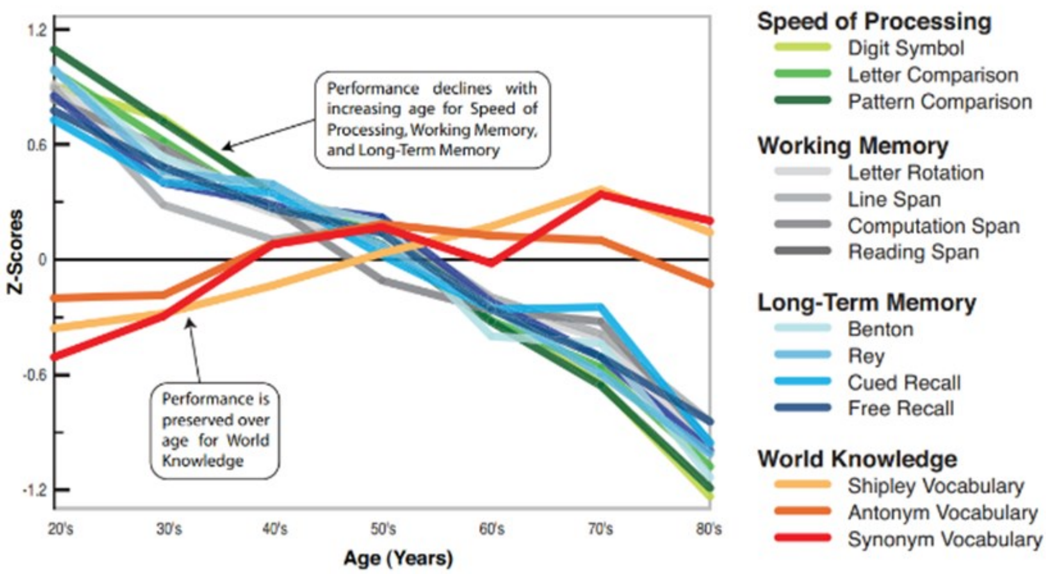


Figure 1.14. Line plot showing tasks that decline with age (speed of processing, working memory, long-term memory) relative to those that improve (world knowledge) from (Park and Reuter-Lorenz, 2009).

Figure 1.14 presents a summary of a research study that examined participants aged between 20 and 89 years. The study involved a series of assessments, which included three tests designed to measure processing speed, two tests focused on visuospatial working memory, and two tests aimed at evaluating verbal working memory. Furthermore, participants were required to complete assessments for both verbal and visuospatial recall, in addition to three separate vocabulary trials (Park and Festini, 2017, Park and Reuter-Lorenz, 2009). The results of the study reveal a significant correlation between ageing and the deterioration of various critical cognitive functions (Park and Reuter-Lorenz, 2009). The observed decline in working memory function, characterised as the short-term memory and active processing of information, is believed to be linked to a decrease in decision-making control processes, commonly referred to as inhibitory functions. This reduction in inhibitory functions adversely impacts the ability to effectively select relevant information during specific working memory tasks (Park and Reuter-Lorenz, 2009).

Overall, this indicates that decreased attentional, memory, and inhibitory functions may significantly inhibit perceptual abilities in older individuals. However, studies indicate that the most pronounced impacts of age-related decline in memory and attention are observed in challenging tasks rather than simple ones (Reuter-Lorenz and Lustig, 2005). It is plausible that cognitive training could leverage neural compensation to mitigate some extent of this decline (Zanto and Gazzaley, 2014).

1.3.5 Can Motion Perception Actually Improve with Age?

Age-related visual impairments can possess neurological or optical origins and can be classified as ranging from mild to severe. The visual impairments associated with optical factors are often due to the reduction in the clarity of the optical media, which is commonly caused by presence of a cataract, whereas visual impairments associated with neurological factors mostly appear as a consequence of deterioration in physiological function and the knock-on effects on higher cortical areas (Betts et al., 2005).

Some alterations associated with ageing may lead to unintended enhancements in performance for certain tasks. For instance, Betts et al. (2005) examined the concept of 'spatial suppression', which suggests that as a stimulus enlarges, distinguishing its motion becomes more challenging. However, Betts et al. observed that performance improves with age, as older individuals require shorter stimulus presentations to make accurate decisions. The researchers suggest that this phenomenon may be attributed to reduced centre-surround suppression in older individuals, potentially stemming from alterations in brain chemistry.

Consistent with the literature cited above, research has demonstrated that perceptual training, as outlined by Adini et al. (2002), has been shown to have an enhanced impact on certain tasks including location identification, orientation discrimination, motion perception, depth perception, spatial phase, hyper-acuity, and texture segmentation. This suggests that the decline associated with ageing may be delayed or mitigated if individuals engage in regular practice. Investigations into perceptual learning have demonstrated that the effects of training are frequently highly specific to the attributes of the stimuli involved (Chung et al., 2004). Enhancements in fundamental stimuli through perceptual learning can lead to improved outcomes on standardised vision assessments, as well as advancements in practical vision applications, including enhanced reading abilities and athletic performance (Deveau and Seitz, 2014, Deveau et al., 2014). While this may be preventable from a neurological standpoint, it may not be entirely preventable through medical intervention in the context of age-related ocular and systemic diseases.

1.3.6 How Does Ageing Impact Motion Processing?

Evidence suggests ageing can have a detrimental effect on several aspects of motion processing, however it is still important to discuss why this might occur. Previous studies have provided three possible explanations for deteriorated motion perception in an elderly population: neuroanatomical, neurophysiological and psychophysical.

1.3.6.1 Neuroanatomical

The human visual system extracts and decodes visual information from two parallel streams or pathways; the ventral and dorsal processing streams which derive from the parvocellular (P) and magnocellular (M) cell pathways, respectively. Importantly, there are connections between both visual pathways; they are not segregated (Kristensen et al., 2016, Ward et al., 2018)

The human visual area MT, a sub-division of V5/MT+, is intricately engaged in the cortical processing of speed-related information, representing a crucial cortical region within the magnocellular pathway in humans (Carther-Krone and Marotta, 2022, Huff et al., 2018). A substantial number of neurons within the V5/MT+ region are specifically attuned to the speed of a moving visual stimulus (Giaschi et al., 2007, Chawla et al., 1999), and are believed to directly contribute to the perception of visual speed (Kawakami et al., 2002, Laycock et al., 2007). Injuries to the head, especially to the MT area have a negative impact on the ability to perform tasks involving speed discrimination and pursuit (Greenlee and Smith, 1997, Barton et al., 1996b, Hunfalvay et al., 2021, Cooper et al., 2012). Also advancing age may deteriorate and damage the M pathway, for example, data from a study by Trick and Silverman, (1991) suggested that there might be a predictable deterioration in motion sensitivity by approximately 1.4% each decade of advancing life. The authors concluded that this is due to neurodegeneration of the primary visual pathway, probably the M pathway, which arises as part of the natural ageing process. Neuroimaging studies have demonstrated that the activity of the human area V5/MT+ in the typical brain is significantly elevated during tasks involving speed discrimination compared to other visual discrimination tasks (Corbetta et al., 1991, Huk and Heeger, 2000, Beauchamp et al., 1997). It has been documented that the relationship between neural activity and the ability to discern speed can be anticipated based on the speed-tuning characteristics of V5/MT+ cells (Liu and Newsome, 2005). Prior research also indicates that the speed sensitivity of V5/MT+ neurons could potentially be utilised to produce acceleration sensitivity for the subsegment phases of visual motion processing (Price et al., 2005, Schlack et al., 2007). The visual system may utilise V5/MT+ neurons that are specialised in detecting speed to carry out intricate motion processing tasks, including self-motion and depth perception (Perrone and Stone, 1994, Perrone and Thiele, 2002). Given the preceding information, it is apparent that any dysfunction of speed-selective neurons in the V5/MT+ area has the potential to negatively impact the perception of speed. Therefore, it is tempting to suggest that the reduced ability of older adults to perceive speed could be linked to the deterioration or dysfunction of the V5/MT+ region in the human brain.

1.3.6.2 Neurophysiological

Most research investigating age-related neurophysiological changes have been done on animal models. Data from non-human primates have identified that ageing is associated with a decrease in the number of myelinated fibres and neuronal synapses that consequently will attenuate the rate of neural signals (Peters et al., 2001a, Peters et al., 2001b). Whilst unsurprising, this finding has been linked to increased latencies and delayed information transfer in V1 (Wang et al., 2005). There is also evidence that ageing contributes to overall loss of volume in V1 (Yu et al., 2006), along with increased neural noise, and increased spontaneous excitability in both V1 and extrastriate areas (Fu et al., 2013, Yang et al., 2009a, Yu et al., 2006, Zhang et al., 2008). Overall, these findings can conclude that visual deficits associated with ageing are likely due to this extensive neurophysiological degeneration (Billino et al., 2008).

1.3.6.3 Psychophysical

Psychophysical studies have investigated the contribution of the ageing process to direction discrimination, and speed and direction of dynamic objects (Yang et al., 2009a, Gilmore et al., 1992, Billino et al., 2008, Mapstone et al., 2008). Three psychophysical theories attempt to explain these reductions in visual performance: (1) additive neural noise, (2) multiplicative neural noise and (3) reduced tolerance to exterior noise (Lu and Dosher, 1998, Lu and Dosher, 1999).

To better understand these theories, it is important to first consider signal detection theory. The signal detection theory forms a beneficial exemplar for highlighting certain factors that might affect motion perception, particularly relating to direction discrimination. The theory presumes that within our visual system there is a randomly fluctuating level of background neural activity (‘noise’), which means in order to detect the presence of a stimulus, this internal neural noise must not exceed the neural signals triggered for stimulus detection (‘signal’). As age progresses this internal neural noise also increases as a result of impairment in cortical inhibition which is referred to as “additive neural noise” (Bower and Andersen, 2012). This additive neural noise can lead to deterioration in global motion discrimination (Bower and Andersen, 2012).

A second factor that impacts the effectiveness of visual perception is “multiplicative neural noise”. This factor is a valuable concept for elucidating phenomena that exhibit patterns consistent with the principles outlined in Weber's law (s = Δ /I) (Lu and Dosher, 1998, Lu and Dosher, 1999, Schwartz, 2006). This indicates that the nature of noise is defined by its amplitude being directly impacted by the intensity of the input signal, i.e. the stronger the neural noise the more signal strength the individual needs to distinguish the signal from the noise (Lu and Dosher, 1998, Lu and Dosher, 1999). As previously noted, research has suggested that internal noise may contribute to declines in motion perception among older individuals, although the differentiation between additive and multiplicative noise remains ambiguous.

A final explanation for motion perception is the reduced tolerance to the exterior noise volume. The observer’s neural system will learn (through experience) to extract and split the significant data from unimportant data (Lu and Dosher, 1998, Lu and Dosher, 1999). This is apparent when older observers take part in experiments with noise embedded within the visual stimuli (Lu and Dosher, 1998, Lu and Dosher, 1999). The ageing visual system has reduced perception to the external noise and when the examiners reduce the noise signal during the experiments the older observers struggle to distinguish the signal from the noise (Bennett et al., 2007b, Andersen and Atchley, 1995, Gilmore et al., 1992). Yet neurophysiologically, increasing age also increases neural noise intensities and leads to a decline in directional adaptation of neurons in the V1, to such an extent that the thresholds for motion and direction discrimination rises with age (Hua et al., 2006).

In brief, the perception of motion in individuals as they age can be influenced by a combination of neurological and ocular factors, with neurological factors being the primary contributor to the decline. Therefore, if research indicates that individuals with cataracts experience more pronounced deficits in motion processing compared to their age-matched counterparts, it is probable that the cataract itself is the main influencing factor rather than other potential variables.

1.4 Measuring Perception

Broadly speaking, perception is characterised by the Longman Dictionary of Contemporary English as: “(a) an individual's cognitive understanding and conception of something; (b) the process of observing and detecting stimuli through the senses of sight, hearing, etc.; (c) the innate capacity to swiftly comprehend or discern things.” (Dictionary, 2024). This suggests that perception involves not only the physical act of visual observation, but also the ability to understand and interpret visual information. Consequently, perception is inherently subjective, presenting difficulties in achieving objective quantification.

1.4.1 Measuring Visual Acuity

Visual acuity (VA) refers to the ability of the visual system to resolve spatial details specifically high spatial frequencies (De Valois and De Valois, 1980, Jackson and Bailey, 2004). It measures an individual's ability to perceive and distinguish a target of a specific size at a given distance. This parameter is essential for evaluating the clarity of vision in individuals (Bailey and Lovie-Kitchin, 2013, Bhootra, 2019). The assessment of human visual performance requires an understanding of the limitations of the visual system, including its ability to differentiate specific elements or accurately recognise particular objects (Jackson and Bailey, 2004, Manzano and Lagamayo, 2015, Kaido, 2018).

As the visual acuity expresses the angular size of the smallest target that can be just recognised by the observer, there are many ways to express and quantify this angular size (De Valois and De Valois, 1980, Holladay, 2004, Bailey and Lovie-Kitchin, 2013, Manzano and Lagamayo, 2015). The most common ways are the: Snellen fraction, decimal notation, minimum angle of resolution, logarithm of the minimum angle of resolution (logMAR), visual acuity rating (VAR) and visual efficiency (Kaido, 2018, Myers et al., 1999, Bailey and Lovie-Kitchin, 2013).

Whether visual acuity is undertaken for research or habitual clinical examination it will follow a specific procedure (Bailey and Lovie-Kitchin, 2013), and will be measured performed both monocularly and binocularly (Bhootra, 2019). If using a Bailey-Lovie / ETDRS chart, visual acuity is recorded in logMAR and is recorded as an improvement of -0.20 logMAR for every complete line of five letters read correctly. This test is usually performed under good illumination conditions.

However, due to the fact that the cataract varies in its morphology and degree among individuals, the evaluation of a cataract patient's visual incapacity is therefore a complex task and cannot be based simply on VA testing nor on the objective measurement of the amount of cataract (Brown, 1993).

1.4.2 Measuring Contrast Sensitivity

Visual acuity testing is commonly used as a clinical benchmark for various eye assessments and in several occupational eligibility requirements. However, it is important to note that VA testing alone does not offer a comprehensive assessment of an individual's visual perception(Spear, 1993, Owsley, 2011, Roark and Stringham, 2019, Shandiz et al., 2011). While VA testing provides information on high spatial frequencies, it does not encompass the full spectrum of visual patterns, particularly excluding low spatial frequencies (Elliott et al., 1996, Myers et al., 1999, Carkeet, 2001, Roark and Stringham, 2019, Shandiz et al., 2011).

Research has shown that VA as good as 0.00 logMAR does not necessarily indicate that a cataract patient is able to see clearly (Elliott and Situ, 1998, NCBI, 2017). For example, the patient may still experience glare and reduced contrast sensitivity. This has led to the suggestion that measures of contrast sensitivity and glare could be a more appropriate way of evaluating these patients' vision as opposed to VA (Elliott et al., 1996). However, other studies have shown that in patients with mild cataracts, contrast sensitivity is only reduced for high spatial frequencies in nuclear cataracts, suggesting that VA is just as useful for mild cataracts (Chylack Jr et al., 1993).

Contrast sensitivity can be measured clinically using a Pelli-Robson chart (see Figure 1.15). The fundamental principle underlying this chart is that the letters decrease in contrast progressively as one moves downward through the chart, with the letters organised in triplets. Each letter within a triplet maintains a consistent contrast level, while the contrast reduces by a predetermined amount of 0.15 log units for each subsequent triplet. The patient is positioned at a standardised distance of 100 cm (3 meters) from the chart, which enables the evaluation of contrast sensitivity at a spatial frequency of approximately 1.5 cycles per degree (cpd). This mid-range spatial frequency is particularly relevant for routine visual tasks, such as face recognition and reading signs. The significance of this spatial frequency range lies in its ability to reflect the capacity to recognise objects with moderate detail across varying lighting conditions. During the assessment, the patient is instructed to read as many letters as possible, and their score is determined by the lowest contrast level they can accurately identify. However, a notable limitation of this methodology is that the chart requires external illumination at approximately 85 cd/m² to ensure precise measurement of contrast sensitivity. Even with adequate lighting, the Pelli-Robson chart frequently yields inconsistent results across repeated assessments due to variations in testing conditions, patient fatigue, or subjective interpretation of the letters (Benjamin, 2006). Despite these limitations, the Pelli-Robson chart continues to be a prevalent clinical instrument for evaluating contrast sensitivity, particularly among populations with visual impairments, such as individuals with cataracts

Figure 1.15. Pelli-Robson chart for measuring contrast sensitivity from (Vision, 2020).

1.4.3 Psychophysics

In daily life, humans engage in numerous visual perception tasks, such as recognising faces, identifying objects, and navigating environments. The efficiency of the perceptual system depends on various factors, including the complexity and positioning of visual targets, their similarity to surrounding stimuli, and the contrast between the stimulus and its background (Mihali and Ma, 2020). To understand these processes, researchers must quantify and control the influence of these variables.

Psychophysical methods provide a reliable means of measuring the ability to detect and discriminate visual stimuli. These methods are widely used in clinical settings to assess perceptual abilities, such as visual acuity (VA), colour vision, and visual field testing (perimetry). Psychophysics is broadly defined as the study of the relationship between psychological sensitivity (perception) and the physical properties of stimuli (Gescheider, 2013, Aaen-Stockdale, 2008).It investigates how physical attributes of a stimulus, such as intensity or wavelength, relate to an individual's capacity to perceive that stimulus at a threshold level (Schwartz, 2006).

Psychophysical techniques are not limited to vision, however, extend to other sensory systems, including hearing, touch, taste, smell, and even the perception of time. These methods involve the use of quantifiable experimental stimuli, such as moving objects or musical tones of varying intensities, to evaluate three key functions: determining stimulus thresholds, detecting stimuli, and discriminating between them (Gescheider, 1997, Wackermann, 2010, Prins, 2012).

1.4.3.1 Psychophysical Methods

The origins of psychophysics can be traced back to Gustav Theodor Fechner's seminal work in 1860, which established the field as the study of the relationship between physical stimuli and their perceptual experiences (Gescheider, 1997, Lu and Dosher, 2013). Psychophysics provides a quantitative framework for understanding how humans perceive the physical world, bridging the gap between objective stimuli and subjective perception (Figure 1.16).

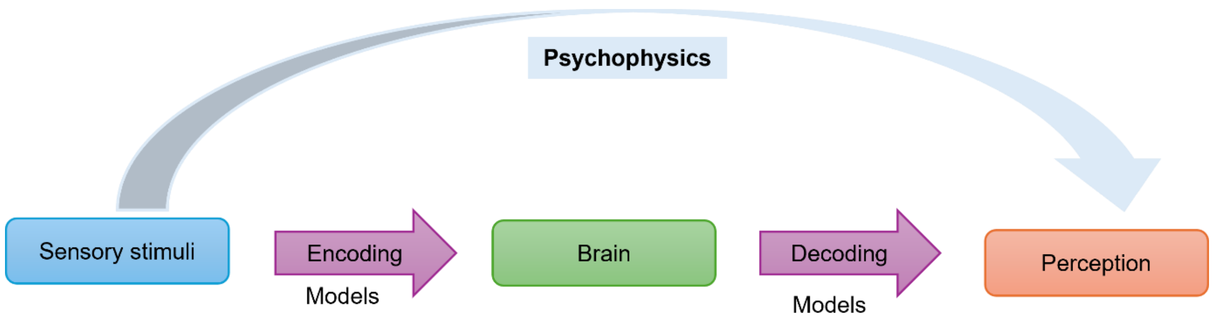


Figure 1.16. A schematic illustration summarising the standard theory of perception. including the role of psychophysics as a quantitative study of the relationship between a physical stimuli and perception.

Psychophysics plays a pivotal role in developing scales that quantify sensory experiences relative to physical stimuli. For example, the human visual system is sensitive only to light within a specific wavelength range (380–740 nm), beyond which perception diminishes regardless of (Rosenthal and Rosenthal, 1992, Cecie et al., 2005). This limitation contrasts with other species, such as honeybees, which can detect ultraviolet light (Wakakuwa et al., 2007), or certain snakes capable of sensing infrared radiation (Chen et al., 2012). Furthermore, perceptual experience does not scale linearly with physical stimulus intensity—a doubling of frequency, for instance, does not correspond to a doubling of perceived brightness (Wackermann, 2010, Prins, 2012, Lu and Dosher, 2013). These observations highlight the complexity of sensory perception and underscore the importance of psychophysical methods in elucidating these relationships.

1.4.3.1.1 Types of Psychophysical Methods

Psychophysical methods are essential for evaluating perceptual and performance-based functions, offering insights into the fundamental processes underlying sensory perception. These methods aim to quantify the relationship between physical stimuli and subjective experiences, enabling researchers to infer internal cognitive and neural processes based on observable behavioural responses (Jäkel and Wichmann, 2006, Marks and Gescheider, 2002). Among the various experimental paradigms used to determine absolute and differential thresholds, this study focuses on two key methods: the method of constant stimuli and reaction time measurements.

1.4.3.1.1.1 Method of Constant Stimuli

The method of constant stimuli is a widely used psychophysical technique for measuring perceptual thresholds with high precision. In this method, stimuli are presented at fixed, predetermined intensities in a randomised order across trials. By eliminating predictability in the sequence of stimulus presentation, this approach minimises biases related to anticipation or expectation (Figure 1.17), thereby enhancing the reliability of the data collected (Schwartz, 2006, Aaen-Stockdale et al., 2007, Gescheider, 2013). A typical application of this method involves a two-interval forced-choice (2IFC) procedure, where participants are presented with two intervals—one containing the target stimulus and the other serving as a control or blank interval—and are tasked with identifying the interval containing the stimulus. The range of stimulus intensities is carefully selected to span the expected threshold, ensuring that performance varies from near-chance levels to near-perfect accuracy. This design allows for the construction of a psychometric function, which describes the relationship between stimulus intensity and the probability of correct detection (Schwartz, 2006, Aaen-Stockdale et al., 2007, Gescheider, 2013).

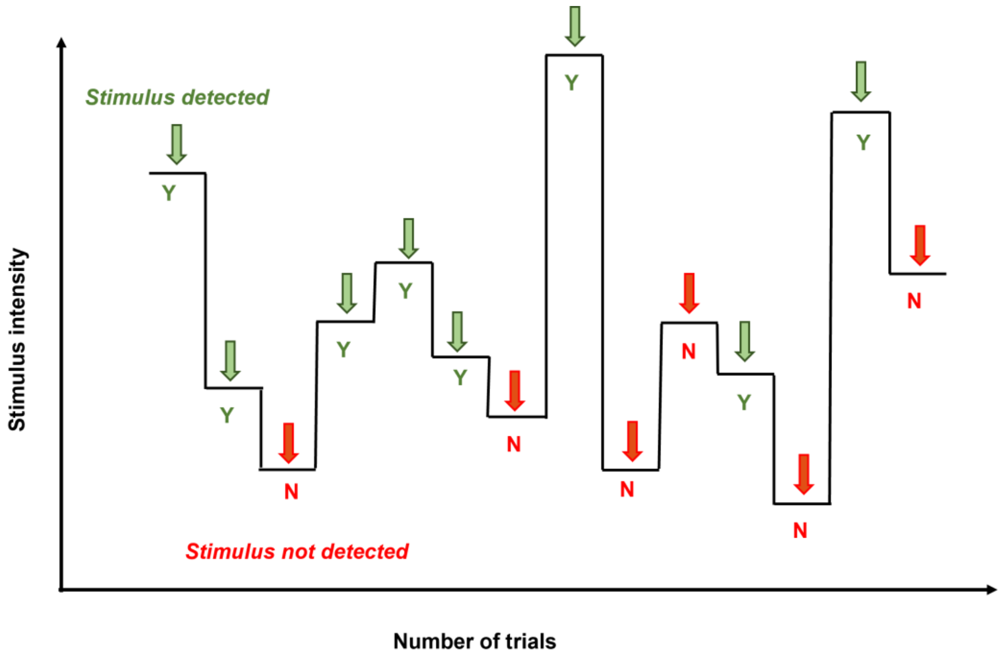


Figure 1.17. Method of constant stimuli demonstrating yes-no paradigm.

The psychometric function is typically sigmoidal in shape, with its midpoint corresponding to the detection threshold—the stimulus intensity at which participants can detect the stimulus 50% of the time. The slope of the function reflects sensitivity, indicating how rapidly detection performance improves with increasing stimulus intensity. When measuring differences between stimuli rather than detection thresholds, the midpoint corresponds to the point of subjective equality (PSE), where two stimuli are perceived as identical. Additionally, the just-noticeable difference (JND)—the smallest detectable difference between two stimuli—can be derived from the function, typically measured as the distance between the 50% and 75% points (Burro et al., 2011). The structured and randomised design of the method of constant stimuli ensures robust data collection, making it particularly suitable for studies requiring precise threshold measurements. In this thesis, the method will be applied to investigate how cataract-induced visual impairments affect motion perception.

1.4.3.1.1.2 Reaction Time Measurements

Reaction time (RT) is a critical metric in psychophysical research, representing the interval between the onset of a stimulus and the initiation of a voluntary motor response. Measured in milliseconds, RT serves as an indicator of the efficiency of neurophysiological, cognitive, and motor processes involved in sensory processing and decision-making (Batra et al., 2014, Adam et al., 1999). It includes several sequential stages, including sensory reception, information processing, decision formation, and motor execution (Mohan et al., 1984, Malathi et al., 1990, Baayen and Milin, 2010).

In psychophysical experiments, RT is often categorised into three types: simple, recognition, and choice reaction time. Simple RT tasks involve a single stimulus and response, whereas recognition tasks require participants to distinguish between relevant and irrelevant stimuli within a set. Choice RT tasks are the most complex, involving multiple stimuli and corresponding responses, thus demanding higher levels of cognitive processing (Miller and Low, 2001). Research has shown that variations in RT across these categories primarily reflect differences in cognitive processing time, as motor preparation and execution times remain relatively constant (Miller and Low, 2001, Baayen and Milin, 2010).

In this study, RT measurements will be used to assess the impact of cataract-induced visual impairments on sensorimotor coordination and decision-making speed. Given the critical role of rapid reflexes in dynamic visual tasks, such as driving or navigating complex environments, understanding the effects of cataracts on RT is essential for evaluating their broader implications for patients' quality of life and safety (Batra et al., 2014).

1.5 Summary

This thesis adopts a multi-faceted approach to investigate the impact of cataracts on motion perception. Through surveys (Chapter 3), subjective insights into the experiences of cataract patients are gathered, complemented by behavioural experiments (Chapters 5–8) that use simulation filters (Chapter 4) to replicate cataract-like visual impairments in healthy participants. These experiments leverage the method of constant stimuli and reaction time measurements to provide controlled, quantitative insights into how cataracts affect perceptual thresholds and decision-making processes. Finally, a case study involving real cataract patients (Chapter 9) offers a direct comparison to simulated conditions, enriching the understanding of the genuine effects of cataracts on motion perception. Together, these components aim to advance knowledge in the field and inform strategies to mitigate the challenges faced by individuals with cataracts in everyday life.

Chapter 2 **General Methods**

2.1 Introduction

This chapter outlines the measurements, equipment, stimuli, as well as experimental and analytical techniques used in this thesis.

The experiments described in this thesis used a range of clinical and behavioural investigative techniques. Figure 2.1 shows an illustrative breakdown of experimental protocols and group divisions.

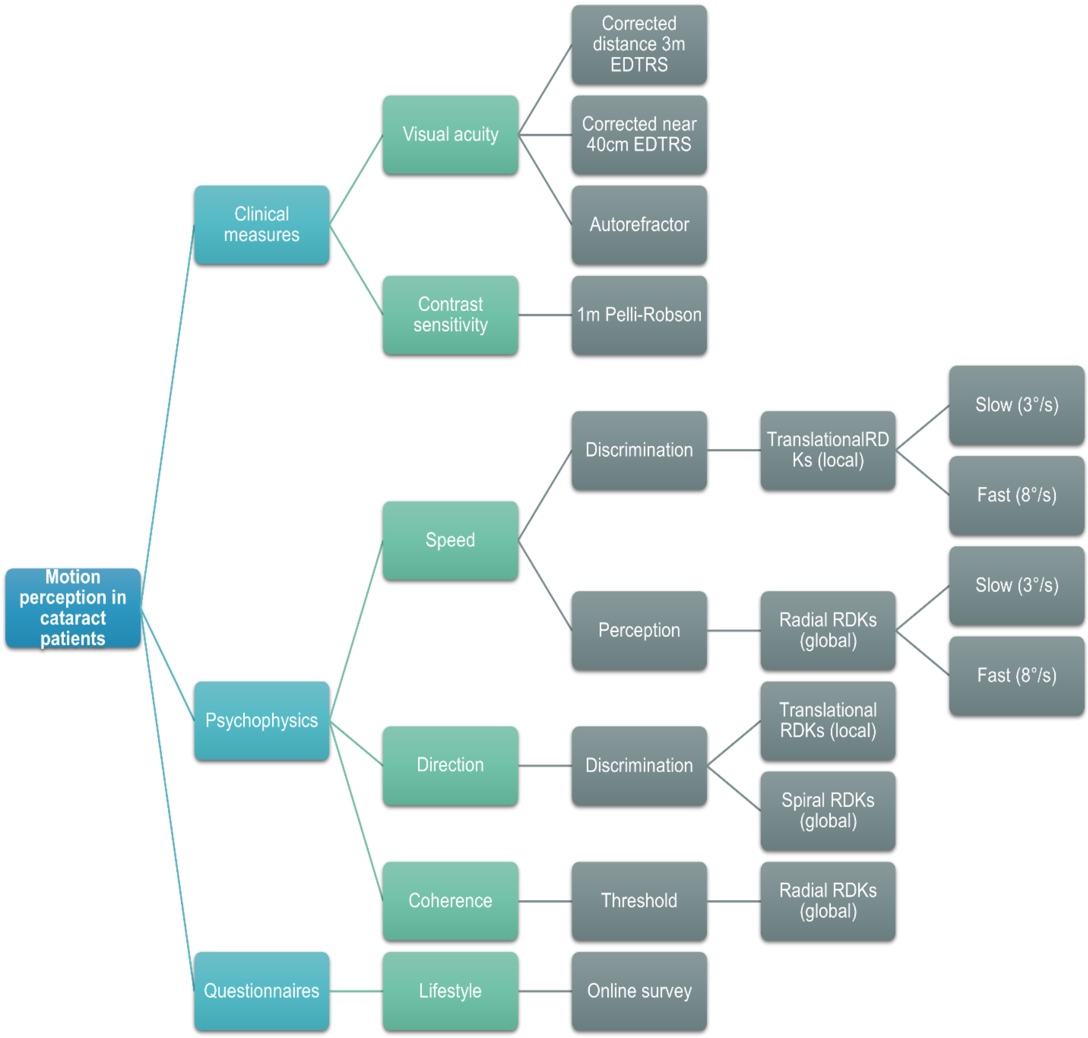


Figure 2.1. Schematic representation of the three investigative branches of the project (blue boxes) and their associated methodologies (grey boxes). The observer groups included participants who completed the online survey, as well as those who attended psychological assessments and clinical examinations.

2.2 Observer Groups

Data was gathered through three primary components: firstly, the collection of clinical data, followed by the implementation of behavioural (psychophysical) experiments, and finally, the distribution of surveys.

For each experiment, the data collection process involved the categorisation of observers into three distinct groups. The initial group, referred to as "<30 controls," consisted of individuals aged 18-30 years with no cataracts, serving as the control group for comparison purposes. These observers also engaged in experiments involving simulated cataracts. The second group, denoted as "age-matched controls," comprised observers over 30 years of age, who also served as control subjects for experiments involving simulated cataracts. Additionally, this group underwent supplementary visual field screening examinations to assess their visual function. The third and final group, labelled "cataracts," consisted of individuals aged 50 or older who had developed cataracts as a result of ageing. This group underwent the complete clinical examination as detailed in the subsequent section. All three groups were free from ocular and neurological pathologies that could potentially impact their attention and perception. Further specifics regarding the experimental procedures are outlined in Figure 2.1.

The surveys contained of two online questionnaires, with data being gathered through online means. Observers were recruited through social media advertisements, emails, and an advertisement at Aston's Eye Clinic entrance. Observers voluntarily chose to participate based on their own eligibility for each questionnaire. Further elaboration on the recruitment process will be provided in Chapter 3.

If observers were interested in taking part in the clinical part of the study, they were asked to read through the Participant Information Sheet (Appendix 5**: Participant Information Sheet**) and they had the opportunity to discuss the study and ask any related questions. Also, before signing the consent form the observers were again received a very detailed explanation about the study.

Observers were included in the study if:

(a) There were no current ocular pathologies on clinical examination, except in the essential presence of ageing lenticular opacity for group 3.

(b) There was no previous history of eye pathologies that might affect visual function, e.g., amblyopia.

(c) There was no family history of glaucoma or diabetes.

(d) Baseline distance visual acuity was recorded as + 0.2 logMAR or better in each eye separately.

Twenty - three individuals between the ages of 20 and 70 years were selected from the West Midlands and Aston University to take part in the research. The group consisted of 8 male and 15 female observers.

The research was conducted in compliance with the guidelines set forth by the Research Ethics Committee at Aston University's College of Health and Life Sciences. All observers were provided with a comprehensive explanation of the experimental protocols, and their written consent was obtained, with the opportunity to withdraw from the study at any point.

2.3 Clinical Investigation of Vision and Ocular Health

Observers were briefly questioned about their eye health history and any potential co-occurrence of physical or neurological conditions that could impact their performance or cause discomfort during the psychophysical experiments.

2.4 Equipment's and Protocol

2.4.1 Distance visual acuity (DVA) monitor

In this study, DVA was measured with observers best refractive correction at distance of 3 m using a computed LCD monitor chart Rexxam from Grafton Optical.

The Bailey-Lovie design was used for the letters utilised in the study. This design features five letters per row, with a 0.1 log unit progression for each row from top to bottom. Each letter on a row corresponds to a value of 0.02 on the logMAR scale for that specific line. Importantly, with a logMAR measurement, a low number indicates higher levels of VA; for example, if a person scores -0.1 logMAR with two letters on the line below, this would be recorded as -0.14 logMAR (-0.1 + (-0.02×2)). This recording scale was chosen over other scales due to it is precise evaluation (Carkeet, 2001, Holladay, 2004, Benjamin, 2006, Bailey and Lovie-Kitchin, 2013). The VA records for all our observers are shown in Table 2.1.

Table 2.1. Distribution of all observers' best corrected DVA. The variability of the optimal corrected distance visual acuity across all observers.

Group 1 (below 30 years old)			**Group 2 (30 years and above)**			**Group 3 (Cataracts)**		
ID	DVA		ID	DVA		ID	DVA	
	RE	LE		RE	LE		RE	LE
SC 1	-0.14	-0.12	SC 5	-0.10	-0.10	Cat 1	0.10	0.10
SC 2	-0.10	-0.10	SC 7	0.00	0.00	Cat 2	-0.20	-0.30
SC 3	-0.16	-0.22	SC 9	-0.20	-0.28			
SC 4	-0.10	-0.10	SC 22	-0.14	-0.10			
SC 10	0.00	0.00	SA 1	-0.20	-0.3			
SC 11	-0.10	0.00	SA 2	-0.20	-0.20			
SC 13	-0.10	-0.18	SA 3	-0.16	0.00			
SC 14	-0.20	-0.20						
SC 15	0.00	-0.10						
SC 16	-0.10	0.00						
SC 19	-0.10	-0.10						
SC 20	-0.08	-0.08						
SC1021	0.00	0.10						
SC1023	-0.10	-0.10						

SC1025	-0.10	-0.10						
Average	***-0.09***	***-0.09***		***-0.14***	***-0.14***		***-0.05***	***-0.10***
SE	***0.01***	***0.02***		***0.03***	***0.05***		***0.15***	***0.20***

In the evaluation process, efforts were made to reduce bias and minimise memorisation by initiating VA assessment in the observers with their left eye, followed by the right eye, and then both eyes together. The letters used for measurement were alternated for each assessment.

2.4.2 Near visual acuity (NVA) chart

Following DVA examination a NVA assessment was performed using a Precision Vision SLOAN two-sided ETDRS Near Point Test (Myers et al., 1999). This test was carried out at distance of 40 cm which aligns with standard protocols for NVA measurement (Myers et al., 1999, Benjamin, 2006, Wang et al., 2022a).

The observers were measured for NVA with their habitual VA, which means the person's best VA with their habitual optical device that they are using (commonly spectacles or contact lenses) for performing habitual close distance daily tasks. However, it cannot be discounted that observers' optical corrections might include some prescription errors that can happen either in clinical examinations or due to their eyes' structural and refractive status, yet those deviations should not be inappropriate to the level where there is a very much difference between habitual prescription and autorefractor readings.

The NVA scores were obtained in the same way as for DVA. First examining left eye then right eye and after that binocularly with both eyes, the scores were also documented in logMAR (Myers et al., 1999, Carkeet, 2001, Wang et al., 2022a). To avoid a memorisation factor, the chart was flipped at the time when they were swapping between eyes. The overall NVA averages for our observers are presented in Table 2.2.

Table 2.2. Average values for the observers' NVA

Group 1 (below 30 years old)			**Group 2 (30 years and above)**			**Group 3 (Cataracts)**		
ID	NVA		ID	NVA		ID	NVA	
	RE	LE		RE	LE		RE	LE
SC 1	-0.30	-0.28	SC 5	-0.20	-0.20	Cat 1	0.30	0.30
SC 2	-0.10	-0.10	SC 7	-0.10	-0.10	Cat 2	-0.20	0.00
SC 3	-0.20	-0.30	SC 9	-0.10	-0.20			
SC 4	-0.20	-0.10	SC 22	-0.10	-0.10			
SC 10	0.00	0.00	SA 1	-0.20	0.00			
SC 11	-0.10	-0.10	SA 2	-0.20	-0.20			
SC 13	-0.20	-0.10	SA 3	-0.10	0.00			
SC 14	-0.30	-0.30						
SC 15	-0.20	-0.10						
SC 16	-0.10	-0.20						
SC 19	-0.10	-0.10						

SC 20	-0.02	0.22						
SC 21	0.00	0.00						
SC 23	-0.16	-0.06						
SC 25	-0.10	-0.20						
Average	***-0.14***	***-0.11***		***- 0.13***	***-0.10***		***0.05***	***0.15***
SE	***0.02***	***0.03***		***0.02***	***0.03***		***0.25***	***0.15***

2.4.3 Contrast sensitivity (CS) chart

As discussed in Chapter 1, several studies have suggested that CS provides a more useful indication of real or functional world vision that VA and visual field tests do not provide (Elliott et al., 1996, Roark and Stringham, 2019, Shandiz et al., 2011, Lord et al., 1991). For example, CS has been found to be directly correlated with controlling balance, driving, reading, and many other daily life activities (Elliott et al., 1996, Fraser et al., 2013, Shandiz et al., 2011). Therefore, combining CS with VA (and visual fields, for groups 2 and 3) can provide a better estimation of the observers' visual function (Kaido, 2018, Elliott et al., 1996, Myers et al., 1999, Zhang et al., 2008, Shandiz et al., 2011, Lord et al., 1991).

There are several ways of measuring and recording CS values depending on whether Weber (Pelli-Robson) (Denis, 1988, Roark and Stringham, 2019) or Michelson contrast (all grating charts) is being used (Pesudovs et al., 2004). The Pelli–Robson chart (Myers et al., 1999) provide more consistency in terms of determining CS than grating CS exams (Myers et al., 1999, Benjamin, 2006). Importantly for this project, the Pelli-Robson chart also allows estimation of vision in patients with functional vision loss, like moderate and severe cataracts and low vision (Denis, 1988, Jackson and Bailey, 2004). However, the disadvantage of this CS test is that the final recording point is highly dependent on the amount of time that the patients were given to stare at the letters close to threshold, as with low contrast, more time may be required to recognise the presented targets (Denis, 1988, Myers et al., 1999, Jackson and Bailey, 2004).

The Pelli-Robson chart is a printed chart with dimensions of 86 × 63 cm, typically mounted on a wall and used to examine patients at a standardised distance of 1.00 meter. Essentially, as it measures contrast sensitivity rather than visual acuity, the size of the letters remains constant throughout the chart, while the contrast decreases progressively from the top left corner toward the bottom right corner. The chart is divided into two columns and consists of 16 sets of triplets, with each letter measuring 4.9 cm in height (corresponding to 2.8 degrees of visual angle at 1 meter). It evaluates spatial frequencies ranging from approximately 0.50 to 1 cycle per degree (Myers et al., 1999, Jackson and Bailey, 2004, Benjamin, 2006).

Hence, in this this study CS was measured using a Pelli-Robson letter chart. The CS measurements were performed under bright externally uniformly illuminated room with an intensity of 85 cd/m^2, and observers were instructed to read letters in a single attempt, starting from high-contrast letters at the top left corner and progressing towards the lowest contrast letters they could accurately discern. Monocular examinations were conducted initially (LE followed by RE), followed by binocular assessments with the observers' best corrected refractive correction. The aggregate readings for the observers are presented in.

Table *2.3*. In relation to the CS of the observers, there was no significant difference detected between groups 1 and 2. However, group 3 exhibited a reduction in visual acuity, which aligns with the anticipated effects of cataract.

Table 2.3. An overview of average CS readings.

Group 1 (below 30 years old)			**Group 2 (30 years and above)**			**Group 3 (Cataracts)**		
ID	CS		ID	CS		ID	CS	
	RE	LE		RE	LE		RE	LE
SC 1	1.60	1.60	SC 5	2.25	2.25	Cat 1	1.50	1.50
SC 2	1.65	1.50	SC 7	2.25	2.25	Cat 2	1.50	1.50
SC 3	1.95	1.50	SC 9	1.50	1.50			
SC 4	1.50	1.95	SC 22	1.50	1.80			
SC 10	1.95	1.65	SA 1	1.50	1.50			
SC 11	1.95	1.65	SA 2	1.95	1.95			
SC 13	1.95	1.95	SA 3	1.95	1.95			
SC 14	1.80	1.95						
SC 15	1.80	1.95						
SC 16	1.95	2.25						
SC 19	1.95	1.50						
SC 20	1.80	1.80						
SC 21	1.80	1.95						
SC 23	2.25	2.25						
SC 25	1.95	1.95						
Average	***1.86***	***1.83***		***1.84***	***1.89***		***1.50***	***1.50***
SE	***0.05***	***0.06***		***0.13***	***0.12***		***0.00***	***0.00***

2.4.4 Autorefractometer

The term "automated refraction" refers to the substitution of human judgment in the assessment of refractive error with the logic of a designated instrument, computer, or a combination of both (Vishnyakov et al., 2008). In this context, the term "automated refraction" expresses the reliance on machine-based judgment with minimal operator influence to achieve the objective refraction (Campbell et al., 2006, Gurnani and Kaur, 2022).

Nowadays autorefractors are widely used in numerous ophthalmic and optometric practices, as they enable rapid and unbiased assessment of vision, which is advantageous in various contexts, including evaluating postoperative results, estimating refractive error, and gathering data for clinical research (Vishnyakov et al., 2008, Cleary et al., 2009, Gurnani and Kaur, 2022). Numerous studies have indicated that autorefractors can offer highly dependable measurements compared to subjective assessments (Wood, 1987, Sheppard and Davies, 2010, Nagra et al., 2021, Gurnani and Kaur, 2022).

Autorefraction is a method of objectively measuring the refractive error of an eye without relying on verbal or subjective responses from the patient. It is essential to provide clear instructions to ensure the patient's cooperation, as their participation is necessary for obtaining accurate and reliable results during the objective examination (Cleary et al., 2009, Rotsos et al., 2009, Sheppard and Davies, 2010, Gurnani and Kaur, 2022). Autorefraction has been found to be more repeatable, replicable, quicker, and user-friendly compared to the traditional objective refractive measurement using a retinoscope (Campbell et al., 2006, Cleary et al., 2009, Rotsos et al., 2009, Sheppard and Davies, 2010). The net refractive error is calculated using an instrument operator that has been programmed to adhere to predetermined criteria (Campbell et al., 2006, Gurnani and Kaur, 2022).

In current practice, the primary source of electromagnetic radiation in autorefractors is derived from near-infrared (NIR) sources. The light is directed into the patient's eye, with measurements taken of the reflections from the retina (Gurnani and Kaur, 2022). These data are used to determine the parameters necessary for the eye to focus light without correction, thereby indicating the degree of refractive error present in the eye (Vishnyakov et al., 2008, Nagra et al., 2021, Gurnani and Kaur, 2022). The choice of near-infrared light is based on its efficient reflection off the posterior retina, as opposed to visible light which would be absorbed by the photoreceptors (Vishnyakov et al., 2008, Gurnani and Kaur, 2022). Additionally, near-infrared light is imperceptible to the normal human eye, ensuring no adverse reactions during the examination procedure. Consequently, patients do not experience photophobia or miosis, and their accommodation remains unaffected (Campbell et al., 2006, Gurnani and Kaur, 2022).

Two categories of autorefractors commonly used in clinical settings are closed-field autorefractors and open-view autorefractors (Mallen et al., 2001, Nagra et al., 2021). Closed-field autorefractors, which are widely used and relatively cost-effective, employ an internal fixation target to minimise proximal accommodation (Yeow and Taylor, 1989). These systems are frequently used in research, particularly in the fields of refractive error and ocular accommodation (Wood, 1987, Mallen et al., 2001). However, their performance in patients with cataracts may be limited due to the scattering of light caused by lens opacities, which can interfere with accurate measurement of refraction (Mallen et al., 2001, Nagra et al., 2021). Conversely, open-view autorefractors employ external fixation targets (Nagra et al., 2021). By maintaining the parameters associated with a distant target and ensuring sustained fixation, the risk of proximal accommodation is reduced (Mallen et al., 2001, Nagra et al., 2021). Additionally, it is believed that conducting the examination using the open-view type is considered a more natural viewing task (Nagra et al., 2021, Cleary et al., 2009, Mallen et al., 2001), which simulates a more natural viewing condition within eye clinics (Cleary et al., 2009). Importantly, open-view autorefractors tend to perform better in patients with cataracts compared to closed-field systems, as they are less affected by light scatter and provide more reliable measurements in the presence of media opacities (Nagra et al., 2021)

The accuracy of the measurements obtained from autorefractor systems relies on accurately determining an endpoint. Achieving this endpoint involves the system comparing the current measurements (endpoint) to a stored automated emmetropic image within the system. This system-generated image varies based on the patient's ocular focal distance and pupil size (Campbell et al., 2006, Gurnani and Kaur, 2022). The typical standard pupil diameter ranges from 2.5 to 3 mm, and in cases of smaller pupil sizes, which are often observed in older individuals, the results are frequently significantly compromised (Campbell et al., 2006, Gurnani and Kaur, 2022).

Figure 2.2. Open field autorefractor (Rubido, 2004).

In the present study, to ensure the accuracy and consistency of the findings, an open field autorefractor (Figure 2.2) was employed. This particular autorefractor uses a real viewing target. A summary of the autorefractor averages for our observers is presented in Table 2.4.

Table 2.4. An overview of average readings for open-view Rexxam autorefractor for the dominant eye. Table abbreviations are as following: Right eye (RE), left eye (LE), spherical refractive error (Sph), astigmatic refractive error (Cyl), astigmatic refractive error axis

Group 1	ID	RE			LE		
		Sph	Cyl	Axis	Sph	Cyl	Axis
	SC 1	-2.00	-1.75	180	-2.25	-1.00	168
	SC 10	-4.87	-0.25	12	-5.25	-1.00	31
	SC 11	-1.75	-0.25	10	-1.75	-0.25	20
	SC 13	0.00	-0.50	12	-0.50	-1.25	102
	SC 14	-1.12	-0.50	36	-0.75	-0.62	159

	SC 15	-3.50	-0.25	46	-3.00	-0.37	107
	SC 16	-3.62	-1.75	15	-4.75	-0.87	167
	SC 17	4.00	-0.75	14	3.00	-0.87	26
	SC 21	1.75	-0.37	6	4.25	-1.37	158
	SC 23	-1.25	-0.75	178	-1.00	0.00	0.00
	SC 25	0.25	0.00	0.00	1.50	0.00	0.00
Average		***-1.14***	***-0.65***	***49.20***	***-1.10***	***-0.61***	***86.73***
SE		***0.59***	***0.14***	***16.98***	***0.69***	***0.12***	***17.90***
Group 2	SC 9	-4.50	-0.37	52	-4.75	-0.50	128
	SC 22	-5.87	-0.25	16	-5.00	-0.75	4
	SA 1	-0.75	-0.50	164	-0.75	-1.00	69
	SA 2	0.37	-2.25	111	0.00	-2.12	74
Average		***-2.69***	***-0.84***	***85.75***	***-2.63***	***-1.09***	***68.75***
SE		***1.49***	***0.47***	***32.61***	***1.31***	***0.36***	***25.38***
Group 3	Cat 1	+2.50	-1.50	134	+1.75	-0.25	14
	Cat 2	-0.75	-0.50	164	-0.75	-1.00	69
Average		***0.88***	***-1.00***	***82.67***	***0.50***	***-0.63***	***41.5***
SE		***1.63***	***0.50***	***81.33***	***1.25***	***0.38***	***27.5***

Inter-pupillary distance (IPD), also referred to as pupillary distance (PD), is the measurement in millimetres that connects the centres of both eyes' pupils. Monocular IPD is the distance from each eye to the bridge of the nose, which can vary slightly between eyes for the same individual due to anatomical differences (Osuobeni and Al-Fahdi, 1994, Dodgson, 2004). Determining the monocular IPDs is necessary for accurately positioning each lens in alignment with a patient's visual axis for eyeglasses (Kumah et al., 2016). In this study, the interpupillary distance (IPD) was digitally measured using an autorefractometer. Table 2.5 provides a summary for the observers IPD values.

Table 2.5. Inter-pupillary distance (mm)

ID	**Group 1**	**ID**	**Group 2**	**ID**	**Group 3**
SC 1	63	SC 7	57	3001	62
SC 10	64	SC 9	65	3002	63
SC 13	59	SC 22	64		
SC 14	64	SA 1	63		
SC 15	61	SA 2	67		
SC 16	63				
SC 19	64				
SC 21	63				
SC 23	50				
SC 25	70				
Average	***64.00***		***63.20***		***62.50***
SE	***1.21***		***1.69***		***0.50***

2.4.5 Simulated lenses

In practical application, there are two methods for simulating cataracts. The first method involves using an optical system to induce physical changes characteristic of cataract development in an otherwise healthy system (de Wit et al., 2006b, Zuckerman et al., 1973). This approach commonly employs simulating lenses or filters (Zuckerman et al., 1973). The second approach entails presenting images or stimuli that have been altered to reflect the visual changes associated with cataract development (de Wit et al., 2006b).

In this study, an optical system was used to replicate (simulate) the scatter of cataracts by professional photographic filters positioned in front of the eye. The filters were assessed and contrasted with the light scattering properties of cataracts.

The observers in Group 1 and 2 of this study, who were in the age range of 18- 43 years old, engaged in psychophysical tests under conditions designed to replicate aspects of cataracts and age-related vision impairments, such as simulated cataracts. This was fundamental for evaluating the correlation between the efficacy of clinical assessment and the impact of cataracts on the everyday visual perception of patients. Additionally, it allowed for a comparison of image quality under "normal" conditions and when affected by cataracts within the same observer.

The visual impairment associated with age-related cataracts was simulated using two varieties of Hoya Fog 'scattering' filters (Hoya Fog lenses; A and B; 55mm). These filters were mounted on a clamp system connected to the headrest, enabling the simulation of three distinct levels of age-related cataract severity: (a) Mild cataract, represented by the Hoya Fog A (HFA) filter, which allows 75% light transmission. This level corresponds to early-stage cataracts, where light scatter is minimal and visual acuity is only slightly impaired. (b) Moderate cataract, represented by the Hoya Fog B (HFB) filter, which permits 76% light transmission. Although this percentage appears similar to the mild condition, the HFB filter introduces greater light scattering due to its design, which mimics the increased opacification and disruption of the lens structure seen in moderate cataracts. The additional scattering significantly impacts contrast sensitivity and glare, despite the relatively high light transmission percentage, making it representative of moderate visual impairment. (c) Severe cataract, simulated using two Hoya Fog B (HFBB) filters, resulting in 62% light transmission. This configuration produces substantial light scatter, mimicking the dense opacification characteristic of advanced cataracts, which severely degrades visual function. (d) A baseline condition (uncovered eye) with no filter applied, representing normal vision without any simulated impairment. A more comprehensive analysis of the impact these filters had on the observers' vision, including their effects on contrast sensitivity, glare, and motion perception, is presented in Chapter 4.

The filters used in the simulation were assessed using a spectrometer to evaluate their optical properties. The outcomes related to the visible transmission factor (Tv) were compared against the D65 standard illuminant values, as defined by BS EN ISO 4007 and BS EN ISO 12311. These results are illustrated in Figure 2.3, which presents the light transmission rates of the simulated lenses applied in the experiments. The 75% transmission rate of the HFA filter indicates its capacity to transmit visible light while minimally scattering shorter wavelengths, thereby simulating the effects associated with a mild cataract. Conversely, the HFBB filter, which represents a severe cataract simulation, exhibits significantly reduced transmittance (62%) and blocks more of the shorter wavelengths, mimicking the increased light scatter and absorption seen in advanced cataracts. This spectral analysis demonstrates how the filters replicate the progressive reduction in light transmission and the selective attenuation of shorter wavelengths that are characteristic of age-related cataracts.

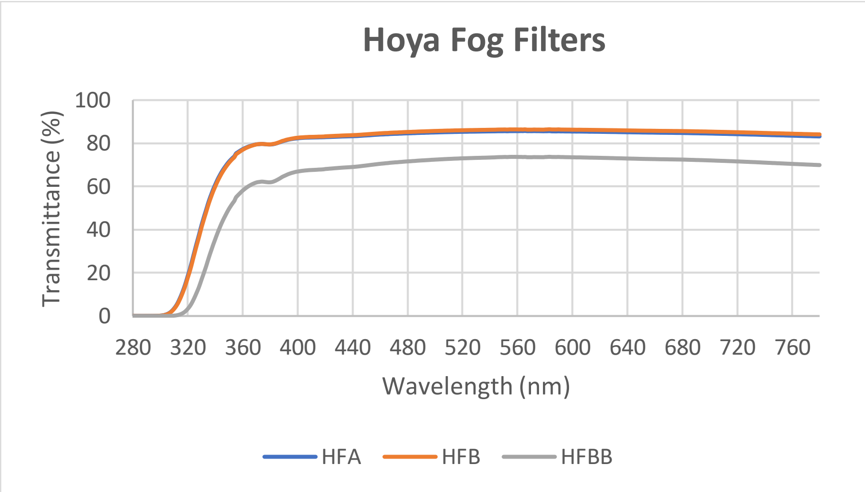


Figure 2.3. The light transmission rates of the simulated lenses utilised in the present experiments were as follows: 85% for the HFA filter, 86.2% for HFB, and 73.2% for HFBB.

2.4.6 Psychophysical experiments timing of stimulus presentation

Psychophysics is a field of study that involves experimental techniques aimed at investigating the correlation between characteristics of a physical stimulus and the subjective behavioural response to that stimulus (Wackermann, 2010, Prins, 2012).

The primary objective of psychophysics extends beyond the mere examination of responses to stimuli, instead focusing on the analysis of responses and image characteristics to gain insight into the fundamental processes of perception (Falmagne, 1982, Klein, 2001). This field seeks to elucidate the mechanisms underlying perception, which can be investigated through the analysis of perception parameters derived from both human subjects and primates (Hladik et al., 2003, Fujita, 1997). When conducting it on individuals, researchers commonly present observers with visual stimuli, typically shown on a screen, and request responses through the use of buttons or controls (Klein, 2001, Wichmann and Hill, 2001, Frund et al., 2011). The accuracy rate is commonly defined as the degree of correctness in distinguishing between two potential responses, such as "present" versus "absent," "longer" versus "shorter," or "above" versus "below" (Kiefer et al., 2023, Prins, 2012). Whilst on primate studies, such as those involving monkeys, researchers may induce the animals to interact with buttons while concurrently observing neural responses in their brains. Both experimental approaches are considered within the realm of psychophysics (Fujita, 1997, Hladik et al., 2003).

In the field of visual psychophysics, accurate timing of display, especially for brief stimulus presentations, is frequently necessary. The timing of stimulus presentation holds significant importance in psychophysics and can significantly impact the overall experience of an experiment, distinguishing between a challenging and frustrating setup and one that is comfortable and engaging (Wichmann and Hill, 2001, Wackermann, 2010, Frund et al., 2011, Prins, 2012, Lu and Dosher, 2013) (Figure 2.4). The illustration shows a motion-speed trial, wherein the trial is initiated by the observer's reaction to the preceding trial. Typically, forced choice tasks are most effective when self-paced, as this empowers the observer to regulate the pace of the experiment without interfering with the essential temporal parameters.

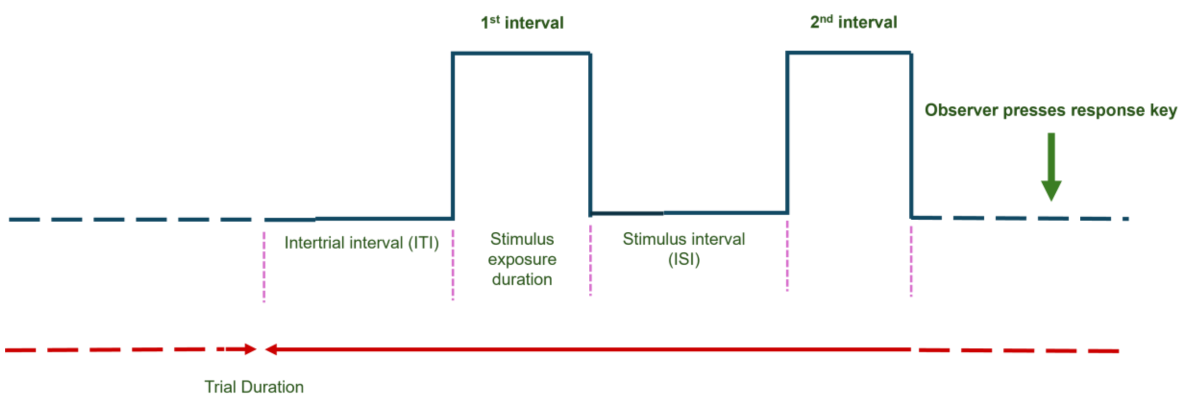


Figure 2.4. Example timing of stimulus presentation during a forced choice trial.

An appropriate interstimulus interval (ISI) is also important to minimise both for forward and backward masking effects between stimuli. There is no hard and fast rule here, and the experimenter is encouraged to try out different ISIs until the task feels easy (Wackermann, 2010, Lu and Dosher, 2013, Schwartz, 2006, Aaen-Stockdale et al., 2007, Gescheider, 2013). For these experiments where two intervals were used, a random ISI that centred around 0.5s was used for every trial, so that participants could not necessarily predict the arrival of the next interval.

Specific points are identified as the level of stimulus intensity that results in a 50% correct response on the psychometric function (Klein, 2001). Due to variations in an individuals' responsiveness to stimuli, multiple measurements of the stimulus threshold are combined to obtain a precise determination of the absolute threshold (Prins, 2012, Lu and Dosher, 2013, Schwartz, 2006, Aaen-Stockdale et al., 2007).

When evaluating the threshold value for observers, two key metrics are considered: sensitivity and specificity. Sensitivity refers to the true positives or hits, while specificity pertains to the true negatives or correct rejects (Schwartz, 2006, Gescheider, 2013).

2.4.6.1 Psychometric Function measurements

The psychometric function is a key component in psychophysics (Klein, 2001, Falmagne, 1982), serving as a widely accepted mathematical framework (May and Solomon, 2013). It shows the correlation between stimulus intensity and observer responses (Wichmann and Hill, 2001, Frund et al., 2011, Prins, 2012).

The slope of the established psychometric function is a meticulously constructed regression line, reflected in the data present is not readily observable and requires estimation by the examiner (Klein, 2001, Wichmann and Hill, 2001, Frund et al., 2011, Prins, 2012, Lu and Dosher, 2013). The examiner interprets and analysis these data by fitting a psychometric function and calculating the inverse of that function to achieve the anticipated performance level (Klein, 2001, Wichmann and Hill, 2001, Frund et al., 2011). A prevalent approach involves assuming that the genuine function can be characterised by a particular parametric model and subsequently estimating the model's parameters by maximising the likelihood (Klein, 2001, Falmagne, 1982). In general, this model involves mapping various levels of stimuli to determine the perception threshold (Wichmann et al., 2018, Macmillan and Creelman, 2005). This is done by applying a two-parameter function to variables that represent stimulus levels and response outcomes (Dobson and Barnett, 2018, McCullagh and Nelder, 1989). The degree of response at a specific level of performance can be described as a parameter set by an observer or a statistical measure, like the accuracy of responses in a certain number of trials at a given stimulus intensity (Wichmann and Hill, 2001, Wichmann et al., 2018).

In the psychophysical experiment, it is essential that the used stimulus is capable of evoking a particular level of performance. The association between performance and stimulus intensity can be deduced from the form of the function, thus, in the context of the data gathered in this research, emphasis will be placed on sigmoid-shaped psychometric functions characterised by an S-shaped curve (Figure 2.5) (Falmagne, 1982, May and Solomon, 2013).

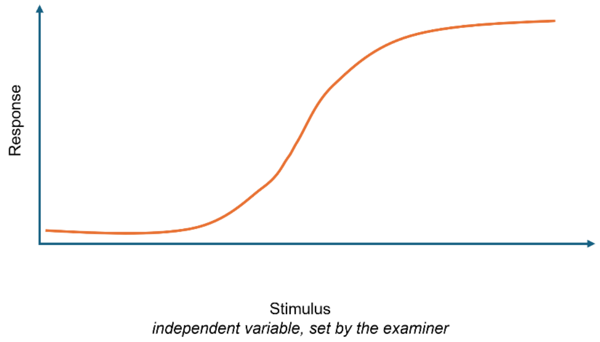


Figure 2.5. An illustration for psychometric function shows an S-shaped curve for two forced choice method, Measures the level of response, obtained from an observer's performance or a statistical measure like the percentage of correct responses in a given task.

As conducted by Miranda and Henson study in 2008, concerning on the frequency of visual perception, by implementing a series of light flashes with varying intensities that were consistently displayed at a specific position within the observer's visual field. The observer's task was to provide a response when they could see the each flash light (Miranda and Henson, 2008). The values were established by the likelihood, aligning with the theoretical propositions outlined by Blackwell (1946) and Crozier (1950) include Gaussian and reverse Weibull, as well as Weibull and logistic cumulative distribution functions (Blackwell, 1946, Crozier, 1950). Despite the different shapes obtained between these functions, it is difficult to differentiate between these plots based on the accuracy of their fits, all of which are considered acceptable due to the large number of data points.

Analogously, in a prior study conducted by Strasburger (2001), both Weibull and logistic cumulative distribution functions were used to investigate character recognition based on character contrast through an alternative forced-choice experiment. The study emphasised the difficulty in selecting the most appropriate parametric model. Strasburger found variations in the estimates of slope and threshold between the two models, yet the adequacy of fit was insufficient to definitively ascertain which model effectively captured performance across the range of stimuli (Strasburger, 2001, Treutwein and Strasburger, 1999). In line with these data, in this thesis a logistic fit is used across all psychophysical methods, in order to produce consistent and reliable fits.

2.4.6.1.1 Psychophysical thresholds

A psychometric function holds a large amount of information that can be simplified into a single measure for summarisation. Threshold is determined by considering the range of responses, which can vary from 0 to 100%.

Psychophysical information is obtained by assessing an individual's performance on a psychophysical task at different stimulus levels. The current study used the constant stimuli method, where data points were gathered through a series of experimental trials conducted at a fixed stimulus intensity.

For the nature of this experiment a logistic function was applied. As this function is commonly employed for modelling a psychometric function due to its applicable characteristics. It initiates at 0 and gradually rises to 1 in a sigmoidal fashion, which aligns with the typical behaviour observed in the measured psychometric function.

The standard logistic function is represented by a specific mathematical formula (Kudryashov, 2015, wikipedia.org, 2024):

$$f\ (x) = L/(1 + e)^{-k(x - \mathrm{x}0\ )}$$

Equation 2.1. Standard logistic function equation

The equation involves the probability, indicated as f(x), that a given sustaining capacity L will be perceived as longer than a standard duration. It is evident that the formula incorporates two variables, k and x. Modifying these parameters results in alterations to the precise form of the logistic function. Parameter k influences the rate at which the function ascends as it traverses its midpoint (p = 0.5), whereas parameter x dictates the timing at which the midpoint (x_0) is reached. To determine k and x, this can be achieved using MATLAB. k and x are then calculated by fitting the best possible line between x and y.

The concept of determining a threshold involves identifying d25 and d75, which represent the durations that result in judgments that are 25% and 75% longer (Figure 2.6). This can be visually obtained quite easily from each accompanying graph that clarifies the definitions of d25 and d75. However, once the values are known, it becomes possible to directly calculate these two durations using the logistic formula, that is applied to the MATLAB code.

Similarly, the methodology employed of determining the point of subjective equality (PSE) (Figure 2-6) is identical to that of finding either d25 or d75 for threshold values. The key distinction lies in the fact that for the PSE, the goal is to identify d50, which represents the point where 50-50 judgments occur.

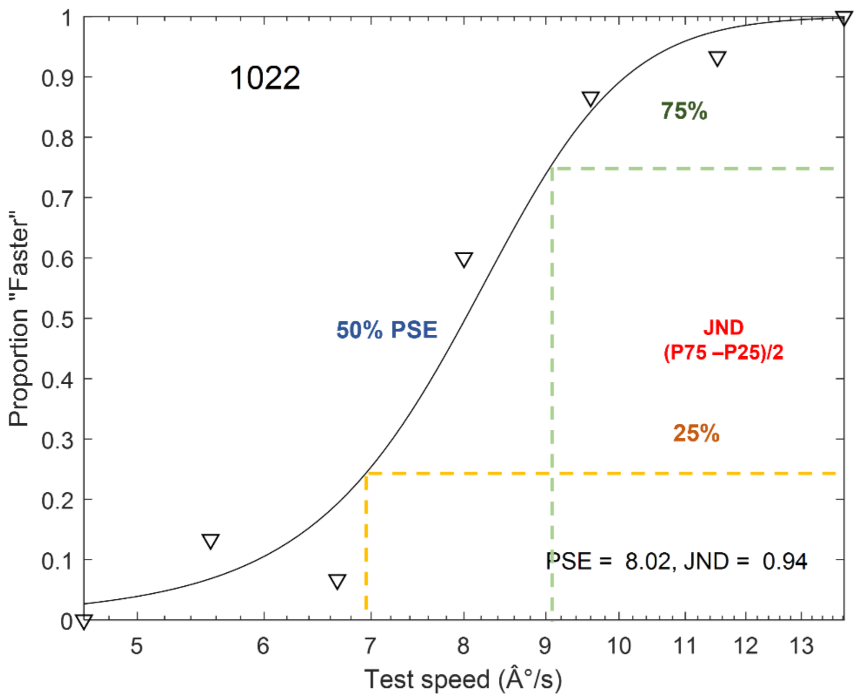


Figure 2.6. An illustration for psychometric function for a single observer completing a single condition, for two forced choice method applied for speed discrimination experiment of this thesis. The interpretation of the data plotted on a psychometric function curve for one of our observers, representing the main features of the plot and relation of noise presence to the procedure outcomes. The change in stimulus between the Point of Subjective Equality (PSE) and the 75% threshold is defined as the Just Noticeable Difference (JND).

Using data from current experiments in this study, the psychometric function and the JND were determined by applying a psychometric function to evaluate the percentage of responses that suggested the amount of speed stimulus elements surpassed a defined threshold in a specific task.

The JND maintains a stable relationship with the baseline sensory threshold, leading to a consistent ratio of JND to the reference level. This principle is commonly referred to as Weber's Law in scientific literature (Bower and Andersen, 2012, Schwartz, 2006). Generally, the reported data results plotted into curves in such an experiment representing the number of decisions in which the test stimulus was reported for example as faster, more oblique, tighter, than the given reference stimulus, as function of the reference data for example speed. Then psychometric functions will be fitted to these data (as will be shown in the coming experimental chapters), leading to two important measures. The PSE which as mentioned before and the JND, which is the speed difference between the PSE and 25% or a 75% decision score. Measuring the slope of a psychometric curve in 2IFC experiments can give an estimate of the motion sensitivity changes in that given specific stimulus (Zanker and Braddick, 1999).

One important observation offered by the psychometric function relates to the assessment of whether an individual's ability to detect or discriminate stimuli is hindered by a reduced average neural reaction to the presented stimulus, or by significant variability in the responses. Elevated thresholds are not only caused by a limited reliance of the response on the stimulus, but also by the existence of responses that exhibit high variability, making it difficult to consistently detect significant changes. The incline of the psychometric function indicates the level of perceptual disruption, which may arise from factors like additional elements in the study or the variability in participants' reactions. Consequently, when comparing different demographic cohorts, if one group consistently demonstrates greater thresholds than another, the steepness of the psychometric function can be employed to determine whether the difference is due to reduced response intensity or increased perceptual disturbances (Park et al., 2017, Reynolds and Heeger, 2009).

2.4.7 Apparatus

The psychophysical experiments were conducted using a Lenovo ThinkVision L1900PA monitor with a resolution of 1,280 × 1,024 pixels (horizontal by vertical) and a refresh rate of 60 Hz. Observers were seated in a darkened room at a fixed distance of approximately 57 cm from the monitor, which measured 37.5 cm × 30 cm. The centre of the screen was aligned with the observer's viewing eye, while the non-viewing eye was occluded using an occluder. A chin rest and forehead rest were used to stabilise the observer's head position, ensuring consistent viewing conditions. Simulation filters, when required, were securely positioned in front of the viewing eye using a clamp system (Figure 2.7).

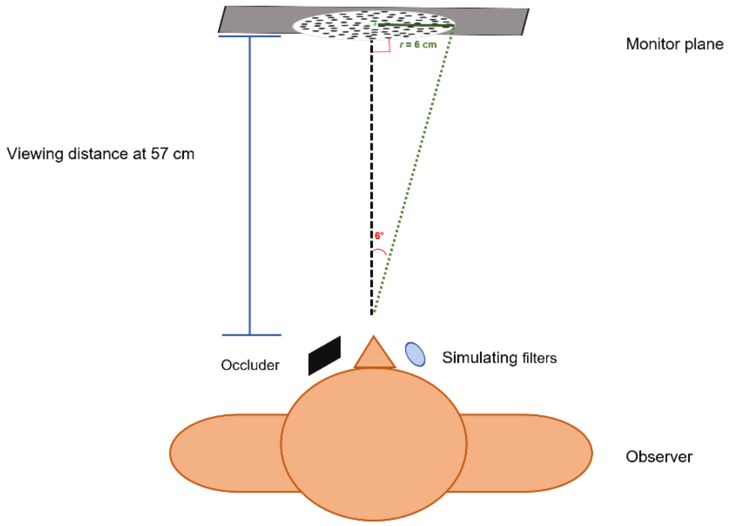


Figure 2.7. An illustration for experimental procedure scheme that was used for the behavioural experiment. The monitor with the viewing task that was at fixed distance of 57 cm. The observers performed the task monocularly occluding the fellow eye and using the simulated cataract lenses in un-occluded eye for the groups 1 and 2 and bare eye for group 3. The viewing angle was 6° and the diameter of the viewing circle was 12 cm.

All tasks were performed monocularly, and observers wore their optimal refractive correction suitable for the working distance of 57 cm. Data collection and analysis were facilitated using a combination of hardware and software tools, as detailed in the following sections.

2.4.8 Statistical Methods

Data collected during the experiments were entered into Microsoft Excel spreadsheets for initial processing and analysis. Psychometric curves were constructed, and just-noticeable difference (JND) values were calculated by MATLAB Psychophysics Toolbox and averaged using Microsoft Excel 2010. Graphs were generated using Excel, and all figures were prepared using Microsoft PowerPoint 2010.

Statistical analyses were conducted using SPSS software. Key statistical tests included analysis of variance (ANOVA) to compare group differences and t-tests to evaluate normality and other specific hypotheses. These analyses were applied across experimental chapters to ensure robust interpretation of the results. All statistical tests were performed with a significance level set at $p < 0.05$ unless otherwise specified.

2.4.9 Software

The experiment was conducted using a set of custom written functions applying Psychophysics Toolbox extensions (Brainard and Vision, 1997, Kleiner et al., 2007) running in MATLAB versions 2011b and 2013a (MATLAB).

2.4.10 General Psychophysical Protocol

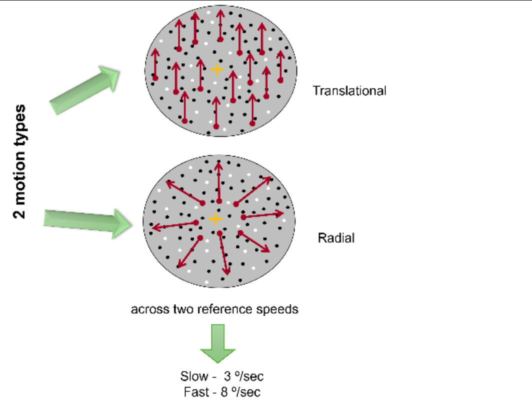
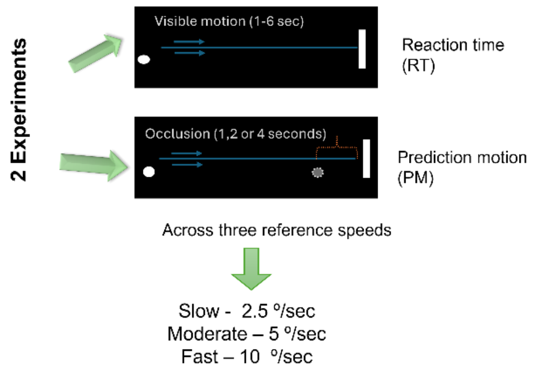
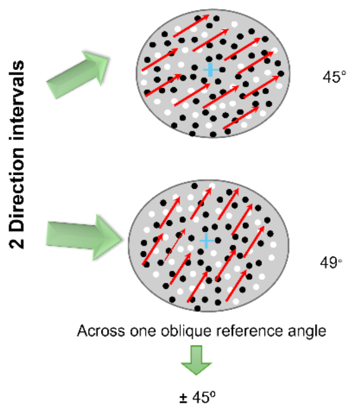
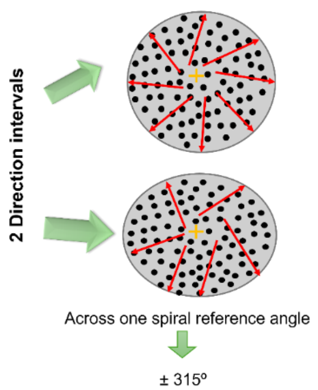
This research used psychophysical behavioural assessments to measure potential signs of decline in perceptual abilities related to motion processing in individuals with cataracts (Ward et al., 2018). This was accomplished through the use of various computer-based tasks designed to assess threshold detection and discrimination in motion perception.

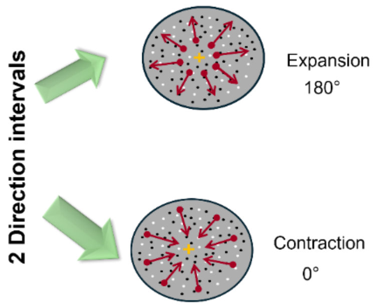
These data will enable the examiner to assess if there is any impairment in the dynamic vision of cataract patients in comparison to individuals of similar age. All stimuli were programmed and regulated using the Psychophysics Toolbox Version 3 (Brainard and Vision, 1997, Kleiner et al., 2007) add-in for MATLAB (MATLAB).

All psychophysical assessments (refer to Table 2.6) were conducted over multiple one-hour sessions. Observers were advised to take regular breaks within each session to maintain optimal levels of concentration and attention.

Table 2.6. A summary of the behavioural tasks used in this research.

	Task name	**Stimuli per trial**	**Task**

Speed	**Discrimination:** - Translational - Radial		*The observer's task was to decide which one of the radial/ or translational dots moving intervals was slower/ or faster?*
	Perception: - Reaction time - Motion perception		*The observer's task was to decide when target reached the end of the track.*
Direction	**Discrimination:** - Translational		*The observer's task was to decide which one of the intervals was moving more toward the right in CW direction.*
	Discrimination: - Spiral		*The observer's task was to decide which one of the intervals had dots with the "tightest" (most rotated) direction.*

Coherence	**Threshold:** - Radial		*The observer's task was to decide whether the signal dots were expanding or contracting.*

Chapter 3 **Survey**

3.1 Introduction

Evidence highlights that increased blur and reduced contrast sensitivity can impact perception of motion (Elliott et al., 1996, Fraser et al., 2013); two factors commonly present in cataract patients. However, typically clinical evaluations focus on distinguishing between the unhealthy and normal eyes, evaluating the degree of needed intervention and disease progression (Brown, 1993, Elliott et al., 1996, Wan et al., 2020b, Zhang et al., 2019). In order to begin investigating the perceptual experience of cataract patients, it is first important to qualify their subjective experience and to understand whether clinicians consider motion-related perception to be clinically relevant.

With regards to cataracts themselves, the main effect on the visual system is an increase in light scattering, either toward the retina or forward within the eye (Brown, 1993). This scattering causes reduced contrast sensitivity, glare and reduced visual acuity (Brown, 1993, Fraser et al., 2013) meaning the image reflected onto the retinal surface will be desaturated and reduced in contrast (Figure 3.1).

Figure 3.1. left picture shows normal vision for healthy eyes, right picture the cataract eye with reduced contrast using a simulated filter for grade III cataract (oxford grading) from (Brown, 1993).

However, this reduced image quality in cataract patients arises from a number of factors, not just as a result of the cataract formation and morphology, as it is also affected by the pupillary diameter and degree of cataract opacity filling the pupil (Brown, 1993, Fraser et al., 2013). Cataract patients typically suffer from glare in very bright light conditions like those found on a bright sunny day or at night when the light reflected from headlights especially when driving as it shown in Figure 3.2.

Figure 3.2. The effect of glare on cataracts: the left image depicts the image formed in a normal eye, while the right picture demonstrates an eye with cortical cataract and the glare from headlights from (Brown, 1993).

Other frequently presenting symptoms include myopic shift, astigmatism, colour vision shift, diplopia and diminished visual field (Brown, 1993). Figure 3.3 below shows a simulation of monocular diplopia in cataracts.

Figure 3.3. Image simulating monocular diplopia in cataracts by using 1 prism dioptre from Brown (1993).
Monocular diplopia, characterised by the perception of a single object as two overlapping or adjacent images in one eye, results in ambiguity within the visual system (Duke-Elder, 1973). This condition complicates the accurate tracking of moving objects, thereby introducing significant challenges in motion-related experiments by impairing visual clarity, motion processing, and contrast sensitivity. Furthermore, the presence of double images may create a misleading perception of an object's distance, leading to inaccuracies in speed estimation.

The effect of a cataract on a patients' daily life differs from one to another depending on the severity of the cataract and its morphological type (Elliott et al., 1990, Wan et al., 2020b, Zhang et al., 2019). Previous data show that cataracts can affect tasks ranging from mobility, near vision and discrimination (Elliott et al., 1990, Wan et al., 2020a), and evidence shows that cataract patients can present with normal visual acuity but still complain of many reduced visual functions (Elliott et al., 1996). Taken together, this highlights that using only the routine ocular examination of subjective and objective measurements may not be enough for a complete representation of their current functional abilities. It is essential to evaluate the degree of alignment between clinical examinations and patients' actual performance in real-world settings, as well as their ability to engage in daily life activities. This evaluation may be initiated through the implementation of a series of online surveys.

3.2 Methods

The first part of this research consisted in collecting information from the participants through three questionnaires.

The current data were gathered through online methods as well as through the distribution of flyers at Aston's laboratories and Eye Clinic, in addition to several non-NHS eye clinics. Participants were recruited via social media advertisements, email communications, and a notice placed at the entrance of Aston's Eye Clinic. Individuals self-selected to ascertain their eligibility based on the specified criteria for each questionnaire.

3.2.1 Participants

The present study employed an opportunity sampling method, enlisting individuals who voluntarily selected themselves based on the conditions required in an online questionnaire. Participants were encouraged to complete the questionnaire most related to their respective groups, thereby facilitating the collection of data from three distinct populations:

1. **Practising UK-Based Optometrists (ClinQ):** This group included 14 qualified optometrists actively engaged in practice within the UK. These participants contributed professional insights regarding clinical perspectives on cataracts and visual performance.

2. **Age-Matched Controls Without Cataracts (ContQ)**: A total of 7 individuals were recruited for this group. These participants were matched in age to the cataract patient group but had no prior history of cataracts or significant visual impairments, thereby serving as a baseline for comparative analysis.

3. **Cataract Patients (CatQ):** This group consisted of 5 patients diagnosed with cataracts, offering first-hand accounts of their lived experiences and the challenges associated with the condition. By focusing

on these specific groups, the study sought to capture a diverse array of perspectives while ensuring clear distinctions between the groups for the purpose of comparative analysis.

3.2.1.1 Group 1 (ClinQ):

Clinicians who responded had experience ranging from 8 months to 30 years and were located across a number of counties within England.

3.2.1.2 Groups 2 (ContQ) and 3 (CatQ):

Demographics and characteristics are summarised in Table 3.1. Both cataract and non-cataract (control) participants report comparable ages, with an average age of 60 years (±11) for the control group and 69 years (±7) for the cataract group. Two individuals from the control group indicated a diagnosis of myopia and elevated intraocular pressure, while one individual from the cataract group reported a diagnosis of glaucoma in both eyes. Given the limited sample size, these participants were included in the analysis.

According to the participants' reported habitual correction, two-thirds of control participants have low refractive correction while 70% of cataracts have moderate to high corrections. Two participants were not able to provide the type or severity of their cataract, but the remaining participants reported having mature or nuclear cataracts which will directly affect central light transmission of the eye and cause myopic refractive error (Pesudovs et al., 2004).

Table 3.1. Participants' demographic and ocular health

		Patients without cataract	Cataract patients
Age/yrs. (avg.)		60	69
Ocular pathologies	Myopia	1	
	Slight squint	1	
	IOP		
	Glaucoma		1
Cataract presence	OD		2
	OS		1
	OU		2
Type of cataract	Nuclear		2
	Cortical		1
	Posterior Subcapsular		0
	Not known		3
Best habitual prescription *	No to low prescription	4	1
	Medium prescription	1	
	High prescription	1	1

	Not known	2	
**The refractive error was classified in the following scheme: Myopia – low (0.00 to ≤ -0.50 D), medium (-0.75 to -4.50 D) and high (≥ - 5.0 D) (Flitcroft et al., 2019), hyperopia – Low (0.00 to +3.00 D), medium (+3.12 to +5.00 D) and high (>+5.00 D) (Benjamin, 2006).*			

3.2.2 Design

All of the surveys were distributed online using Microsoft Forms (see Appendices:

Appendix 1 – ClinQ to Appendix **3 – CatQ**).

3.2.2.1 ClinQ

A 13-question survey that combined qualitative "open" questions (8), yes/no questions (3), Likert scale questions (1), and ranking questions (1) was used to gauge clinician attitudes regarding the evaluation and referral of cataract patients. Table 3.2 shows the factors clinicians were asked to rank from most important for referring cataract patients to least important.

Table 3.2. Table showing factors for consideration. Factors marked with an asterisk are considered appropriate referral criteria by NICE.

Factors to be Ranked
Whether the patient is a driver
*The patient's reported quality of life
The patient's reported visual experience
*The potential for positive surgical outcomes
The measured VA
*The risks of surgery for the patient
*Whether the patient is requesting surgery
*If the cataract is bilateral, relative to unilateral
The patient's access to support (e.g. carers, family)
The patient's fear of leaving the cataracts any longer

3.2.2.2 ContQ and CatQ

Subjective assessment of vision and visual experience was measured using a 17-question survey that used a combination of qualitative 'open' (7), yes/no (3), Likert scale (4), and multiple choice (3). Importantly, three questions asked the patient to record the quality of their left eye, right eye, and both eyes respectively, ranging from 'extremely poor' to 'very clear'. One of the Likert scale questions asked participants to describe the impact of their cataract on daily activities that require motion perception e.g., driving, reading, walking, video calls. Each of the daily activities was split into visual disability categories in keeping with (Elliott et al., 1990): mobility, near, or discrimination (see Table 3.3).

Table 3.3. Table showing groupings of each question type from the Cataract Survey (see (Elliott et al., 1990)).

Question:	**Visual Disability Category:**
Driving	Mobility
Reading	Near
Walking indoors	Mobility
Walking outside	Mobility
Enjoying being a passenger in a car	Mobility
Reading moving LED signs (e.g. on a bus/ train)	Discrimination
Watching TV	Discrimination
Using your mobile phone	Near
Doing video calls	Discrimination

The multiple-choice questions featured three distinct low-contrast grating options: low, mid, and high. Each option represented a distinct spatial frequency. These gratings were viewed on the participants' personal screens, which included PCs, iPads, and other similar devices. As part of the online survey, participants typically positioned these screens at a comfortable viewing distance of roughly 40 cm, though the exact distance varied depending on individual preferences and home screen configurations. The gratings were either oriented vertically or drifted either leftwards or rightwards or were oriented horizontally and drifted upwards or downwards (see Figure 3.4). Participants had to select the option that best described the movement of the grating e.g., “vertical stripes moving left”. There was also an option to select “the video wouldn’t play/ technical difficulties” so as to remove any erroneous data.

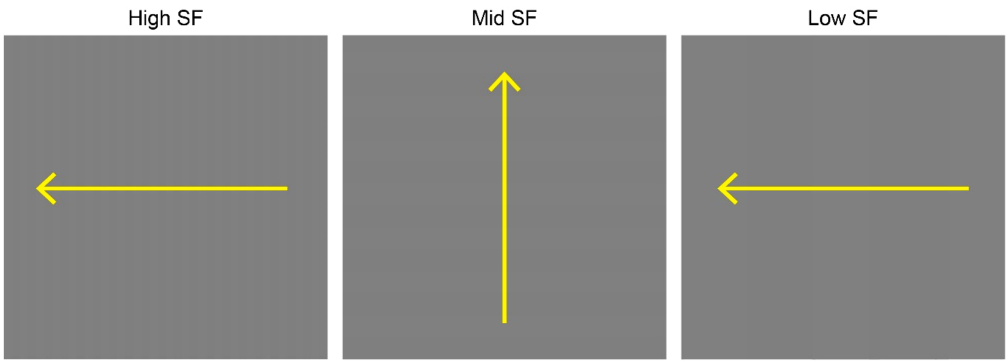


Figure 3.4. Stills from the drifting gratings shown in CatQ and ContQ. Yellow arrows indicate the direction of motion.

3.3 Results

3.3.1 ClinQ

In terms of motion-related vision, clinicians reported that patients seem to most commonly report struggling with driving, although one respondent mentioned that some patients report "dizziness and lack of orientation: unsteady vision when walking" (P7).

Likewise, 100% of respondents confirmed that they do ask open questions about the patient's visual experience, however respondents also highlighted that many patients might not openly discuss struggling with motion-related tasks, due to concerns that their driving licence might be taken away from them, which highlights that there may be a mismatch between the patients' reported vision and the need to refer them.

In response to the question about whether patients seem to report worse vision than the clinical examination would suggest, 14% said "rarely", 29% said "sometimes" and 57% said "often" (see Figure 3.5).

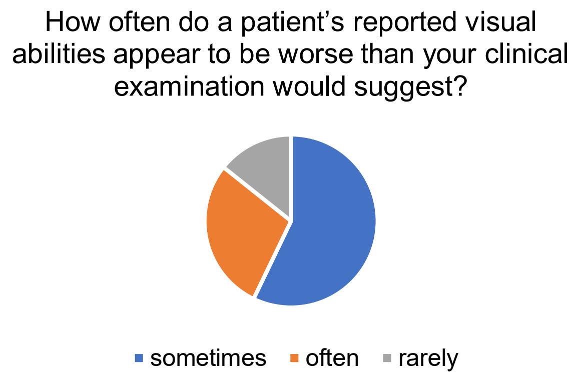


Figure 3.5. Pie chart showing responses to how often cataract patients feel that their vision is worse than the clinical examination would suggest.

In assessing the relative significance of the factors influencing referral decisions (see Table 3.2), "quality of life" was ranked as the most important factor by 71% of respondents. When the average rankings for each factor are examined, it becomes clear that the patient's quality of life (average score of 7.83), reported visual experience (average score of 7.88), driving status (average score of 7.88), and chance of successful surgery (average score of 7.88) are the most important factors (see Figure 3.6), The rankings show a relatively small margin of error, with the standard error of the mean (SE) for all factors being about 0.203. However, as is shown by the error bars, there was some amount of variability in the responses.

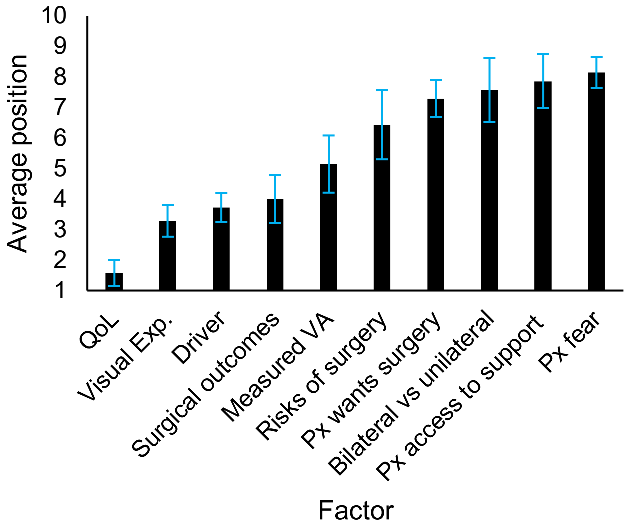


Figure 3.6. Average position in ranking of factors affecting decisions for cataract referral. A raking of 1 would be considered “most important”, whilst 10 is “least important”. Error bars show standard error of the mean (SE).

3.3.2 ContQ and CatQ

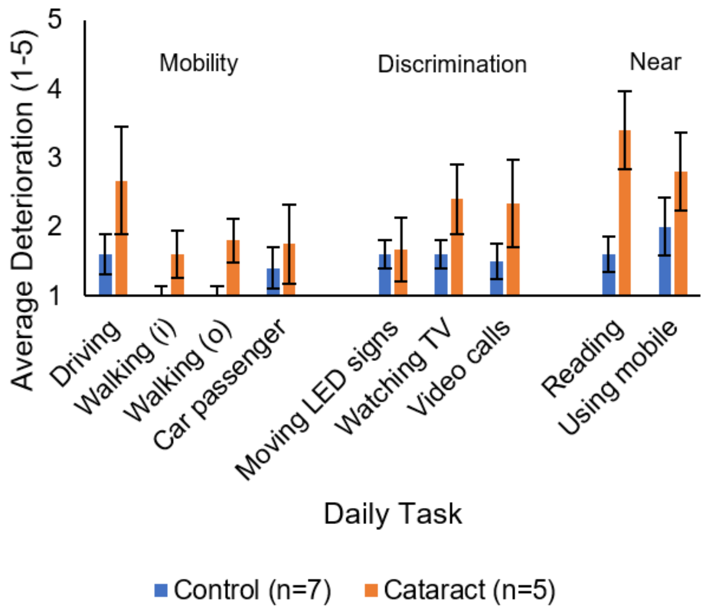


Figure 3.7. Shows the average reported decline in tasks for both the control (blue) and cataract (orange) participants in the three domains (mobility, discrimination, and near). Control participants reported a degree of deterioration in the last two years, while participants with cataracts reported a degree of deterioration since diagnosis (In a group of cataract patients, the average time since diagnosis was four years for the first patient, six years for the second, and two years for the remaining three. When these values were totalled, the average time since diagnosis for all patients was found to be three to two years). This figure provides a concise summary of the cohort's temporal progression from diagnosis to the current assessment point. A rating of five indicates a significant deterioration, while a rating of one indicates no deterioration at all. The standard error of the mean (SE) is displayed by error bars.

In comparison to the control group, cataract patients report worse performance on key daily tasks in all three domains, according to the data shown in the above figure (Figure 3.7). The daily activities of cataract patients were mildly to moderately impaired, whereas those of the controls were largely unaffected and almost normal.

It is difficult to analyse these data as the sample sizes are so small, but currently, it appears as though discrimination tasks show the smallest relative difference between the two groups. The majority of participants in both groups report deteriorated performance for tasks that requires near acuity: reading and using mobile phones, with those with cataracts experiencing twice the deterioration relative to the control group. Mobility tasks (e.g. driving and walking) affected cataract participants worse than control participants, especially for walking outside and inside where control participants reported no deterioration, but cataract participants reported a mild deterioration.

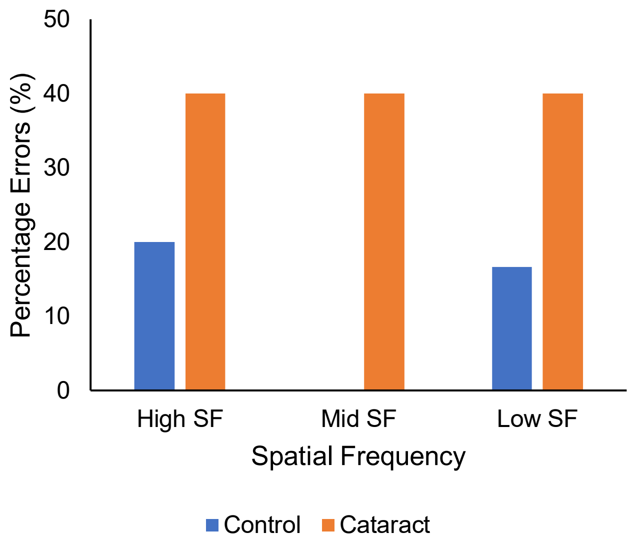


Figure 3.8. Percentage of errors for identifying the orientation and direction of the moving, low contrast gratings in the questionnaire. Control (blue) participants seem to make fewer errors than cataract (orange) participants across all levels of spatial frequency (SF).

Three moving, low-contrast gratings were shown to participants at three different spatial frequency levels during the experiment, and they were asked to report the orientation (e.g. vertical or horizontal) as well as the motion's direction (e.g. up, down, left, or right) of the gratings. While spatial frequency was systematically changed to evaluate how variations in line density affected perception, the gratings' contrast was purposefully kept low to test the participants' capacity to pick up on subtle visual information. Although these details are not stated specifically, it is likely that the contrast levels were constant throughout trials for a particular condition and that the videos were consistent in terms of duration, movement speed, and display settings to guarantee experimental control. To guarantee that only trustworthy data was included in the results, two participants from the control group who complained about technical issues with the videos were removed from the analysis for the impacted conditions. A focused investigation into the effects of spatial frequency and contrast on motion and orientation perception was made possible by the meticulous control of variables and attention to technical details, which also helped to preserve the integrity of the experimental design.

Although it is challenging to draw conclusions because of the small sample size, Figure 3.8 suggests that people with cataracts might have a harder time accurately determining orientation and direction from low contrast moving images over a wide range of spatial frequencies. 40 percent of the cataract participants, in fact, stated that they could only see a "grey square" for each of the videos, meaning they could not see any motion at all.

3.4 Discussion

3.4.1 ClinQ

The clinicians' questionnaire (ClinQ) results indicated that quality of life is the main factor that clinicians take into account when considering whether or not to refer a patient for surgery. However, there was a reasonable amount of variability in the ranking positions, where one respondent (P6) put quality of life as 4^{th} most important. Similarly, the factors that align with NICE guidelines for referrals (quality of life, surgical outcomes, risks of surgery, whether the patient wants the surgery, and whether the cataracts are bilateral) scored average rankings of 1, 4, 6, 7 and 8 respectively (see Figure 3.6).

According to clinicians' responses, the majority of their patients complained that they struggled with driving, and all clinicians agreed that cataract patients do not like to discuss their driving difficulties due to the fear of losing their driving licence, a poignant issue which highlights how important it is that clinicians are able to accurately assess the all-round, dynamic vision of the individual without needing to rely on subjective reports.

The data also show that half of the respondents indicated that their patients' actual visual experience is "often" worse than the clinical examination might suggest. Although there are several possible explanations for this, it seems likely that this will be because a high contrast visual acuity measure is not very ecologically valid as a stimulus. Instead, this highlights the importance of including the contrast examination for cataract evaluation and places a greater emphasis on finding ways to measure "real-world" visual elements, e.g., motion.

3.4.2 ContQ and CatQ

The results indicate that cataract patients may experience deteriorated performance for visual acuity tasks across all three tested domains (mobility, discrimination and near). These findings indicate that the perception of an individual with a cataract could be deteriorated for both the central and peripheral retinal areas, as their experience of all activities was deteriorated compared to the control groups (

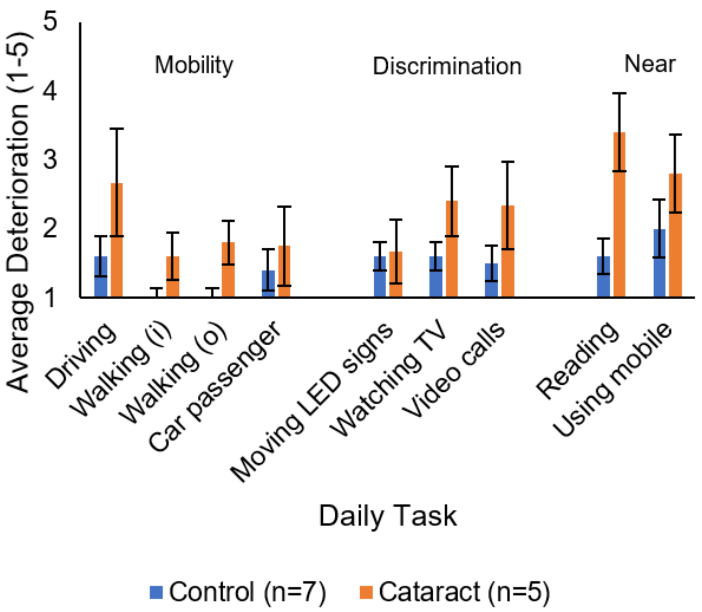


Figure 3.7). For example, the mobility activities (including walking and driving) have a contribution from peripheral retinal processing, and near tasks (including reading and using mobile phones) are processed by the central retinal area. Also, their motion detection and discrimination appeared to be deteriorated across all spatial frequency thresholds.

This reported deterioration is not an uncommon finding, as studies done by Elliot et al (1996) and Fraser et al (2013) found that daily tasks requiring the use of distance or near vision like reading, face recognition, walking, judging the speed of upcoming vehicles or moving objects, usually shows an acceptable performance in cataract patients under normal illumination levels. However, their perceptual and navigational abilities deteriorate significantly under dim illuminations. Supporting this outcome, Wan et al (2020) found that the ability to perform daily activities of severely deteriorated cataracts patients improved significantly after intraocular lens implantation (Wan et al., 2020a). These previous studies suggest that cataract patients might only experience minimal problems with daily life activities under normal light conditions but as the light changes and the illumination levels decrease, their capabilities may also decrease, as in twilight conditions. One consideration from this might be that those patients will be advised not to travel or drive at night (Fraser et al., 2013). However, provisional data from our online surveys shows that cataract patients believe themselves to experience deteriorating vision across all domains, and 40% of cataract respondents were unable to perceive motion in an animated video, which would suggest that the visual experience, particularly that of dynamic, moving vision, may be more affected in cataract patients than previously thought.

The findings from this study suggest that visual impairments caused by cataracts significantly affect the perception of moving gratings. However, it is important to consider potential confounding factors, such as the size of the video or the brightness settings of the devices used by participants to view the stimuli. For example, some cataract patients reported seeing the moving gratings as "grey squares," which could potentially be attributed to artificial effects caused by device settings. Fortunately, in this small sample size, the two individuals who reported seeing grey squares used the same device as one of the control participants, who was able to accurately perceive the orientation and direction of the gratings in all cases. This observation suggests that the perceptual deficit is more likely associated with the presence of cataracts rather than technical variations in device settings.

While the results provide valuable insights, several limitations must be acknowledged. First, the relatively small sample size poses a significant challenge to the generalisability of the findings. Recruiting additional participants, particularly those with cataracts, was difficult due to logistical constraints and the unique circumstances of the pandemic. A larger participant pool would strengthen the reliability of the results and allow for more robust statistical analyses, enabling broader extrapolation to the wider population.

A second limitation relates to the online nature of the survey. While this approach was necessitated by the pandemic, it introduced challenges in monitoring and controlling participants' environments. For example, it was impossible to verify whether participants adhered to instructions or responded honestly. These factors may introduce variability into the data, highlighting the need for caution when interpreting the results. Although the online format was the most practical solution during this period, future studies should aim to collect data in person to enhance reliability.

Finally, while the online survey served as a useful starting point, the data would be more reliable if tested in a controlled laboratory environment. Lab-based experiments would allow for precise control over variables such as stimulus presentation, lighting conditions, and participant behaviour, thereby enhancing the validity of the findings. However, logistical challenges during the pandemic limited the feasibility of conducting lab-based experiments at the time of this study.

Chapter 4 Filters and Cataract Simulation

4.1 Introduction

In the forthcoming behavioural experiments, simulated filters will be applied on young controls. Specifically, trying to create conditions that mimics cataract features and elderly vision generally as, for example: reduced retinal illumination and contrast (Spear, 1993). However, it is important to identify that ageing affects vision through a complicated interaction between neural and optical factors (Spear, 1993, Owsley, 2011). Although the most obvious indicators of age-related vision loss are frequently optical changes, such as decreased transparency of the ocular media, decreased pupil size (senile miosis), and increased light scattering from cataracts, they represent only part of the story. Neural changes also represent an important role, such as decreases in visual processing speed (Grady, 2012), reduced sensitivity to fine details (Owsley et al., 1983), deficiencies in glare recovery (van den Berg et al., 2009), and reduced motion detection (Trick and Silverman, 1991). For example, older adults frequently experience increased sensitivity to glare produced by bright lights or reflective surfaces, which can greatly affect everyday activities like driving at night or navigating environments with uneven lighting (Owsley, 2011). Furthermore, the process of neural adaptation to low-light environments tends to slow down as individuals age, which increases challenges faced in dimly illuminated environments (Jackson et al., 2002).

One of the most noticeable effects of cataract development is the progressive deterioration of various visual functions. Studies has indicated that stereopsis, or depth perception, often declines before there is a notable impairment in visual acuity (VA) (Wood et al., 2010, Brown, 1993). This earlier loss of stereopsis could be explained by conditions like the Pulfrich effect, where reduced light transmission in one eye disrupts binocular vision and depth perception (Pluháček et al., 2022). Light sensitivity, colour sensitivity, and contrast sensitivity are additional visual functions that are impacted. Although the Pulfrich effect may also contribute to distortions in depth perception, the focus of this study is on more general impairments in motion perception caused by cataract progression.

For the last century or so, the majority of clinical investigations into cataracts have evaluated visual functions by the way of viewing static objects; for example, using VA and CS charts (Long and Zavod, 2002, Wood et al., 2010, Sheedy and Bailey, 1993), neglecting the fact that in the real complex visual world, the majority of objects are dynamic rather than static (Wentworth and Buck, 1982, Sheedy and Bailey, 1993). Many methods for measuring dynamic visual functions have been developed in recent years. To evaluate people's reactions to dynamic objects or scenes, for example, behavioural science (psychophysical experiments) has been employed (Wentworth and Buck, 1982, Pelak, 2010). This approach will be described in experimental chapters (Chapter 5 to Chapter 8) within this thesis. However, depending solely on static clinical measurements presents a significant problem. High contrast levels (95–100 percent) are used for the majority of these tests, which do not adequately represent actual visual conditions (Long and Zavod, 2002, Pluháček et al., 2022). This chapter primarily addresses the significant issue of how reduced contrast, simulated through cataract filters, affects visual function, specifically visual acuity (VA) and contrast sensitivity (CS).

The main practical challenge encountered in this experiment was the effective simulation of cataracts, ensuring that all potential physical characteristics were adequately represented. Cataracts are not solely characterised by blurred vision and reduced visual acuity, which can be readily imitated using opaque materials (Pluháček et al., 2022, Wood et al., 2010). Rather, they encompass a variety of additional visual symptoms that considerably affect patients' vision. Among these symptoms, glare stands out as one of the most significant and well-documented effects (Long and Zavod, 2002, Brown, 1993). It is caused by the scattering of light rays in the existence of bright light when it passes through opacified media within the visual system, causing the light rays to deflect toward the retina, leading to the presence of a concept called retinal straylight that causes a blinding effect either at day or night time as in the presence of low sunlight levels or looking toward headlights at night (Brown, 1993, Long and Zavod, 2002, Spear, 1993). Glare is a very important factor as, it is the first complication cataracts will start to record even before their vision starts deteriorating measurably on an eye test chart, and this complication might be as important and serious to the cataracts that it might stop them driving at night, when it is still in its early stages of development (de Wit et al., 2006a, Pretto et al., 2012, Fraser et al., 2013). To effectively address the challenge of simulating cataracts, a set of professional camera lens filters (HOYA filters; for a complete description, (see Chapter 2 section 2.4.55) were used, these filters have a dual effect of scattering light rays and inducing a blurring effect. These filters have also been shown to mimic three phases of cataract conditions from mild with 75% to severe with 62% of light transmission. All these features collectively constructing an excellent tool able to replicate cataract condition in three different phases.

This chapter aimed to quantify the effects of the scatter filters, in order to determine the effect on visual experience, and to identify which type of cataract the filters most closely replicate.

4.2 Methodology:

4.2.1 Simulated cataracts

In practice there are two ways of simulating the visual experience observed through a cataract: the first involves using an optical system that interferes with the normal healthy system and therefore applies the physical changes that happens in cataract to that healthy one (de Wit et al., 2006b), and the most common strategy in this approach is to use simulating lenses or filters (de Wit et al., 2006b). The other approach involves presenting images or stimuli that have been deliberately distorted in their appearance to appropriate visual changes associated with cataract development (de Wit et al., 2006b).

In the current experiment the first approach (altering the optical system) was used to simulate the scatter of cataracts by applying optical physical changes using professional camera lens filters, which are typically used on top of cameras to induce haze or 'diffuse, soft light' in the photographs (see Figure 4.1Figure *4.1*). Almost all provided the desired visual acuity and contrast sensitivity values. Two different levels of filter were used (Fog A and Fog B) in combination to induce three levels of simulation: mild (1xA), moderate (1xB) and severe (2xB).

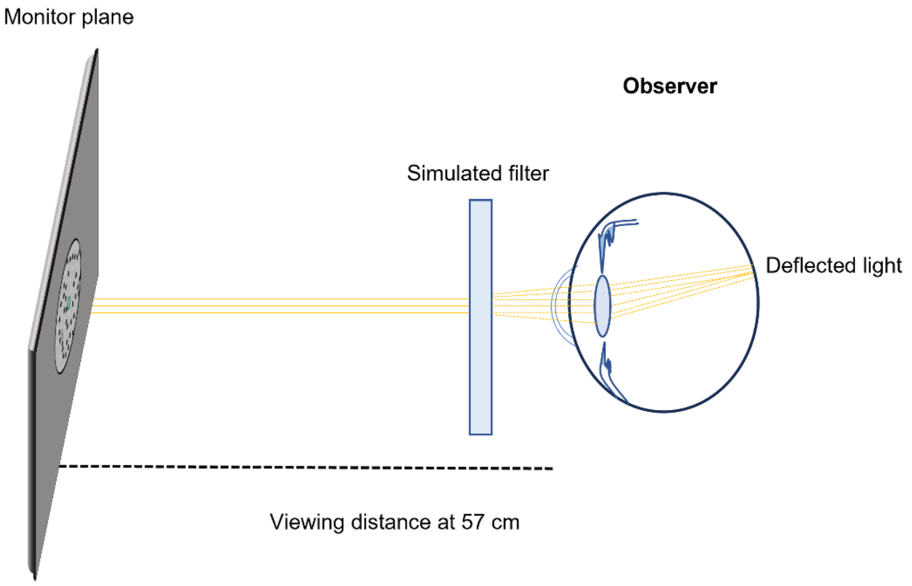


Figure 4.1. Schematic illustration showing the filters application in lab during behavioural experiments as an example, causing deflecting light resulting in scattering of light rays mimicking cataract conditions.

The influence of these filters on visual perception is demonstrated in **Error! Not a valid bookmark self-reference.**. The precise light transmission was assessed using a spectrometer, and research by de Wit et al (2006) indicates that the filters mimic the behaviour of cataracts. Similarly, the effect of the filters on individuals' visual function was measured and is shown in Table 4.2. These filters were measured and compared with the light scattering characteristics of people with cataracts.

Table 4.1. The effect of filters on vision across four conditions: no filter – natural eye, Mild filter -HFA, moderate – HFB, severe - HFBB. Applying these conditions to natural scenes and Pelli-Robson CS chart.

Eye simulation status Filter	**Light transmission**	**Real life image**	**Distance VA chart**
Natural eye No filter	100%		

Mild visual loss HFA	75.29%		
Moderate visual loss HFB	75.79%		
Severe visual loss HFBB	62.22%		

4.2.2 Visual acuity and contrast sensitivity

It is well known that developing cataracts affect visual functions (e.g., CS, colour sensitivity, light sensitivity) before showing a detectable reduction on VA tests (Wood et al., 2010, Brown, 1993, Zhang et al., 2008). In this experiment healthy individuals' visual functions were compared using simulated filters (explained above) to genuine cataractous vision.

4.2.2.1 Observers

For this experiment, seven observers (4 males, 3 females; age range 30 to 62 years) were recruited from staff members at Aston University. All the experiments were undertaken with the observers wearing their best refractive correction suitable for distance vision (6m), and these observers were compared to cataractous observers using their data from previous experiments (Chapter 2) age range (51 to 70 years). All observers were absent from any ocular pathological diseases, or neurological diseases that could affect their attention or perception. demographic data for all participants vs cataracts is presented in Table 4.2.

Table 4.2. The demographic data for the participants compared to cataracts averages. Gender information is abbreviated (M – male; F – female).

Observers	Gender	Age (years)
S 1	F	30
S 2	M	44
S 3	F	33
S 4	M	32
S 5	F	62
S 6	M	50
S 7	M	39
Cataracts	F (2)	60.5

4.2.2.2 Clinical investigations

Prior studies have indicated that achieving optimal Visual Acuity (VA), such as 6/6, does not necessarily ensure that an individual's overall visual performance is functioning at an optimal level (Elliott et al., 1996). This limitation leads to the recommendation that measuring CS may provide a more accurate reflection of describing the real visual functions (Roark and Stringham, 2019). For example, many cataract patients can achieve a 6/6 score on VA chart, however, in real life they experience glare and reduced CS which affects their day-to-day experience (Elliott et al., 1996, Brown, 1993). In light of this context, the decision was made to exclusively measure distance VA and CS in the current experiment. This choice is justified on two grounds: firstly, VA alone is inadequate to capture the full effect of visual impairments such as cataracts, and secondly, CS offers essential insights into functional vision that enhance the understanding of VA measurements. By concentrating on these two parameters, the objective was to achieve a balance between simplicity and clinical significance while facilitating meaningful comparisons with empirical data from individuals with cataracts. Data is presented in **Error! Not a valid bookmark self-reference.** where it's contrasted with data from individuals with actual cataracts.

This experiment was performed monocularly across all four simulated conditions (none, mild, moderate and severe using natural eye, HFA, HFB and HFBB filters) initiated with VA then CS. Prior to starting data collection the observers were asked to relax and blink many times, to make sure that they are comfortable (Bhootra, 2019). Visual acuity is recorded in logMAR, at distance of 3 m using a computed LCD monitor chart Rexxam (detailed examination procedure explained in Chapter 2).

Pelli-Robson chart, a commonly used tool for evaluating contrast sensitivity under controlled circumstances, was used to measure contrast sensitivity. In this test, observers were asked to read as many letters as they could see while seated one meter away from the chart (see Chapter 2, p 6657 for a detailed examination procedure). As advised by Bailey and Lovie-Kitchin (2013) and Bhootra (2019), the tests were carried out in well-lit environments. It's important to recognise the Pelli-Robson chart's limitations, though (Bhootra, 2019, Bailey and Lovie-Kitchin, 2013). Although it offers accurate contrast sensitivity measurements at a specific spatial frequency, it ignores how spatial frequencies change in various visual tasks and real-world situations (Bullimore et al., 1991, Owsley, 2003). Furthermore, the chart uses high-contrast letter recognition, which might not adequately account for the effects of glare or other dynamic visual impairments that people with cataracts frequently experience (Elliott et al., 1996, Pesudovs et al., 2004). The Pelli-Robson chart is still a useful and clinically validated technique for determining contrast sensitivity in controlled environments in spite of these drawbacks. **Error! Not a valid bookmark self-reference.** displays the visual data collected by observers under simulated conditions.

Table 4.3. The clinical data for the observers under simulating filters compared to averages of cataracts patients. Four levels of simulation applied: No filter -natural eye, Mild visual loss – HFA, Moderate visual loss –

HFB Severe visual loss – HFBB. Vision function tests include corrected distance visual acuity, DVA & contrast sensitivity, CS.

	No filter		HFA		HFB		HFBB	
	VA (logMAR)	Log CS	VA (logMAR)	Log CS	VA (logMAR)	Log CS	VA (logMAR)	Log CS
S 1	-0.22	1.90	-0.14	1.80	0.00	1.65	0.10	1.15
S 2	-0.16	2.00	-0.10	1.90	-0.10	1.65	-0.02	1.25
S 3	0.12	1.65	0.12	1.50	0.14	1.35	0.14	1.35
S 4	-0.16	1.65	-0.16	1.50	-0.08	1.35	0.06	1.35
S 5	0.12	1.50	0.20	1.65	0.30	0.90	0.30	0.90
S 6	0.10	1.50	0.20	1.50	0.30	1.65	0.30	1.65
S 7	-0.10	1.80	-0.10	1.50	0.00	1.20	0.00	1.20
Cataracts	0.00	1.50						

4.1 Results

From the short review above, key findings emerge the simulated cataract filters impaired observers' performance on both measures of visual function (VA and CS) compared with the baseline condition. The mean performance of the observers VA dropped using severe simulating filter (HFBB) to 0.13 Log MAR from -0.04 log MAR without filters. Similar results were found with CS, the difference in recordings for mean performance under HFBB filter was 1.26 log compared to 1.71 with normal condition as shown in Figure 4.2.

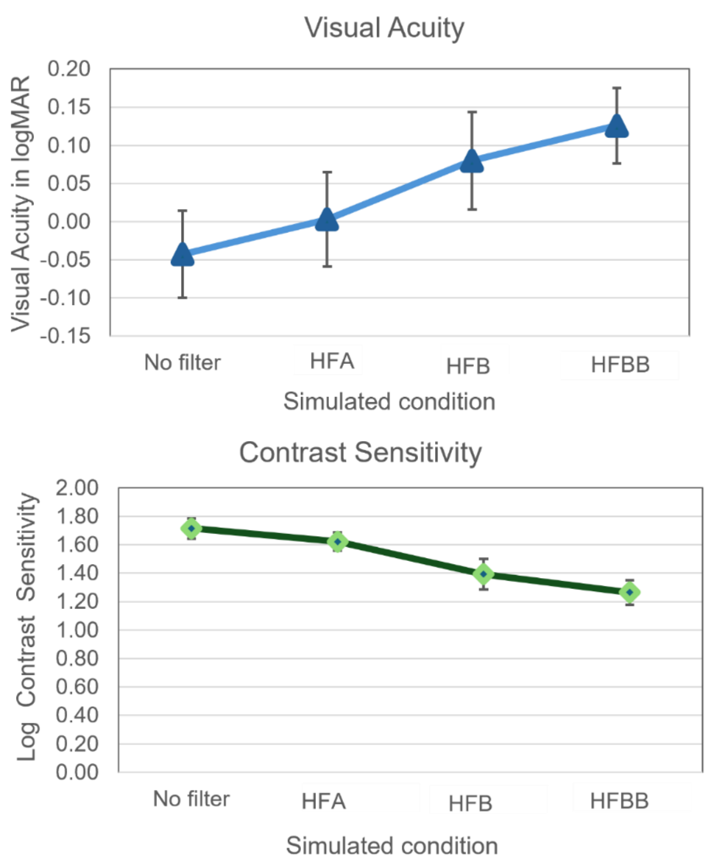


Figure 4.2. Bar charts showing average Log MAR data observers VA (top) and Log CS (bottom) under four simulated conditions that will be applied in lab for all upcoming behavioural experiments. Blue line shows VA

simulated cataract data, while green line shows data from CS simulation. Error bars show standard error of the mean (SE).

The detailed experimental data are presented in **Error! Reference source not found.**. These results s uggest that visual function performance is influenced by alterations in the ocular media, particularly the increased opacity associated with simulated cataract conditions. Specifically, as the ocular media exhibit greater opacity (for instance, due to the application of simulated filters), visual functions such as VA and CS are observed to decline. This correlation highlights the effects of light scattering and diminished retinal illumination on functional vision. To statistically evaluate these effects, a repeated measures ANOVA was performed to compare the clinical measures (VA and CS) across four simulated conditions (no filter, HFA, HFB, HFBB). The analysis indicated a significant relationship between the clinical measures and the simulated conditions, with a notably stronger effect observed for VA ($p = 0.001$) in comparison to CS ($p = 0.007$). The repeated measures ANOVA serves as a statistical technique to identify differences in means among related groups—in this instance, the performance of the same observers under varying simulated conditions. The results suggest that modifications in ocular media substantially impair visual function, with VA demonstrating greater sensitivity to these changes than CS. Additionally, a significant impact of age on CS was noted under the most extreme simulated condition (HFBB), with $p< 0.000$, indicating that older individuals may experience disproportionately greater reductions in contrast sensitivity when confronted with substantial ocular opacity

Table 4.4. The results of observers' performance using the simulated filters. The table shows the mean performance (with standard error, SE) across four simulated conditions in relation to three measures: VA, CS, and the interaction between age and CS under the severe simulated condition (HFBB)

Measures	**Mean performance (SE)**				**ANOVA**		
	No filter	HFA	HFB	HFBB	df	F	p
VA (log MAR)	-0.04 (0.06)	0.00 (0.06)	0.08 (0.06)	0.13 (0.05)	(3, 18)	16.51	0.001
CS (log CS)	1.71 (0.07)	1.62 (0.06)	1.39 (0.11)	1.26 (0.09)	(3, 18)	8.46	0.007
Age (years)*				41.43 (0.00)	(1, 6)	83.78	0.000
**The measure of age was calculated between Age and the CS of the HFBB filter.*							

Together, the present findings confirm that there is a relation between clarity of the optical media and visual functions, as alterations in ocular opacity - simulated through the application of filters - resulted in quantifiable reductions in both VA and CS. Notably, these visual functions are not solely determined by the clarity of the optical media; they are also substantially influenced by age. The data indicate that older adults exhibit a more marked decline in CS, particularly under conditions that mimic severe ocular opacity (HFBB, $p < 0.000$). This observation implies that the ageing process may intensify the effects of optical degradation, potentially attributable to age-related alterations in ocular physiology, such as diminished retinal function or heightened sensitivity to light scattering. These findings underscore the interplay between optical media clarity and age in determining visual performance, thereby highlighting the necessity of considering both variables in evaluations of functional vision.

4.2 Discussion:

In line with the published previous literature outcomes, visual conditions: CS and VA deteriorated for both normal simulated cataractous conditions moving towards more severe filters and cataract status. These findings agree with the research conducted by Long and Zavod (2002) and Wood et al. (2009; 2010), which indicated that simulated cataracts substantially impair visual function, resulting in quantifiable reductions in contrast sensitivity across all spatial frequencies. Particularly, the Pelli-Robson chart, used in this investigation to evaluate contrast sensitivity, assesses performance at a fixed spatial frequency of 1 cycle per degree (cpd). This spatial frequency is representative of medium-sized text or objects encountered in everyday life, thereby rendering it clinically relevant for the evaluation of functional vision. The results of this study indicate that simulated cataracts lead to a significant decline in CS at this spatial frequency, aligning with previous research findings.

The cataract simulating method applied in these experiments (either this or next behavioural experimental chapters) was using filters to mimic the physical interactions of light rays with the ocular media. These filters effectively replicate significant visual impairments associated with cataracts, including glare and blurriness, by scattering light rays as they traverse the filter material. Specifically, the filters simulate the opacification of the ocular lens, resulting in the scattering of incoming light in multiple directions rather than allowing it to focus sharply on the retina. This scattering phenomenon, referred to as retinal straylight, contributes to the perception of glare, particularly under bright lighting conditions or in high-contrast environments, such as when encountering headlights at night or sunlight during the day. Current methodology of employing optical filters, in contrast to alternative simulation techniques such as image processing—which involves generating images with diminished contrast to replicate cataracts—presents several advantages. By physically modifying the interaction of light with the ocular media, optical filters yield a more authentic and applicable simulation of real-world cataract conditions. This approach aligns with the findings of de Wit et al. (2006), who emphasised the superiority of optical simulation elements over image-based methods in generating ecologically valid assessments of visual function.

The application of simulated filters in experimental settings presents a valuable methodology for guiding clinical decisions regarding the appropriate timing for cataract surgery referrals. Although enhancements in VA are frequently regarded as the primary determinant for surgical intervention, the experiments point that an exclusive focus on VA may neglect other significant dimensions of visual function and overall quality of life. For example, symptoms such as glare, reduced contrast sensitivity, and challenges in performing daily activities (such as nighttime driving or reading in low-light conditions) can profoundly affect a patient's quality of life long before VA reaches clinically critical thresholds. By integrating findings from simulated cataract scenarios—specifically the impacts of glare and contrast sensitivity— a more comprehensive understanding can be gained of the necessity to address these broader functional deficits. This underscores the potential justification for considering cataract surgery as a proactive measure, rather than deferring intervention until VA declines. Such a perspective is consistent with contemporary trends in ophthalmology that prioritise complete patient care and the enhancement of quality of life as essential outcomes of cataract treatment (de Wit et al., 2006b, Brown, 1993).

It is considered important as the number of elderly people in the UK is rising steadily, with projections predicting that by the year 2066 there will be an additional 8.6 million people aged 65 and over (Storey, 2018). There is also the reported risk that patients who live with cataracts for over six months are more likely to experience vision loss, reduced quality of life, and an increased number of falls (Hodge et al., 2007).

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Chapter 5 **Investigating the Effect of Light Scatter on** Speed Discrimination

5.1 Introduction

This thesis explores motion perception and investigates its importance. Prior theoretical developments highlight that early childhood is a critical developmental stage when the capacity to perceive and interpret speed emerges (Ahmed et al., 2005, Braddick et al., 2003, Wattam-Bell et al., 2010). This process is essential for encoding the speed of a moving object, enabling individuals to sustain visual attention on the object and proficiently direct their actions towards it within a dynamic environment (Braddick et al., 2003). The human visual system's ability to integrate local motion cues to form a unified perception of motion across the visual field is referred to as Global Motion Perception (GMP). This process allows for the precise determination of motion speed and direction (Yan et al., 2023).

Furthermore, it is essential to precisely represent the relative velocities of objects within the visual field to aid locomotion. This is particularly significant as retinal motion is continuously activated by a combination of ocular shifts, self-motion, and the movement of objects. (Braddick et al., 2003). The information processed by the human brain arises from the dynamic and often distorted images that objects in our environment project onto the retina. Fascinatingly, the brain uses a process known as saccadic suppression to eliminate the perception of distorted or blurred motion during fast eye movements called saccades. This ensures a steady visual experience even when eye movements are constant (Bridgeman et al., 1975, Thiele et al., 2002). During fast eye movements, or saccades, a neural mechanism known as "saccadic suppression" temporarily lowers visual sensitivity to minimise motion blur and maintain visual stability. This phenomenon demonstrates how the brain can effectively filter out distracting or superfluous information, enabling more meaningful and clear visual processing (Matin, 1974). This process aids in our understanding of our own location and the proximity of objects as we move through our environment. Another set of visual functions that motion data supports include object recognition, depth perception, trajectory tracking, and scene segmentation (Manning et al., 2012). For example, during self-motion, motion parallax, a depth cue derived from relative motion, is essential for differentiating between objects at different distances (Nawrot and Stroyan, 2009). Perceiving speed has practical applications as well (see Chapter 6), such as when deciding whether to cross a road, which significantly depends on person’s ability to gauge a vehicle's speed. According to studies, humans are skilled at calculating the time-to-contact (TTC) of approaching objects—an essential ability for surviving in dynamic environments (Regan and Gray, 2001). Hence, gaining insights into how speed discrimination is perceived in diverse environments is of utmost importance (Warren Jr and Saunders, 1995).

Translational motion trajectories are computed in the V5/MT+ area from the projections extended from the primary visual cortex (Majaj et al., 2007, Rust et al., 2006). Visual motion perception has been shown to adapt and adjust over time, as it is influenced not only by the immediate physical motion of a stimulus but also by other contextual factors. This means that our perception of motion is not static;

rather, it is continuously refined based on prior experiences, environmental conditions, and the characteristics of the stimulus itself (Thompson, 1982). One important factor is environmental contrast, as many psychophysical studies have shown that stimuli in low-contrast environments seem to move more slowly. (Thompson, 1982, Stone and Thompson, 1992).

Cortical area V5/MT+ has a fundamental role in motion perception as it is understood to be the prime area where the first detection of motion stimuli signals are evaluated and combined (Edwards and Badcock, 1995, Gilmore et al., 1992). Research involving adult humans has also demonstrated the involvement of V5/MT+ in the processing of speed (Huk and Heeger, 2000). An fMRI study done by Huk and Heeger (2000) indicated increased activity in the MT region during a speed discrimination task compared to a contrast discrimination task. Furthermore, research conducted by Corbetta et al. (1991) using positron emission tomography (PET) revealed heightened neural activity in the middle temporal area when attention was directed towards speed as opposed to shape or colour. Hence, it is anticipated that the ability to discern speed in tasks will depend on the unification of signals within motion-sensitive regions, such as area V5/MT+ (Huk and Heeger, 2000, Corbetta et al., 1991).

Motion information is processed by the dorsal stream of the brain, where area V5/MT+ integrates the local motion signals processed in primary visual cortex into global motion signals (Aaen-Stockdale et al., 2007, Yamasaki and Tobimatsu, 2011). In the real-world, many types of motion signals are present, including the global- radial optic flow and local- translational motion signals shown in Figure 5.1. Within motion perception, a well-known phenomenon known as the 'aperture problem' occurs when local motion signals are not enough to accurately determine an object's global motion (Trick and Silverman, 1991, Adelson and Movshon, 1982, Fennema and Thompson, 1979). This happens because motion is first processed by the visual system in small, localised areas of the visual field, which can cause ambiguity in determining the actual direction or speed of an object's movement. For example, it is challenging to determine the true global motion when viewing an object through a narrow aperture because only the motion component perpendicular to the object's edges is detected (Adelson and Movshon, 1982, Burr and Thompson, 2011). Therefore, this makes identifying actual objects speeds challenging for individuals (Adelson and Movshon, 1982, Fennema and Thompson, 1979). This limitation makes it more difficult to accurately identify object speeds as it is not always straightforward to incorporate local motion signals into a coherent global representation (Fennema and Thompson, 1979, Pack and Born, 2001).

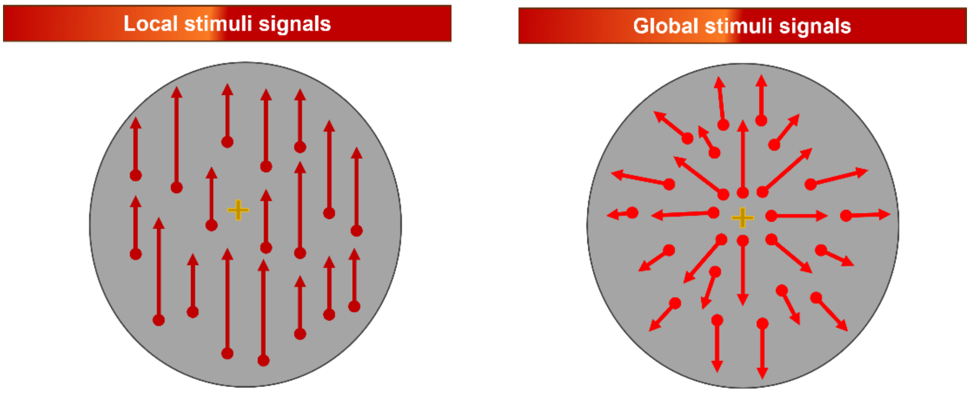


Figure 5.1. Visual motion stimuli used in this study. (a) local or translational stimuli that moves vertically upwards. (b) global or radial stimuli that moves radially and outward.

It is of interest to examine whether perceived variations in environmental contrast, such as those brought on by cataracts or foggy conditions, have an impact on motion perception in a way that is consistent with results from controlled psychophysical studies. Physiological research has shown that neurons in the visual cortex generally respond more strongly to stimuli with higher contrast, with firing rates increasing uniformly as contrast levels rise (Thompson et al., 2006, Priebe et al., 2003). However, speed information needs to be encoded differently from contrast, involving a neural mechanism capable of separating these two variables (Stone and Thompson, 1992). For instance, the lower-contrast grating is always seen as moving more slowly than the higher-contrast grating when two gratings have the same velocity but different contrast (Stone and Thompson, 1992). This effect shows how contrast affects perceived speed, potentially leading to slower perceived motion in low-contrast settings such as fog.

Numerous studies have explored the influence of the natural ageing process on speed perception, revealing a correlation between advancing age and reduced speed accuracy in perceiving motion (Allen et al., 2010, Snowden and Kavanagh, 2006). Specifically, older adults frequently need faster speeds to determine the velocity of moving objects accurately, indicating a decline in motion sensitivity with age. This raises a significant concern for the current research regarding how age-related decreases in speed perception affect the understanding of results obtained from modern simulations. The group of cataract patients in this study includes older adults who do not match the age of the control group used in the simulations. This adds a possible confounding factor, as the observed differences in speed perception could be attributed to either the presence of cataracts or the natural effects of ageing. In order to address this, it is essential to interpret the results while taking into consideration the baseline variations in speed perception brought on by ageing. For example, future studies might include age-matched control groups or make statistical adjustments for age-related influences to better isolate the role of cataracts in affecting motion perception. This approach would help ensure that the results truly represent the effects of cataracts, rather than mixing them with the overall impacts of ageing.

Research has shown that visual factors such as blurriness and reduced contrast can significantly influence the perception of speed. For instance, Orban et al. (1984) found that lower contrast levels make it harder to differentiate between speeds, particularly for both slow and fast movements. This suggests that contrast plays a crucial role in how humans perceive motion. Building on this idea, it is proposed that variations in contrast range will affect speed discrimination performance. To explore this further, the current study investigates how light scatter, simulated with optical filters, affects the ability to discern speed. The research specifically aims to clarify how light scatter might hinder or change the accuracy of speed perception and discrimination.

This experimental section contributes to the existing body of literature by investigating the influence of speed on the perceived motion of global and local patterns. This experiment distinguishes itself through several key elements: (1) all stimuli used are uniform and exhibit two different motion directions (translation or radial), ensuring constant spatial frequency and orientation; (2) a comparison of the perceived speed of radial (expansion) and translation (moving up) motion under identical speed threshold conditions; (3) an investigation into whether a singular dimension of movement is sufficient to elicit a preference for speed; and (4) an exploration of the potential correlation between adjustments in the apparent speed of motion within specific speed intervals and changes in perceived contrast by using simulated filters.

5.2 Methodology

The ability of humans to discriminate variations in speed can be assessed by instructing observers to differentiate the relative speeds of two consecutively presented stimuli intervals moving at varying velocities. In a study conducted by de Bruyn and Orban (1988), it was observed that individuals were able to discriminate random dot speeds within the range of 0.5–256° of visual angle per second. Discrimination performance within this range exhibited variability, with best speed perception discrimination occurring at intermediate speeds and poor discrimination at the extremes (De Bruyn and Orban, 1988). Orban et al. 1984 also reported similar discrimination characteristics when using a moving bar stimulus (Orban et al., 1984).

The RDK is widely used for the evaluation of motion perception in various research studies (Pilz et al., 2017, Ward et al., 2018), which involves a group of signal dots moving in a coordinated manner in a specific direction, while other dots, referred to as noise dots, move in various random directions. The observer’s task is to identify the speed of the presented moving dots, using a speed threshold, that represents the minimum proportion of single dots required to correctly identify the speed of translational or global motion task intervals, a higher speed threshold indicated poorer performance and worse global / translational motion sensitivity.

5.2.1 Observers:

Preceding the behavioural experimental data collection, clinical evaluations (of vision) corresponded to that described in Observer Groups of General Methods. The experimental procedure was divided into two experiments: Local (translational) and global (radial) experiments, the detailed experimental scheme is illustrated in Figure 5.2.

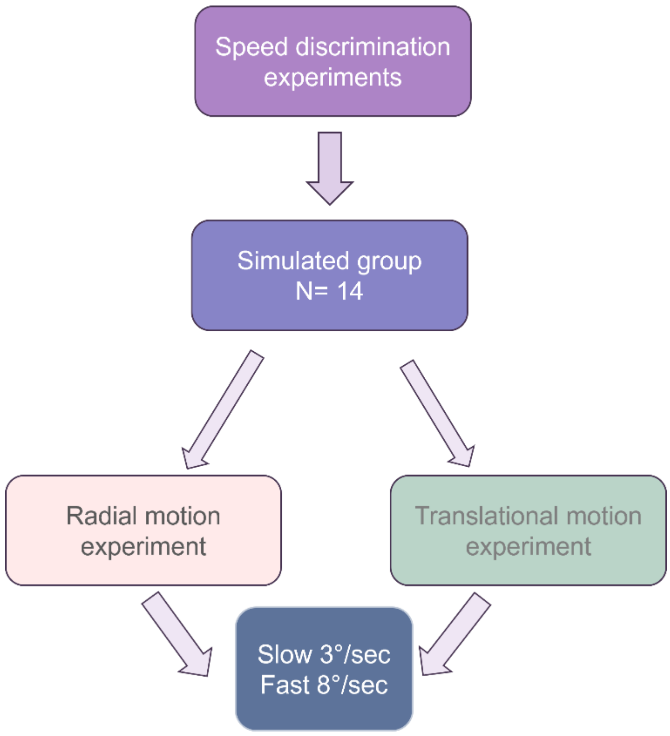


Figure 5.2. A schematic illustration of the directional experiment divisions and included observers in each experiment. Two experiments were implemented for studying speed discrimination, fourteen observers joined the translational and radial motion experiments.

Fourteen observers were included in the "simulated" group (n= 14; age range 20 to 43 years with median of 26.5) of the motion discrimination experiment. All observers were absent from any ocular pathological diseases, or neurological diseases that could affect their attention or perception. Vision data for observers is presented in

Table *5.1*.

Table 5.1. The clinical and demographic data for the observers. Vision tests include (corrected distance visual acuity, DVA; corrected near visual acuity, NVA; contrast sensitivity, CS). Gender information is abbreviated (M – male; F – female).

	Translational & Radial motion for simulated group observers

Experimental groups	< 30 years	≥ 30 years
Number of observers (Gender)	8 (7 F, 1 M)	6 (3F, 3M)
Age (Average ± SE)	22.75 ± 0.92	34.83 ± 2.24
DVA @ 3m in log MAR (Average ± SE)	-0.11 ± 0.03	-0.17 ± 0.02
NVA @ 40 cm in log MAR (Average ± SE)	-0.15 ± 0.03	-0.14 ± 0.03
CS **@1m** (Average ± SE)	1.86 ± 0.04	1.78 ± 0.09

The visual recordings for the observers were determined by assessing the visual acuity measurements of the BCVA for the eye that was used during the behavioural experiment, which was consistently the right eye.

5.2.2 Stimuli and behavioural experimental procedure:

5.2.2.1 Apparatus

The experimental apparatus applied in this study is thoroughly detailed in Chapter 2.

5.2.2.2 Design

In this study the speed experiment was performed under two interval forced choice procedure (2IFC) using a method of constant stimuli (MOCS) (as described in **Error! Reference source not found.** of Chapter 2). In this method, the stimulus magnitude on each trial is randomly selected from a predefined set (Schwartz, 2006).

Motion perception was tested psychophysically by using RDKs to measure speed discrimination thresholds (Hutchinson et al., 2012)(Figure 5.3). The speed discrimination experiment tested two types of motion: local motion (translational) and global motion (radial), across two different reference speeds: slow (3°/s) and fast (8°/s). RDKs were generated and presented using MATLAB R2019 (MATLAB).

The 500 white moving dots (Figure 5.3) were presented within a central circular display, on a homogenous grey background. Each individual dot had a diameter of 0.2 degrees and the aperture had an overall density of 0.69 dots/deg^2. The RDK intervals were presented for 0.2s. Dot density, size, brightness, displacement, radius, background brightness, and spatial of set were kept constant.

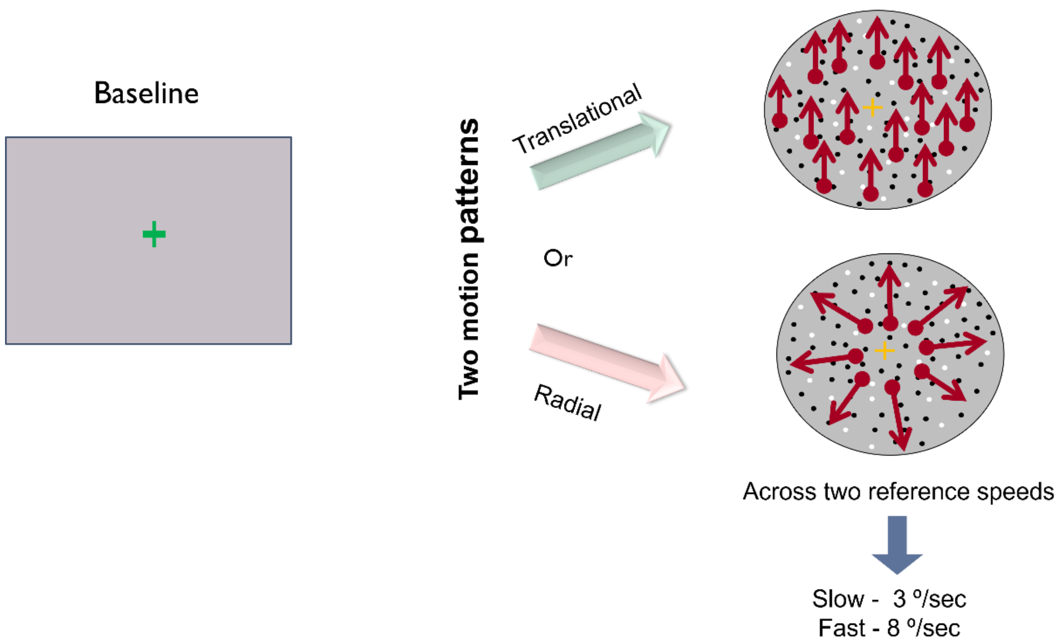


Figure 5.3. Experimental protocol, a static screen show. Two behavioural experiments were used in this task the translational and radial, both experiments were performed under two reference speeds – slow (3°/sec) and fast (8°/sec).

During the speed discrimination experiments, two intervals were presented each time with random choice for the intervals relying on whether the slow or fast experiment were running, at reference speed (3°/sec for slow, 8°/sec for fast) representing one of the intervals whilst the other interval would present a test speed, moving at one of the seven levels around the reference speed (see

Table 5.2). The difference between the speed levels was determined by the step size required for the observer to be able to recognise the difference between speed intervals. Most observers required a step size between 15 – 20, suggesting individual differences between the observers. However, the difficulty was stable depending on the capability (

Table 5.2) to respond during the demo test. On every trial the observers were asked to indicate which interval contained the dots with fastest speed e.g. if one interval contained dots moving at 8°/sec and one contained dots moving at 9.2°/sec then they should indicate that 9.2°/sec is faster.

Table 5.2. Table showing how different step sizes varied between presented speed levels in (°/sec) led to different presentations of test speeds for the translational and radial tasks.

Experiment speed type	**Step size**	**Reference speed**	**Speed (°/sec)**						
Slow	15	3°/sec	1.97	2.26	2.60		3.45	3.96	4.56

	20		1.73	2.08	2.50	3.00	3.60	4.32	5.18
Fast	15	8°/sec	5.26	6.04	6.95	8.00	9.20	10.58	12.16
	20		4.62	5.55	6.66		9.60	11.52	13.82

5.2.2.3 Procedure

A random key press started the test, and a subsequent trial did not begin until a response had been recorded for the previous trial. Before beginning the motion task, observers were presented with a green central fixation cross on a homogenous grey background (Figure 5.4).

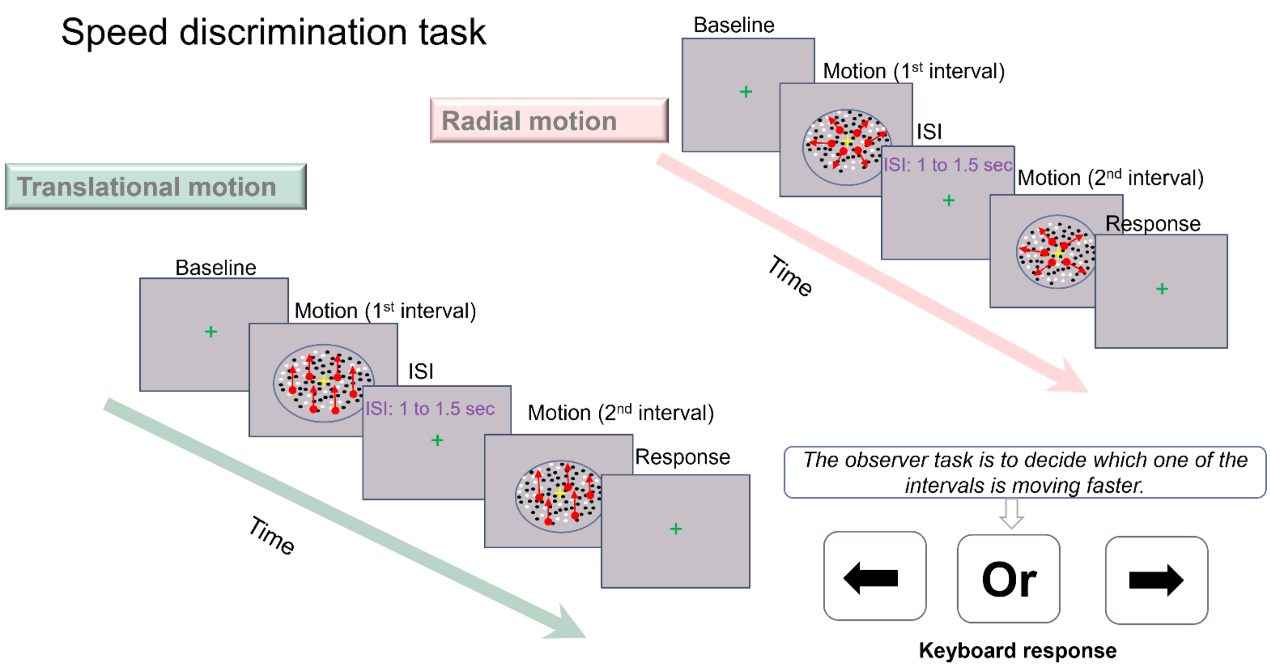


Figure 5.4. Overall procedure using translational and radial motions as an example. The test started with a grey screen containing green central cross that was used as a fixation point during the experiment, a key press required to start the task then two sequential intervals were presented on the screen requiring from the observer to indicate which interval contained faster moving dots.

Subjects were presented with a series of 2IFC. One of the intervals (at random on each trial) contained a moving pattern in which all elements moved in either a translational or radial direction, depending on the condition. In the other interval, the same moving pattern appeared but with different speed of the elements. The observers' monocular task was to keep their eyes always fixated on a central cross and to indicate which one of the intervals contained the faster dots (Figure 5.4).

5.2.3 Psychometric function (PSF)

In psychophysics it is possible to calculate the difference between thresholds, which is called the just noticeable difference (JND) or difference threshold (chapter 2) and it refers to the smallest detectable difference between a starting and a secondary level of a specific sensory stimulus (in full details in of

Chapter 2) (Naseri and Grant, 2012). The JND values for individuals who participated in these experiments are detailed in tablesTable *5.3*

Table *5.4* for translational and radial motion patterns.

Table 5.3. Showing the individual JND values for translational motion pattern corrected by Weber fraction for slow and fast speeds by diving the JND value by applied reference speeds (JND/ 3°/sec and JND/ 83°/sec for slow and fast speeds respectively

Translational								
	Slow 3°/s				Fast 8°/s			
Observer	Baseline	Mild	Moderate	Dense	No filter	Mild	Moderate	Dense
SC 1	0.15	0.17	0.22	0.18	0.11	0.10	0.13	0.15
SC 4	0.23	0.19	0.19	0.24	0.14	0.12	0.10	0.12
SC 5	0.11	0.17	0.13	0.15	0.07	0.05	0.12	0.16
SC 7	0.73	0.43	0.98	0.34	0.23	0.22	0.22	0.22
SC 9	0.24	0.21	0.17	0.18	0.15	0.17	0.17	0.24
SC 10	0.29	0.17	0.22	0.25	0.13	0.18	0.17	0.14
SC 11	0.28	0.36	0.24	0.28	0.14	0.14	0.13	0.15
SC 13	0.11	0.21	0.13	0.15	0.13	0.13	0.10	0.11
SC 14	0.15	0.16	0.18	0.15	0.11	0.13	0.13	0.12
SC 15	0.14	0.15	0.17	0.15	0.11	0.10	0.12	0.14
SC 21	0.08	0.15	0.16	0.14	0.06	0.07	0.08	0.05
SC 22	0.08	0.14	0.14	0.14	0.09	0.13	0.11	0.10
SA 2	0.40	0.32	1.05	0.51	0.22	0.26	0.28	0.26
SA 3	0.25	0.16	0.15	0.21	0.16	0.15	0.15	0.15
Average	*0.23*	*0.21*	*0.30*	*0.22*	*0.13*	*0.14*	*0.14*	*0.15*
SD	*0.17*	*0.09*	*0.31*	*0.10*	*0.05*	*0.06*	*0.05*	*0.06*
SE	*0.05*	*0.02*	*0.08*	*0.03*	*0.01*	*0.01*	*0.01*	*0.02*

Table 5.4. Showing the individual JND values for radial motion pattern corrected by Weber fraction for slow and fast speeds by diving the JND value by applied reference speeds (JND/ 3°/sec and JND/ 83°/sec for slow and fast speeds respectively

Radial

	Slow 3°/s				Fast 8°/s			
Observer	Baseline	Mild	Moderate	Dense	No filter	Mild	Moderate	Dense
SC 1	0.15	0.19	0.23	0.23	0.08	0.12	0.13	0.14
SC 4	0.12	0.13	0.15	0.10	0.06	0.09	0.09	0.09
SC 5	0.08	0.09	0.13	0.13	0.08	0.09	0.09	0.09
SC 7	0.20	0.25	0.32	0.25	0.13	0.17	0.12	0.22
SC 9	0.15	0.20	0.22	0.20	0.01	0.15	0.10	0.10
SC 10	0.12	0.12	0.22	0.21	0.09	0.07	0.14	0.13
SC 11	0.11	0.12	0.15	0.26	0.12	0.15	0.08	0.14
SC 13	0.11	0.11	0.13	0.15	0.09	0.09	0.09	0.09
SC 14	0.08	0.11	0.06	0.08	0.09	0.09	0.08	0.09
SC 15	0.13	0.11	0.10	0.10	0.08	0.09	0.09	0.09
SC 21	0.08	0.09	0.11	0.09	0.05	0.05	0.06	0.05
SC 22	0.21	0.21	0.20	0.27	0.13	0.12	0.12	0.13
SA 2	0.21	0.25	0.28	0.25	0.13	0.17	0.15	0.15
SA 3	0.22	0.21	0.24	0.24	0.13	0.13	0.13	0.18
Average	*0.14*	*0.16*	*0.18*	*0.18*	*0.09*	*0.11*	*0.10*	*0.12*
SD	*0.05*	*0.06*	*0.07*	*0.07*	*0.04*	*0.04*	*0.03*	*0.04*
SE	*0.01*	*0.02*	*0.02*	*0.02*	*0.01*	*0.01*	*0.01*	*0.01*

This chapter focuses on the calculation of the relationship between observer performance and the intensity of RDK stimuli, for which the logistic psychometric function is identified as the most suitable statistical model. As elaborated in section 2.4.6.1 of Chapter 2, the logistic psychometric function is particularly effective for analysing data obtained from psychophysical experiments. This methodology not only corresponds well with the characteristics of the data presented in this chapter however also offers a solid framework for interpreting results in future analyses.

The PSF was generated using the Psychtoolbox on MATLAB software. To determine the JND for each individual, trials were combined across speed, directional patterns, and simulated statuses. A logistic function was then fitted to plot the proportion of responses against target speed. The JND values were calculated as the change in stimulus intensity between the point of subjective equality (PSE) and the 75% detection threshold.

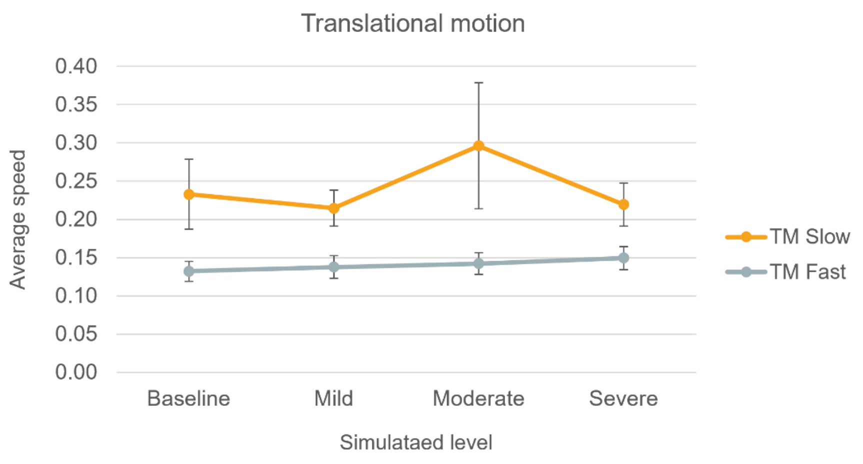
5.2.4 Statistical analyses

An analysis was undertaken to examine variations in speed perception across different simulated patterns and directional speed patterns. This analysis involved the calculation of average JND values using a Microsoft Excel spreadsheet. The data were obtained from diffuse measurements of JNDs related to speed perception. Initially, the JND values were averaged in Microsoft Excel to create a consolidated dataset. These averaged values were subsequently imported into IBM SPSS software for advanced statistical analysis. A repeated measures analysis of variance (ANOVA) model was applied to evaluate the impact of the simulated conditions on speed perception. The ANOVA was performed independently for each of the four filter conditions: no filter, mild, moderate, and severe. These conditions included translational motion patterns at both slow and fast speeds, as well as radial motion patterns at slow and fast speeds.

5.3 Results

The results present two speed thresholds to illustrate differences in motion perception across four simulated conditions: Baseline (no filter), mild (HFA), moderate (HFB), and severe (HFBB). These conditions correspond to varying levels of media contrast alterations, simulating the effects of cataracts in an adult group. The findings aim to elucidate the relationship between reduced media contrast in the simulated conditions and its impact on speed perception. For translational motion (Figure 5.5), the results are presented separately for fast and slow speeds, for the simulated groups. The mean speed thresholds for 14 observers are illustrated, highlighting key trends. Notably, there does not appear to be a significant effect of stimulus contrast (or media opacity) on speed thresholds. However, the data suggests that thresholds for faster translational speeds were generally higher than those for slower speeds, indicating potential differences in perceptual processing based on velocity. a clear and organised manner.

(a)



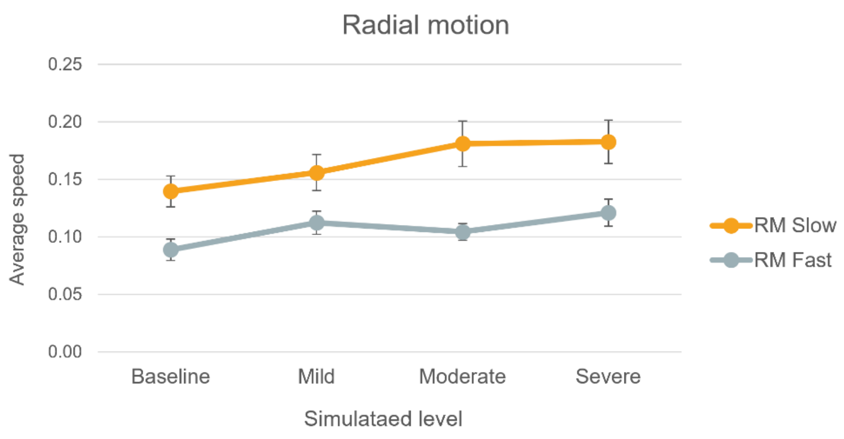
(b)

Measures	ANOVA test results		
	df	F	*p*
TM Slow	(3,39)	1.360	0.273
TM Fast	(3,39)	1.603	0.204

Figure 5.5. Line graph showing the average Weber JND data for translational test directions motion across four simulated levels (Baseline, Mild, Moderate, Severe) for two conditions: "TM Slow" (slow speeds) and "TM Fast" (fast speeds). Error bars represent the standard error of the mean (SE). Below the graph, ANOVA test results are presented, showing the degrees of freedom (df), F-values, and p-values for each condition.

The average speed thresholds for translational motion are depicted in the line graph in Figure 5.5 for the four simulated levels: Baseline, Mild, Moderate, and Severe. Data is shown separately for the two conditions "TM Slow" (slow speeds) and "TM Fast" (fast speeds). The standard error of the mean (SE), which shows variation within each condition, is represented by error bars. While moderate distortions seem to disproportionately affect "TM Slow," with a discernible peak in thresholds, a visual examination of the graph shows a modest increase in speed thresholds for both slow and fast speeds under mild distortions when compared to baseline. On the other hand, "TM Fast" stays largely constant throughout all simulated levels, indicating that faster speeds are less prone to distortions. The four simulated levels' speed thresholds did not, however, differ significantly for either condition, according to statistical analysis using repeated measures ANOVA: $F(3, 39) = 1.360$, $p = 0.273$ for "TM Slow," and $F(3, 39) = 1.603$, $p = 0.204$ for "TM Fast." These results show that whether the motion was slow or fast, the simulated distortions had no discernible effect on how translational motion speeds were perceived. The lack of statistical significance raises the possibility that the precise kind or degree of distortion used was insufficient to alter motion perception in a way that could be measured.

(a)



(b)

Measures	ANOVA test results		
	df	F	*p*
RM Slow	(3,39)	7.333	0.002
RM Fast	(3,39)	4.802	0.008

Figure 5.6. Line graph showing the average Weber JND data for Radial test directions motion across four simulated levels (Baseline, Mild, Moderate, Severe) for two conditions: "RM Slow" (slow speeds) and "RM Fast" (fast speeds). Error bars represent the standard error of the mean (SE). Below the graph, ANOVA test results are presented, showing the degrees of freedom (df), F-values, and p-values for each condition.

With data shown separately for "RM Slow" (slow speeds) and "RM Fast" (fast speeds), the line graph in Figure 5.6 shows the average speed thresholds for radial motion across four simulated levels: Baseline, Mild, Moderate, and Severe. The standard error of the mean (SE), which shows variation within each condition, is represented by error bars. Visual examination shows that faster radial motion ("RM Fast") stays comparatively stable, whereas slower radial motion ("RM Slow") is more prone to distortions, with thresholds noticeably rising at moderate and severe levels. Repeated measures ANOVA statistical analysis supports these findings, demonstrating that speed thresholds for both conditions differ significantly across simulated levels: $F(3, 39) = 7.333$, $p = 0.002$ for "RM Slow," and $F(3, 39) = 4.802$, $p = 0.008$ for "RM Fast". These findings indicate that simulated distortions significantly impact radial motion perception, particularly for slower speeds, highlighting the sensitivity of radial motion to visual contrast and distortion severity.

To examine the pairwise differences in speed thresholds across the four simulated conditions (Baseline, HFA, HFB, HFBB), a post-hoc Tukey's HSD test was conducted following the ANOVA analysis. The results, presented in Table 5.5, demonstrate that there are no statistically significant differences among any of the mean values for both translational and radial motion conditions.

Table 5.5. The results of the post hoc Tukey's HSD test for observers' performance under simulation. The results display pairs of mean performances across four simulated conditions as for motion discrimination experiments including the directional and spiral motion patterns.

	Tukey HSD p-value					
Pairwise Comparisons	**Baseline vs HFA**	**Baseline vs HFB**	**Baseline vs HFBB**	**HFA vs HFB**	**HFA vs HFBB**	**HFB vs HFBB**
TM Slow	0.99	0.81	1.00	0.67	1.00	0.71
TM Fast	0.99	0.96	0.83	1.00	0.93	0.98
RM Slow	0.91	0.33	0.29	0.73	0.68	1.00
RM Fast	0.33	0.68	0.11	0.93	0.93	0.63

The absence of notable differences in pairwise comparisons indicates that the simulated distortions (Baseline, HFA, HFB, HFBB) did not significantly affect observers' performance in motion discrimination tasks. This holds true for both translational and radial motion patterns, regardless of whether the motion was slow or fast. Although some trends were noted in the data (such as higher thresholds for slower speeds under moderate and severe distortions), these effects were not statistically significant.

The findings from this study show clear patterns in the perception of translational and radial motion under simulated conditions. For translational motion, there were no statistically significant differences in speed thresholds at slow ("TM Slow") or fast ("TM Fast") speeds ($p > 0.05$). With faster speeds showing more stability than slower speeds, it appears that the type or degree of distortion used had little effect on how translational motion was perceived. In contrast, the simulated distortions had a significant effect on radial motion, especially for slower speeds ("RM Slow"), where thresholds increased noticeably at moderate and severe levels ($p < 0.05$). Significant but less noticeable effects were also seen at faster radial speeds ("RM Fast"), indicating that radial motion perception is more sensitive to visual distortions than translational motion.

The findings highlight the varying degrees of susceptibility among different types of motion to visual impairments, indicating that radial motion is particularly affected by challenges related to contrast and distortion. However, subsequent research should aim to elucidate the neural mechanisms that underlie these disparities and examine the responses of other motion types, such as rotational motion, to analogous distortions. This would enhance the understanding of motion perception in conditions of compromised visual integrity.

5.4 Discussion

The current experiment examined the effects of simulated lenses (Baseline, HFA, HFB, HFBB) on motion perception, with a particular focus on translational and radial motion patterns at varying speeds. The results indicate that translational motion perception remains notably resilient to visual distortions, regardless of speed conditions ("TM Slow" or "TM Fast"). In contrast, radial motion perception exhibited increased sensitivity to these distortions, especially at slower speeds ("RM Slow"), where significant raises in thresholds were observed under moderate and severe simulated conditions. These findings suggest that radial motion, which involves expansion patterns significant for depth perception and looming detection, is more susceptible to reductions in contrast and spatial resolution than translational motion.

These results align closely with earlier research suggesting that radial motion requires more processing resources due to the integration of local motion signals into global patterns. For example, the increased sensitivity to distortions in radial motion at slower speeds is similar to the findings made by Morrone et al. (1995), who showed that radial motion processing is particularly demanding for the visual system. Similarly, the strength of translational motion perception is consistent with studies underlining the brain's dependence on neural circuits in the dorsal stream, specifically area MT/V5+, to extract coherent motion signals even under suboptimal conditions (Born and Bradley, 2005) This comparison highlights the unique processing forms associated with different types of motion, with translational motion being evolutionarily prioritised for essential functions such as object tracking and navigation.

The stability of translational motion perception can be related to its evolutionary prioritisation for specific tasks such as object tracking and navigation. In contrast, radial motion perception may be more vulnerable to media alterations due to the higher computational demands associated with integrating local signals into global patterns (Morrone et al., 1995). This distinction is further underscored by the differential effects of speed on perception, as faster speeds appear more stable than slower ones—a phenomenon likely linked to the temporal integration properties of the visual system (Snowden and Braddick, 1991).

The findings from the current speed discrimination experiment support previous research showing that reduced media contrast affects speed perception, often leading to overestimations of apparent speed (Stone and Thompson, 1992, Allen et al., 2010, Anstis, 2004, Thompson et al., 2006). For example, Bex et al. (1998) demonstrated that radial motion patterns could be perceived as moving twice as fast under blurred conditions near the observer's eye. Similarly, Orban et al. (1984) reported significant reductions in speed discrimination at lower contrast levels, particularly at both slower and faster speeds. Conversely, McKee et al. (1986) opposed these conclusions, finding no significant impact of contrast on velocity discrimination across various parameters (Bex et al., 1998, Orban et al., 1984, McKee et al., 1986). Such inconsistencies might rise from variations in the way of experimental are designed, including differences in contrast levels and types of motion examined.

By focusing on a narrower range of parameters, the current experiment provides a refined assessment on how contrast distinctly affects the perception of radial versus translational motion. Furthermore, the results confirm that radial motion is perceived as faster than translational motion under comparable conditions, corroborating earlier findings by Geesaman and Ning (1996) and Bex and Makous (1997). The increased sensitivity to global radial motion signals (p = 0.001 and 0.008 for slow and fast speeds, respectively) is consistent with observations by Newsome and Pare (1988), who noted that global motion detection can happen with changes as small as 5% in local motion signals. This emphasis on global motion processing likely reflects the engagement of higher cortical areas, such as the medial superior temporal area (MST), a subdivision of V5/MT+ (Fischer et al., 2012).

The results also support the notion that speed perception under modified environments transparency characterised by media opacity depends more on global motion patterns than on local ones. The significant impact of reduced contrast on observers' ability to discriminate speed levels highlights the dominance of global motion mechanisms, facilitated by regions such as V5/MT+, in integrating motion signals across larger spatial scales (Burr and Thompson, 2011). While global motion processing appears to dominate, it is important to acknowledge that the experimental setup using RDKs may naturally prioritise global processing over local signals (Snowden and Braddick, 1991). Additionally, individual variations in motion perception and task-specific requirements could influence the balance between local and global contributions.

A notable limitation of the present study is participant attrition, likely due to the rigorous characteristics of the experimental design requiring multiple repetitions under varying environmental conditions. This attrition resulted in variability of the data quality, as evidenced by psychometric functions that did not consistently align well with data points. While significant scatter effects were observed in relation to radial motion, these effects were less pronounced for translational motion, potentially due to a smaller sample size or inadequate statistical power.

Future research should aim to address these limitations by recruiting larger participant cohorts and incorporating additional motion types, such as rotational motion, to provide a more comprehensive understanding of how visual distortions affect motion perception. Moreover, while the current study interprets behavioural differences, the underlying neural mechanisms remain unclear. Subsequent investigations using neuroimaging methodologies, such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG), could shed light on the cortical and subcortical pathways involved in processing distorted motion signals. Additionally, exploring the applicability of these findings to real-world contexts—such as driving, sports performance, or virtual reality environments—would enhance their ecological validity and practical significance (Wolfe et al., 2006, Owsley, 2011).

In conclusion, the present research demonstrates that translational motion perception remains resistant in the face of simulated visual distortions, whereas radial motion perception exhibits increased sensitivity, particularly at slower velocities. These results highlight the distinct processing requirements associated with different types of motion and underline the importance of considering both task-specific factors and speed-related variables when assessing motion perception in compromised visual environments. By enhancing the understanding of how visual distortions influence motion perception, this experiment sets the groundwork for developing targeted interventions to assist individuals with visual impairments in their daily activities. Such interventions could include adaptive technologies, training programs, or environmental modifications designed to mitigate the difficulties associated with impaired motion perception (Pelli, 1997, Legge et al., 2001).

Chapter 6 **Investigating the Effect of Light Scatter on Speed Prediction.**

6.1 Introduction

The experiments detailed in the previous chapter concentrated on the assessment of speed discrimination in the context of unobstructed movement of visible objects along radial or translational trajectories. Nevertheless, this idealised scenario may not consistently mirror real-world situations, where moving objects can be obstructed by various obstacles. The Prediction motion (PM) approach has gained significance in the realm of speed estimation due to its ability to gauge motion perception that closely simulates natural life dynamic events, where obstacles frequently impede visibility.

In our daily life activities, we rely on predictive mechanisms to enhance motor control for various tasks by anticipating the time required for objects to reach the required location. For example, this can involve estimating the speed of cars when crossing the street or catching a ball (Deno et al., 1995, Qin et al., 2022, Bosco et al., 2015, DeLucia, 2013, Smeets et al., 1996, Bennett et al., 2010), achieved by extracting physical information such as speed and direction at the moment it becomes visible (Mrotek et al., 2004, Bosco et al., 2015, Bennett et al., 2010).

Recent theoretical advancements have brought to light a significant obstacle that the brain consistently encounters during interactions with the environment (Bosco et al., 2015, Chang and Jazayeri, 2018). This obstacle stems from the presence of indeterminate moving objects in the surroundings, leading to temporal events, and the lack of sensory information that requires humans attention and elicits appropriate behavioural responses (Chang and Jazayeri, 2018, Kwon and Knill, 2013). Many visual scenes are not consistently observable, as the target may frequently vanish from the line of sight. In order to augment visual information, human's sensory system relies heavily on gathering cues from the surrounding environment to construct a full representation of the predicted scene and anticipated occurrence (Bosco et al., 2015, Kwon and Knill, 2013, Lyon and Waag, 1995). For example, when a ball is caught, it may become obscured by surrounding obstacles, requiring the observer to anticipate its reappearance in order to successfully catch it (Chang and Jazayeri, 2018). This occurrence is commonly observed in natural ecosystems, particularly among animals, where predators actively chase and capture their prey. Despite the presence of visual obstructions such as trees and rocks, which the prey may use to conceal itself, predators demonstrate the ability to capture evading prey. This phenomenon accounts for the existence of predictive mechanisms that may compensate for the absence of sensory input (Smeets et al., 1996, Kwon and Knill, 2013, Mrotek et al., 2004, Chang and Jazayeri, 2018). It seems that this ability is acquired rather than being a result of developmental processes (Rosander and von Hofsten, 2000, Von Hofsten et al., 2007).

The potential negative impact of inaccuracies in prediction mechanisms is significant, given that PM plays an essential role in accurately assessing the distances and speeds of moving objects (Smeets et al., 1996, Bennett et al., 2010). Typically, individuals possess the innate ability to anticipate the correct location of dynamic objects, even when they become obscured from view, thus aiding in avoiding potentially dangerous situations (Bosco et al., 2015, DeLucia, 2013, Bennett et al., 2010). A widely recognised possible example from our daily lives where the predictive mechanism is not working properly could be noticed in the occurrence of car accidents, where individuals must manage the speed and positioning of their vehicles in relation to other vehicles on the road. This necessitates timely responses to avoid collisions (DeLucia, 2013).

Research on PM includes a variety of case studies, each with distinct characteristics but often sharing common elements (Kwon and Knill, 2013, Mrotek et al., 2004, Bennett and Barnes, 2006). Typically, these studies involve showing a target for a specific period known as a "visible segment," which is linked to a visible time and distance (Lyon and Waag, 1995, Qin et al., 2022, Mrotek et al., 2004). After the target disappears, the observer is required to estimate when it would reach a specific endpoint based on the assumption that its original path continued during its invisibility. This hidden period is known as the "hidden segment," which involves concepts of "hidden time" and "hidden distance" (Lyon and Waag, 1995, Qin et al., 2022, Kwon and Knill, 2013, Bosco et al., 2015). Humans everyday visual surroundings are filled with dynamic objects that are frequently temporarily obscured by other elements.

The achievement of PM for a particular object can be enhanced by taking into account a range of interrelated factors associated with the entity's movement within its surroundings, such as speed, rate of change in speed, distance covered, time taken, and obstruction of view (Qin et al., 2022, Kwon and Knill, 2013). These factors can assist both researchers in laboratory settings and individuals in their everyday activities in estimating the time to contact (Bennett et al., 2010, Chang and Jazayeri, 2018, Mrotek et al., 2004).The behavioural response to PM is described by clocking mechanism through which the observers gauges the initial time to contact (TTC) which refers to the remaining time before the moving object reaches the observer or a specific spatial location where a potential collision may occur (Bosco et al., 2015, Baures et al., 2018a, Bennett et al., 2010). Chang and Jazayeri (2018) put forward the hypothesis that the human brain can anticipate TTC by integrating kinetic features derived from visual stimuli, such as distance and acceleration, with mental estimations of the time elapsed after an object appears at various locations.

Prediction tasks rely on the perceptions of depth and time-to-collision, which are maintained by different sensory information sources (see Figure 6.1) (DeLucia, 2013, Bosco et al., 2015, Baures et al., 2018b, Smeets et al., 1996). Time lags, caused by the transmission or processing of sensory information require quick responses that involve making adjustments or predictions (Deno et al., 1995).

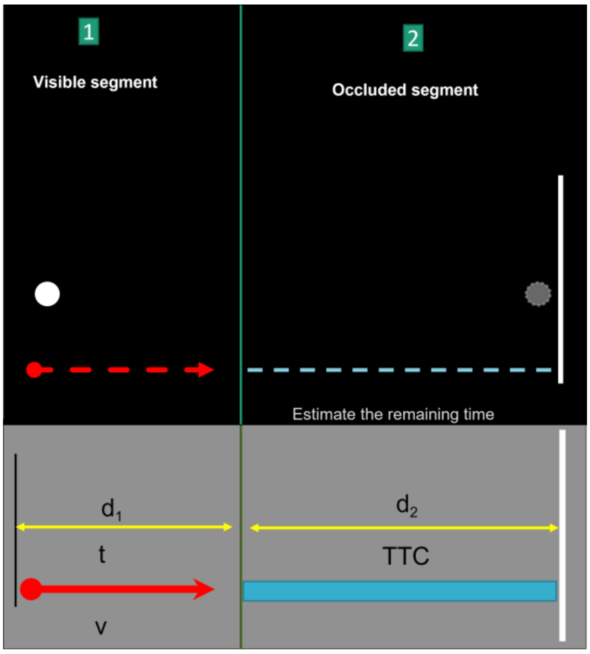


Figure 6.1. General task design for PM. A white dot moves along a path that is divided into two segments, a first segment of length d_1 where the dot is visible (red arrow) and a second segment of length d_2 where the dot is occluded (blue dashed line). The dot moves at a speed of v and the time it takes for it to reach the occluded segment is $t= d_1+d_2/v$.

Building upon the previous experiments outlined in Chapter 5, which focused on speed discrimination. The current experiment seeks to investigate the impact of altered visual perception, induced by simulated filters of varying opacity levels, on individuals' predictive abilities regarding speed. This experiment will specifically examine the differences in predictive capabilities among simulated cataract groups, young adults (aged 18-30 years) and older age group (over 30 years).

6.2 Methodology

6.2.1 Observers:

The experimental protocol initiated with an assessment of the observers' reaction time (RT) to determine the necessary response time and delays required for them to press the button. This was followed by the experimental trial of the PM experiment. The specific experimental procedures are illustrated in Figure 6.2.

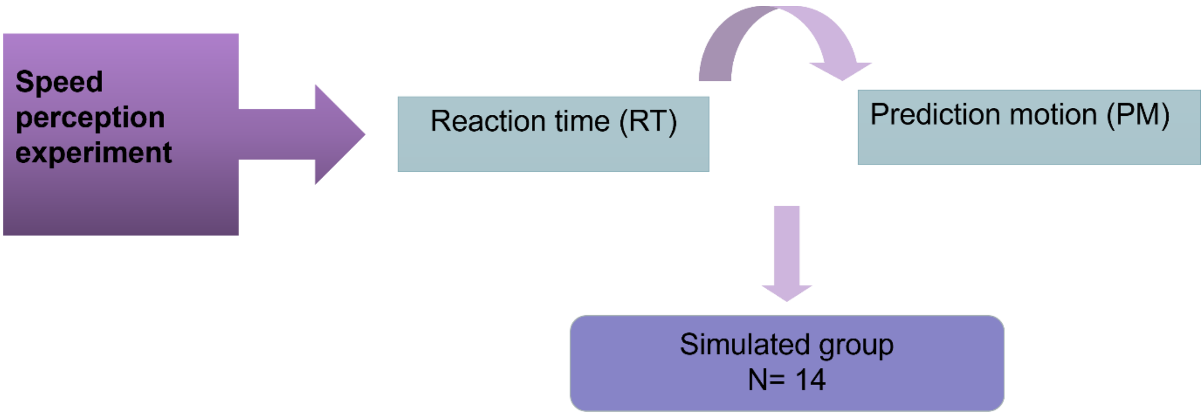


Figure 6.2. A schematic illustration of the speed perception experiment divisions and included observers in the experiment. The experimental procedure divided into introductory experiment reaction time (RT) and main experiment prediction motion (PM).

Fourteen observers were included in the speed perception motion experiment, two of them were the authors (n= 14; age range 20 – 43 years). All observers were absent from any ocular pathological diseases, or neurological diseases that could affect their attention or perception. Vision data for each group is presented in Table 6.1.

Table 6.1. The clinical and demographic data for the observers. Vision tests include (corrected distance visual acuity, DVA; corrected near visual acuity, NVA; contrast sensitivity, CS). Gender information is abbreviated (M – male; F – female).

Implemented experiments	**Speed prediction Simulated group**	
Experimental groups	< 30 years	≥ 30 years
Number of observers (Gender)	8 (7 F, 1 M)	6 (3F, 3M)
Age (Average ± SE)	22.75 ± 0.92	34.83 ± 2.24
DVA @ 3m in log MAR (Average ± SE)	-0.11 ± 0.03	-0.17 ± 0.02
NVA @ 40 cm in log MAR (Average ± SE)	-0.15 ± 0.03	-0.14 ± 0.03
CS **@1m** (Average ± SE)	1.86 ± 0.04	1.78 ± 0.09

6.2.2 Apparatus

The experimental apparatus was described in detail in Chapter 2 of the thesis.

6.2.3 Procedure

The primary experimental procedure consisted of two distinct components: an initial phase focusing on RT and a subsequent main experiment, PM.

6.2.3.1 RT experiment

The initial stage of the experiment was essential for establishing the accurate RT of the observers to an experimental stimulus and the potential time delay involved, particularly the interval between the observer's perception of the stimulus and their response through pressing the computer button.

The task assigned to the observer involved determining the point at which the target reached the end of the track, specifically when the dot made contact (hits) with the bar (see Figure 6.3). The target (showed as a white dot) size was 0.2º with total number of 45 trials. Experiment started by a key press (left arrow) followed by a random delay (200 ms) and on each trial, a white dot appeared along with the target point (white bar) on a black background. The dot then started moving horizontally from right to left or left to right, at one of the reference speeds levels (2.5°/s, 5°/s and 10 °/s) (see Figure 6.4). The observers were instructed to respond promptly when the target reached its intended position, and to ensure precision in their estimation, they were required to press a key at that precise moment. The positive values indicating underestimation (i.e., pressing the key after the dot hit the bar) and negative values indicating overestimation (i.e., pressing the key before the dot reached the arrival point).

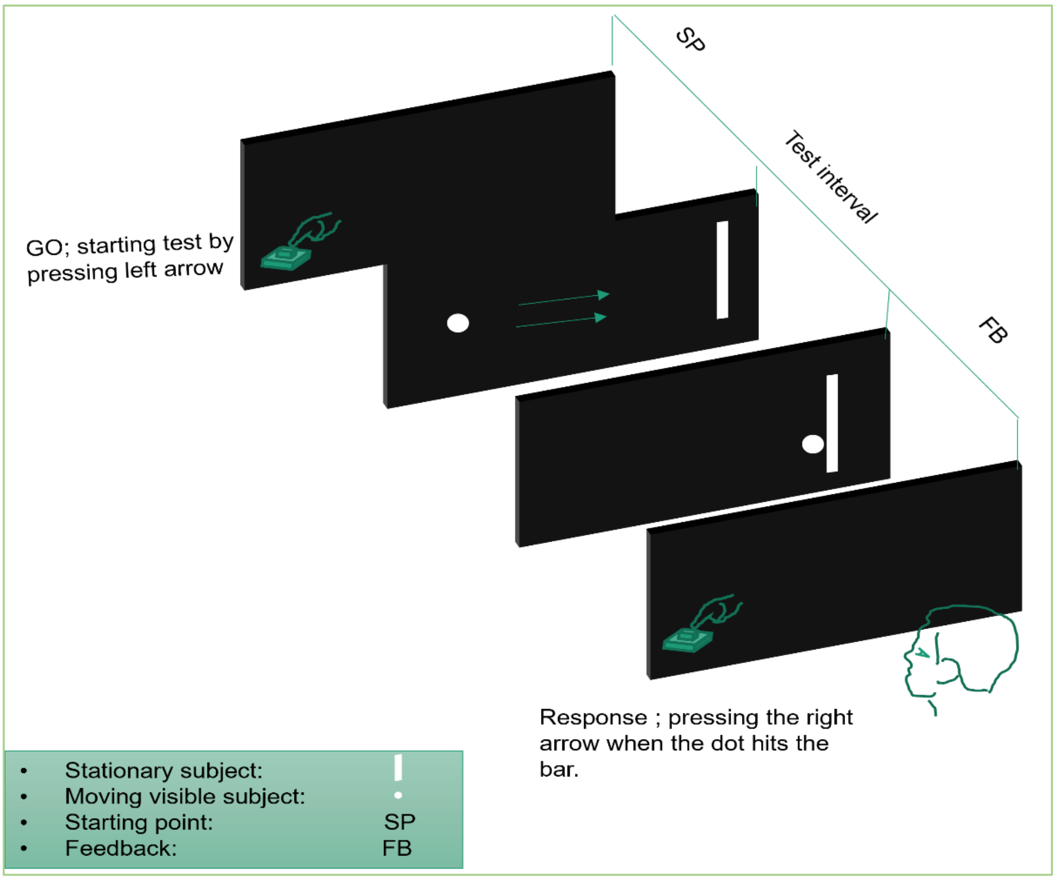


Figure 6.3. The overall sequential procedure involved in the experiment is as follows. Firstly, the observers were required to press the left arrow key to initiate the trial. They were then instructed to maintain fixation on the screen throughout the experiment. Following a random delay of 200 ms, two cues were presented on the screen: a stationary white bar and a moving white dot. The observers were directed to track the white dot and press the right arrow key immediately upon the dot reaching the bar (i.e., the target location)

6.2.3.2 PM experiment

In a manner consistent with the previous trial, the main part of the experiment involved observers being tasked with determining the precise moment at which the target reached its designated location after the same white dot was occluded for a set period of time. To provide an accurate assessment, observers were instructed to press a key at the identified that moment. Prior to each trial, observers were instructed to initiate the process by pressing the left arrow key. Subsequently, the background was displayed, featuring the initial point (showed as a white dot) and the target point (represented by a white bar) (see Figure 6.4).

After a random, normally distributed delay period (200 ms), a white dot appeared on the screen ±10° left or right of the centre of the screen. It would then traverse the screen towards the target (white bar) for a short, random period (either 0.5, 0.7, 0.9, or 1.1s) before it disappeared and remained occluded for a varying duration of 0.75, 1.00, or 1.25s. Observers were instructed to press a right arrow key on the keyboard as soon as they estimated that the dot had arrived at the target (Figure 6.4). On each trial, the dots' velocity was chosen randomly to either be 2.5, 5 or 10 °/s, meaning that an occlusion interval of 0.5s, for example, would be equate to a larger distance for a dot moving 10°/s relative to a dot moving at 2.5°/s. As a consequence of the varying velocities and occlusion times that were used, the starting position of the dot was varied, but could not allow the observers to judge the occlusion time from it.

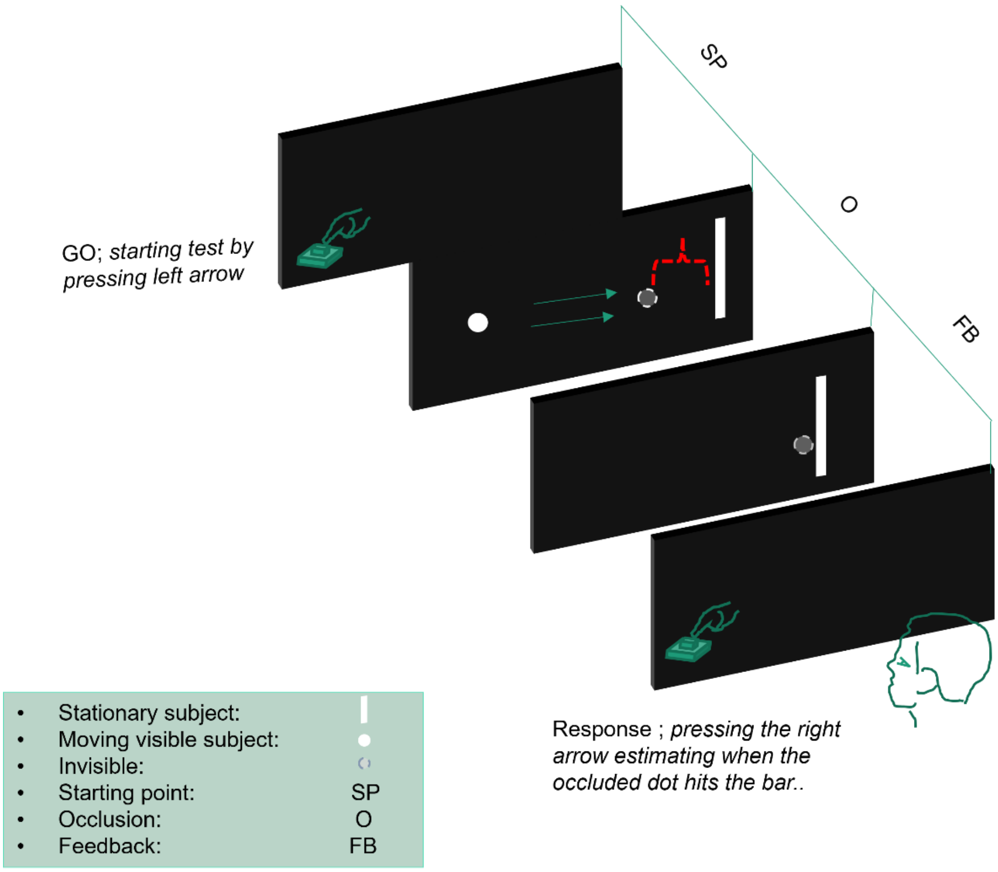


Figure 6.4.s Observers were required to initiate the trial by pressing a designated key (left arrow) and maintain fixation on the screen. Following a random delay of 200 ms, two cues were presented: a stationary white bar and a moving white dot which disappeared before hitting the target. Observers were instructed to track the movement of the white dot and press a key (right arrow) to indicate their judgment of the arrival time when the dot intersected with the bar after being occluded.

6.2.4 Study Design

In the study, the time structure was manipulated by changing its length before the transition point. To investigate differences across speeds as shown in Table 6.2, three levels of speed were used (2.5°/s, 5°/s and 10 °/s) × one visual modality, as control and variable within each level of time structure.

Table 6.2. Table showing how different speeds (slow, moderate and fast) led to different presentation times (sec) and creating various distances (°) between the dot the target for the PM task.

Occlusion Distance (°)	**Speed** (°/s)	**Occlusion duration** (s)
1.875	2.5	0.75
2.5		1
3.125		1.25
3.75	5	0.75
5		1
6.25		1.25
7.5	10	0.75
10		1
12.5		1.25

Two interrelated measures were derived: the initial measure was corrected error (CE), which was determined for each trial by subtracting the actual Time-to-Contact (TTC) from the estimated RT (RT being observers' average duration between the vanishing of the white dot and it's reaching the target location). A positive CE signifies that the observers overestimated the actual TTC, while a negative CE indicates that the observers underestimated the actual TTC.

The second dependent variable averaged the CE separately for each speed level (slow, medium, and fast, see Table 6.2) within each simulated condition for both the simulated groups and the natural eyes within the cataract group.

Within the field of psychophysics, perceived velocity (Vp) refers to an observer's subjective estimation of the speed of an object based on sensory input. This process involves integrating visual cues, such as changes in size, contrast, and motion, to form a mental representation of an object's movement (Shani-Feinstein et al., 2022). Perceived speed is essential for tasks requiring accurate timing and spatial judgments, such as estimating the TTC with an approaching object. In the current experiment, perceived speed (Vp) was calculated using the following formula, as shown in the **Error! Reference source not found.**.

$$\mathrm{Vp} = \left(\frac{\mathrm{TTC}}{\mathrm{CE}}\right) * \mathrm{Va}$$

Equation 6.1. Perceived speed (Vp). Where: TTC (Time to Contact) represents the estimated time remaining until the observer stops or contacts the moving object. CE (Constant Error) reflects the deviation between the observer's response and the actual value, serving as a measure of accuracy. Va (Actual Speed) indicates the true velocity of the object as presented in the experiment.

Estimating TTC was greatly assisted by the mental representation of speed that was developed from the findings of the RT experiment. Responses from observers revealed how precisely they estimated object speed under varying conditions. The mean performance for the three speed measures of slow (2.5°/s), moderate (5°/s), and fast (10°/s) under four simulated conditions (No filter, HFA, HFB, and HFBB) is summarised in Table 6.3.

Table 6.3. The results of observers' mean perceived speed (Vp) across four simulated conditions in relation to three speed measures: slow 2.5°/s, moderate 5°/s and fast 10°/s. Error in Vp was calculated by dividing (TTC) on observers' CE multiplied by presented speed (Va) (Equation 6.1. Perceived speed (Vp)).

	Perceived speed (Vp)							
	No filter		**HFA**		**HFB**		**HFBB**	
	Average ± SD	SE	Average ± SD	SE	Average ± SD	SE	Average ± SD	SE
Slow speed 2.5°/s	0.17 ± 0.75	0.20	-0.02 ± 0.98	0.26	-0.16 ± 0.83	0.22	-0.15 ± 0.82	0.22
Moderate speed 5°/s	-0.19 ± 1.16	0.31	-0.69 ± 1.64	0.44	-0.88 ± 1.50	0.40	-0.69 ± 1.28	0.34
Fast speed 10°/s	-0.64 ± 2.09	0.56	-1.75 ± 2.86	0.79	-2.25 ± 2.66	0.80	-2.08 ±1.85	0.49

The methodology outlined above provides a comprehensive framework for investigating the effects of simulated filters on the accuracy of speed prediction. By including two separate experimental stages—a RT assessment and a PM task—the prediction motion experiment guarantees a strong evaluation of observers' ability to estimate TTC under variable conditions of altered media transparency, speed and occlusion.

The experimental design was structured to isolate key factors influencing motion perception, including perceived velocity (Vp), constant error (CE), and TTC estimation. These measures were derived through psychophysical methods, enabling a detailed analysis of how visual distortions impact the accuracy of speed prediction. The use of randomised delays, varied speeds, and occlusion intervals further minimises possible biases, ensuring that the results reflect genuine perceptual differences under simulated media conditions rather than procedural artifacts.

6.3 Results

Around 65 percent of responses underestimated the time elapsed before contact between the moving dot and the stationary bar. According to this, observers generally assumed the dot arrived at the bar later than the actual contact time. The proportion of underestimation was compared across all speed levels (slow, moderate, and fast) without light simulation in order to determine whether this varied with dot speeds and light scattering conditions. The findings showed that the pattern of underestimations under these conditions did not differ statistically significantly. A repeated measures ANOVA was used to evaluate how light scatter affected accuracy. Accuracy was measured as the absolute deviation of each response from the actual passage point (Kaiser and Hecht, 1995, Rosenblum et al., 2000, Sidaway et al., 1996). All simulated conditions (no filter, mild, moderate, and severe) were analysed by two-way repeated measures ANOVAs for every speed level (Table 6.4). The findings showed that both speed ($F(2, 26) = 17.032$, $p = 0.001$) and simulated condition ($F(3, 39) = 5.120$, $p = 0.025$) had significant main effects.

Table 6.4. The results of observers' performance using the simulate filters. The results showing the mean performance across four simulated conditions in relation to three speed measures: slow 2.5°/s, moderate 5°/s and fast 10°/s.

Measures	**ANOVA**		
	df	F	*p*
Speed (2.5°/s, 5°/s,10°/s)	(2, 26)	17.032	0.001
Filters (No filter, HFA, HFB, HFBB)	(3, 39)	5.120	0.025
Speed Vs filters	(6, 78)	4.663	0.019

To facilitate pairwise comparisons within the ANOVA data, a post hoc Tukey's HSD test was performed (Table 6.5).

Table 6.5. The results of the post hoc Tukey's HSD test for observers' performance under simulation. The results display pairs of mean performances across four simulated conditions as for three speed measures: slow 2. 5°/s, moderate 5°/s, and fast 10°/s.

	Tukey HSD					
	p-values					
Pairwise Comparisons	No filter vs HFA	No filter vs HFB	No filter vs HFBB	HFA vs HFB	HFA vs HFBB	HFB vs HFBB
Slow speed	0.933	0.738	0.748	0.974	0.977	0.000*
Moderate speed	0.778	0.562	0.779	0.984	0.000*	0.984
Fast speed	0.610	0.295	0.394	0.947	0.984	0.998

The results in Table 6.5 demonstrate notable variations among particular mean pairs. Interestingly, notable differences were found between: HFB vs. HFBB (moderate vs. severe filters) at slow speeds (p = 0.000), HFA vs. HFBB (mild vs. moderate filters) at moderate speeds (p = 0.000). According to these results, motion prediction accuracy is greatly impacted by the amount of light scatter, especially at slower speeds and in more severe simulated scenarios

The data plotted in Figure 6.5 further illustrate these trends. Faster speeds led to greater overestimation errors (larger deviations from actual values), while increasing light scatter also resulted in larger errors. This pattern suggests that the perceived speed was typically underestimated by observers (i.e., they perceived the dot as moving faster than it actually was) across all simulated media conditions.

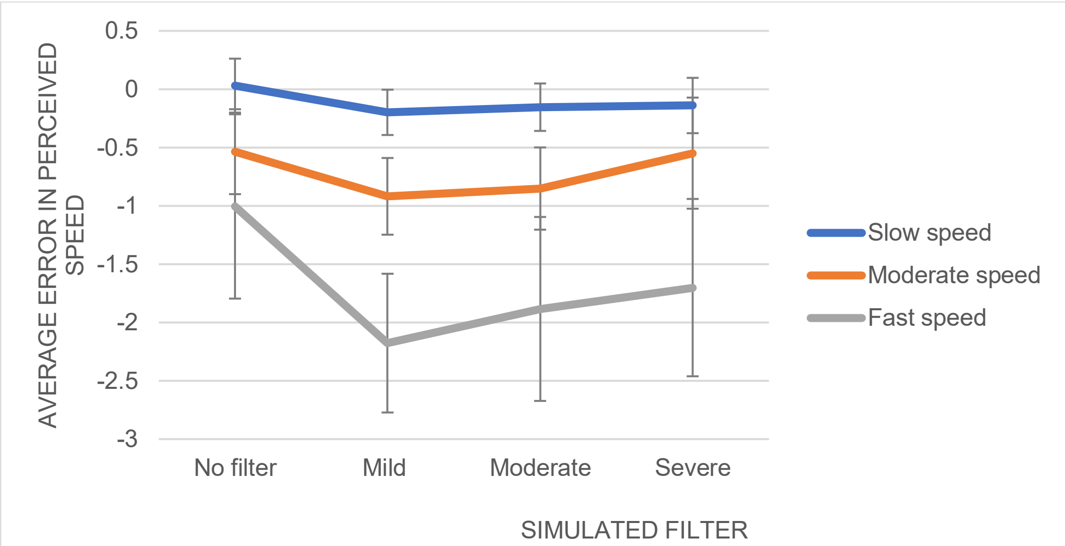


Figure 6.5. The line chart plots show the averages for the average error in perceived speed (Vp) relative to actual speed (deg/ sec) for each condition in cataract simulated observers. Error in Vp was calculated by dividing (TTC) on observers' CE multiplied by presented speed (Va) (Equation 6.1. Perceived speed (Vp)).

Figure 6.5 and Table 6.3. offer a detailed assessment of perceived speed (Vp) across the four simulated conditions. The results show that the degree of underestimation increased as the simulated conditions became more severe, suggesting that higher levels of light scatter and media opacity result in greater perceptual errors. Additionally, the speed of the moving dot influenced the extent of underestimation: At slow speeds (2.5°/s), the average Vp error was -0.15 ± 0.82 under the most severe simulated conditions. At fast speeds (10°/s), the average Vp error rose to -2.08 ± 1.85.

Overall, the results show two important points: First, increasing simulation levels has a significant impact on speed prediction accuracy (p = 0.019, in Table 6.4). Second, Perceived speed shows increased underestimation as both filter severity and speed levels increase. These results suggest that the degree of light scatter significantly affects speed prediction, with greater errors observed under conditions of higher visual degradation.

6.4 Discussion:

In this experiment, it was assumed that individuals estimate time-to-contact (TTC) by combining kinematic variables obtained from visual stimuli, such as speed, with elapsed time estimates derived from the duration an object takes to transition between spatial locations (Chang and Jazayeri, 2018, Qin et al., 2022, Kwon and Knill, 2013, Smeets et al., 1996). Several factors could influence the precision of tracking moving targets.

After the disappearance of an object in experimental trials, observers may exhibit a bias in their anticipation of subsequent target speeds based on the velocity of the preceding trial. This phenomenon, known as velocity priming, can lead to either deceleration or acceleration expectations (Lyon and Waag, 1995, Kwon and Knill, 2013). To mitigate such biases, two schemes were used in this study. First, the RT test presented as a baseline to assess observers' typical performance and identify any delays in response times. Second, the PM trials included three distinct speed levels presented in random order, thereby reducing the likelihood of observers forming expectations about target velocity trends.

Another possible interpretation of the results is that the human perceptual system is more adept at processing medium velocities, which facilitates tracking and prediction. However, slower or faster velocities pose greater challenges, with slow objects often perceived as accelerated and fast objects as decelerated (Lyon and Waag, 1995). Contrary to this expectation, the current findings suggest that observer performance was superior for slow-moving targets compared to moderate- and high-speed targets under baseline conditions. Observers overestimated speeds at faster velocities by approximately 76% and 82%, respectively.

The decline in PM accuracy over time could also be attributed to methodological variations in target velocity, including changes in velocity and acceleration or deceleration during tracking. These findings align with prior studies emphasising the importance of attention and timing in accurate motion perception (Kwon and Knill, 2013). Attention and timing are multifaceted processes, including selective, divided, and sustained attention, as well as the measurement of event duration and anticipation of future occurrences (Coull et al., 2011). Both factors must be translated into measurable representations of time. The visual system's accuracy in tracking moving objects is inherently limited by time delays, although advanced neural control systems can partially compensate for these constraints (Deno et al., 1995).

The results further indicate that motion perception is influenced affected by media contrast and scatter. Specifically, the effective size for detecting motion reduces as contrast levels increase ($p = 0.00$). These findings suggest attention when interpreting prior research on the receptive field characteristics of human motion mechanisms conducted under low-visibility conditions (e.g., Anderson and Burr (1987, 1991), Fredericksen et al. (1994), Gorea (1985), van de Grind et al. (1986), Lappin and Bell (1976), and Watson and Turano (1995)). While these studies provide valuable insights into motion perception at threshold visibility levels, their findings may not generalise to scenarios with higher contrast and signal-to-noise ratios.

Interestingly, the present results diverge from those reported by Senna, Parise, and Ernst (2015), Stone and Thompson (1992), Thompson (1982), Vintch and Gardner (2014), and Weiss, Simoncelli, and Adelson (2002). These studies suggest that reduced contrast leads to the perception of slower motion, particularly at lower velocities. In contrast, the observers in this experiment tended to underestimate perceived speed overall and assumed that dots moved faster under simulated media conditions. This misperception of speed due to contrast has practical implications, as highlighted by Snowden et al. (1998) and Pretto et al. (2012), who linked it to increased accident risks in foggy weather conditions.

Theoretical frameworks propose that the brain is not merely reactive but also exhibits "proactive" or "predictive" characteristics (Bar, 2009, Bar, 2007, Enns and Lleras, 2008, Grossberg, 2009). In this context, "predictive" refers to the brain's ability to anticipate visual stimuli based on contextual cues from prior events. Rao and Ballard (1999) have suggested a theoretical framework positing that predictions are integral to the visual process. They argued that visual cortices learn statistical patterns in the environment and transmit information about unexpected elements to higher visual regions. As a result, predictable stimuli require less neural activity for processing between lower and higher visual cortices (Rao and Ballard, 1999). A decade later, Alink et al. (2010) demonstrated that cortical responses decrease when the appearance or direction of motion can be anticipated, suggesting that the brain processes familiar stimuli with reduced neural activity during early stages of cortical processing (Alink et al., 2010)..

A central question in all PM experiments is how observers cognitively fill the gap during occlusion periods and compensate for the absence of visual information (Bosco et al., 2015, Kwon and Knill, 2013, Baures et al., 2018b). Mental factors, such as prior knowledge and task-related expectations, enhance TTC estimation, although observers may employ different strategies, potentially increasing data variability.

Motion perception is critical for everyday tasks like grasping or reaching for objects. Sensory inputs from cortical sensory areas are relayed to the motor cortex via specific sensory-motor areas in the parietal cortex, enabling action planning and perform actions execution (Lisberger, 2010). Vision plays a dominant role in daily activities, accounting for approximately two-thirds of our information intake (Qin et al., 2022). Therefore, understanding the processes linking sensation to action is essential for comprehending human cognition, decision-making, and memory formation.

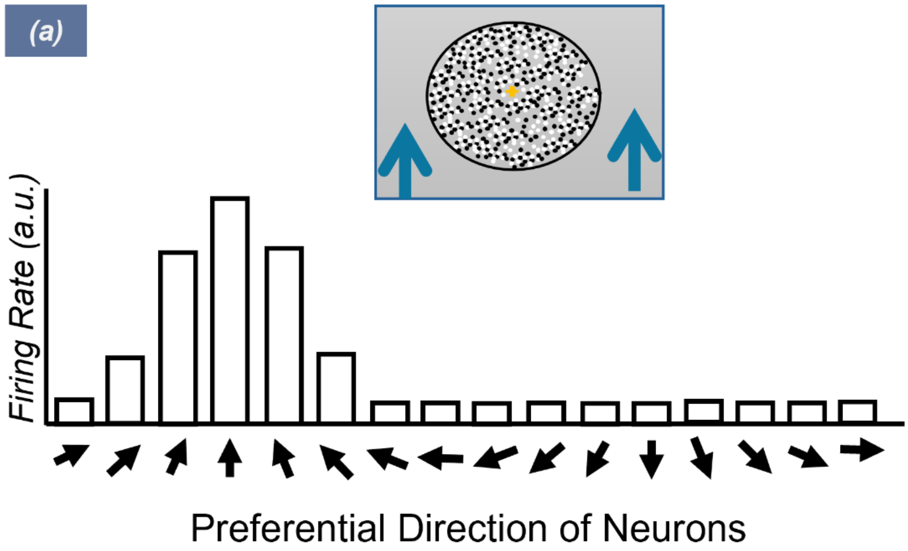
In summary, this investigation revealed that the ability to predict motion cues is influenced by environmental contrast levels. Despite challenges posed by limited engagement from some observers, the speed prediction experiment provides a thorough examination of factors such as velocity and contrast. Future research should aim to resolve discrepancies in findings regarding the impact of contrast on speed perception, contributing to the ongoing advancement of knowledge in visual processing and perception.

Chapter 7 Investigating the Effect of Light Scatter on Ability to Discriminate Direction

7.1 Introduction

Speed discrimination is influenced by light scatter (blur) and appears to be altered with light scatter, according to the previous speed behavioural experiments in this thesis, three key elements are needed to demonstrate how humans see motion: speed, direction, and luminance. On the other hand, object motion is the result of a combination of direction and speed, influencing how the moving target is fully perceived by the sensory and neural representations. The daily activities of individuals are closely linked to visual motion (Palmer, 1999), which is a strongly tied to human behaviour (Palmer, 1999, Burr and Thompson, 2011), Marr emphasised this point when he said that "motion pervades the visual world" (Marr and Ullman, 1981). According to Adelson and Movshon (1982), modifying the contrast of objects can influence the perception of their coherent directional motion (Adelson and Movshon, 1982, Burr and Thompson, 2011).

As discussed in Chapter 1, directional information is encoded in the retina by magnocellular cells (Van Essen et al., 1992, Ward et al., 2018) before being further processed within the cortex in V1 (Van Essen et al., 1992), V3A (Van Essen et al., 1992, Koyama et al., 2005, Ward et al., 2018), and human V5/MT+ (Yang et al., 2009a, Ward et al., 2018). In general, the processing of direction is commonly understood to occur through tuning, as illustrated in Figure 7.1. This implies that neurons sensitive to motion demonstrate selectivity for specific directions, responding more strongly to a narrow range of directions. Consequently, if two moving stimuli are closely aligned in direction, the brain may not detect the differences, suggesting that an individual's sensitivity to direction is constrained by the degree of tuning sensitivity, as shown in Figure 7.1.



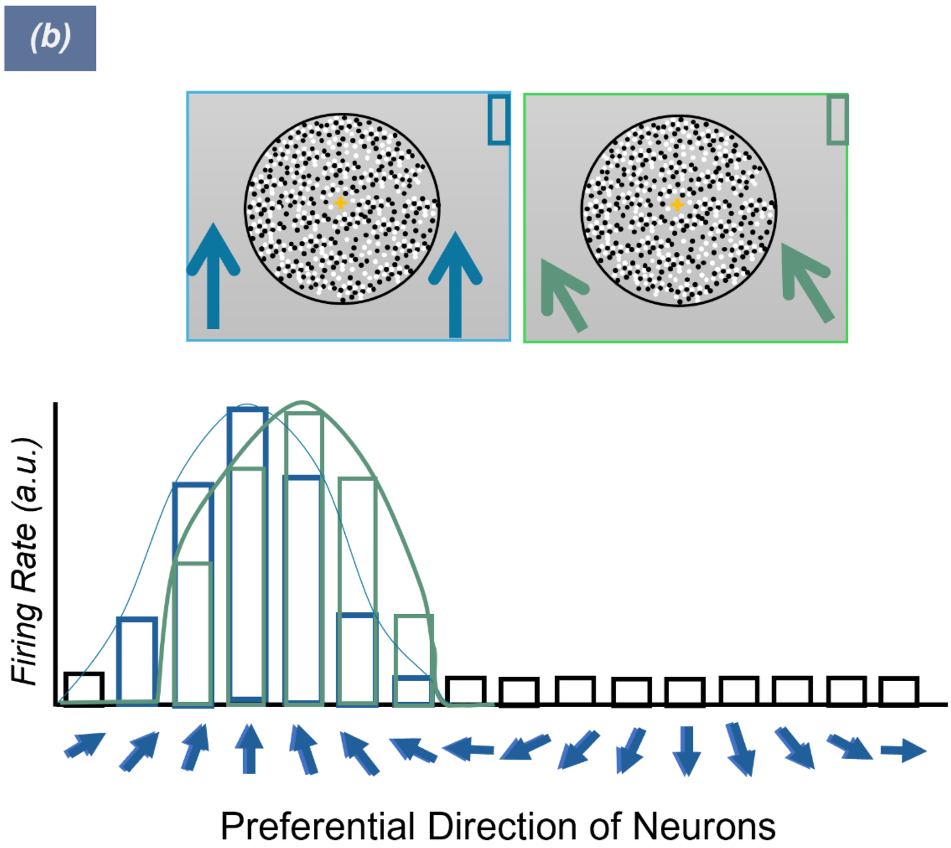


Figure 7.1. Diagrammatic explanation of the direction-selective tuning of neurons in motion-sensitive cortical areas. In example A, the stimulus is moving upwards, so neurons tuned to upward motion fire a lot. However, neurons with similar directional preference will also increase their firing a little, showing tuning (Gaussian). In example B, the blue and green colours show a comparison between two similar directions (blue – upwards; green – up and to the right). Here you can see that the firing responses of the neurons will be very similar, indicating a measure of sensitivity to directional information.

The psychophysical literature provides adequate evidence relative to the presence of neural mechanisms in humans, including perceived motion signals that provides information regarding direction, geometric information's and it is connection with the incident light (Morrone et al., 1995, Blake and Bulthoff, 1991).

In everyday situations, the ability to perceive direction is influenced by various factors, including the location of directional cues within the visual field (Fahle and Wehrhahn, 1991, Raymond, 1994, Holliday and Meese, 2008), as well as age-related changes in the visual system. Studies shows as people age, accurately interpreting directional differences becomes more difficult with age (Ball and Sekuler, 1986, Trick and Silverman, 1991, Snowden and Kavanagh, 2006, Yang et al., 2009a), likely due to reduced neural processing efficiency and increased light scatter within the eye, which distort retinal images and impair motion detection. Additionally, luminance and contrast levels play a critical role in direction discrimination, as variations in these factors significantly affect the ability to recognise similar directions (Grzywacz and Merwine, 2003, Thompson et al., 2006). An object's contrast, determined by its luminance, not only affects direction discrimination however also defines its borders, depth, and shape (Moscatelli et al., 2019). These findings highlight the importance of direction discrimination as an important measure in this thesis, particularly for individuals with increased light scatter, such as those with cataracts, who may experience notable changes in their sensitivity to direction. Age-related declines in neural efficiency, contrast sensitivity, and visual clarity collectively explain why older adults face greater challenges in perceiving direction, highlighting the need to address these impairments to improve quality of life.

Previous experiment within this thesis has showed that light scatter significantly impacts speed discrimination, particularly in radial directions (Chapter 5). Findings revealed that altered light scatter—simulated using specialised filters—can impair speed perception, slowing it down and disrupting the brain's ability to process motion accurately. The perception of visual motion in humans is a complex interaction of multiple factors, including speed, direction, and contrast (Matthews and Qian, 1999, Moscatelli et al., 2019). However, the complete perception of moving objects is not solely determined by direction or speed, yet rather by the combination of both factors, which affects sensory and neural representations (Nienborg et al., 2012, Hussar and Pasternak, 2013). While previous chapters have explored the impact of light scatter on speed perception, its influence on directional discrimination remains under-investigated.

The purpose of this experiment (direction discrimination) is to test the hypothesis that simulating cataract-like conditions in healthy individuals would degrade their ability to discriminate motion patterns. Building on the behavioural motion experiments carried out in previous chapters (Chapter 5 and Chapter 6), this study expanded its to examine how directional discrimination, independent of speed, emerges in motion patterns and how it interacts with complex motion responses (translational vs. spiral). Specifically, the directional discrimination and sensitivity within planar motion properties were examined (e.g., translational motion), in addition to the computational and functional interaction between two different motion patterns (circular and translational) that combine to produce spiral motion. Despite being less common in natural settings, spiral motion serves as a convincing example of how complex motion patterns are processed. For example, when an individual moves their head forward, the resulting optic flow generates a dynamic motion pattern that combines rotational and translational elements.

Key questions guiding this investigation include: What weight structures contribute to directional discrimination rather than spiral motion tuning? How do these structures interact to influence perception in challenging environmental conditions, such as those caused by opacity? And how do these interactions impact the ability of individuals with cataracts to perceive and navigate their surroundings effectively?

By addressing these questions, this study not only contributes to the understanding of motion perception yet also highlights potential implications for improving quality of life in individuals with impaired vision.

7.2 Methodology:

As described in the methodology section of Chapter 5, the RDK was used in this experiment within a similar framework. The primary aim for the observer was to perceive the general motion direction of the moving dots. The motion direction threshold was employed to establish the minimum proportion of signal dots required for correctly identifying the overall motion direction. Similar to the speed perception experiment, a higher motion direction threshold indicated reduced performance and decreased sensitivity to global motion.

7.2.1 Observers:

Before collecting the behavioural experimental data, clinical assessments of vision were conducted as outlined in Chapter 2. The experimental process consisted of two distinct experiments: local (translational) and global (spiral) experiments, with a comprehensive experimental outline provided in Figure 7.2.

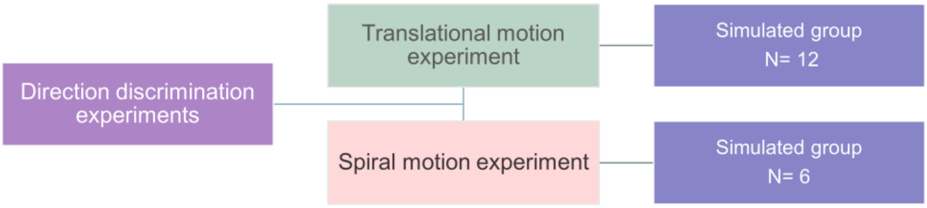


Figure 7.2. A schematic illustration of the directional experiment divisions and included observers in each experiment. Two experiments were implemented for studying direction discrimination, twelve observers joined the first (translational motion) experiment and six the other experiment (spiral motion).

Twelve observers were included in the translational motion experiment, two of them were the authors (n= 12; age range 20-51 years). Whereas six observers were included in the second spiral motion experiment, one of them were the author (n= 6; age range 20- 43 years). All observers were absent from any ocular pathological diseases, or neurological diseases that could affect their attention or perception. Vision data for each group is presented in Table 7.1.

Table 7.1. The clinical and demographic data for the observers. Vision tests include (corrected distance visual acuity, DVA; corrected near visual acuity, NVA; contrast sensitivity, CS). Gender information is abbreviated (M – male; F – female).

	Translational motion	**Spiral motion**
Number of observers (Gender)	12 (6 F, 6 M)	6 (2 F, 4 M)
Age (Average ± SE)	31.17 ± 8.84	31.00 ± 7.79
DVA @ 3m in log MAR (Average ± SE)	-0.15 ± 0.06	-0.13 ± 0.04
NVA @ 40 cm in log MAR (Average ± SE)	-0.14 ± 0.08	-0.15 ± 0.08
CS **@1m** (Average ± SE)	1.82 ± 0.23	1.94 ± 0.188

For all observers the vision recordings were calculated as the acuity readings of the BCVA for the eye that was used in the behavioural experiment.

Within the translational motion, observers were presented with two intervals on each trial. One interval randomly displayed a reference direction set at 45º up to the right (midway between vertical and horizontal positive x, y axes), while the other interval presented a test direction that either matched the reference orientation or deviated by one of three levels on either side of the reference direction. The difference between the directions was determined by the step size necessary for observers to successfully complete the task. Most observers required a step size ranging from 4º to 8º, indicating variability in levels across individuals, yet the task difficulty remained consistent based on individual response abilities as shown in Table 7.2. Observers were instructed to identify the interval containing the dots moving in the most horizontal direction on all trials.

The visual stimuli consisted of a set of 500 white moving dots arranged in a circular pattern at the centre of the display against a uniform grey background with a luminance of 50 cd/m2. Each dot had a diameter of 0.2º, and the overall dot density within the circular aperture was 0.69 dots per square degree. The intervals for the RDK were presented for a duration of 0.2 seconds. Throughout the experiment, factors such as dot density, size, brightness, displacement, radius, background luminance, and spatial arrangement were kept constant.

Table 7.2. Table showing how different step sizes in difference between presented direction (°) led to different presentations of test directions for the translational task.

Step size	More vertical directions			Reference direction	More horizontal directions		
4 °	57 °	53 °	49 °	45°	41 °	37 °	34 °
6 °	63 °	57 °	51 °		39 °	33 °	27 °
8 °	69 °	61 °	53 °		37 °	29 °	21 °

Conversely, complex spiral movement presents a greater challenge in terms of perception due to its generation through a blend of radial and rotational motions (Beardsley et al., 2003). This implies that it has the capability to rotate in either a clockwise or anticlockwise direction, while also being able to contract towards the centre or expand outwardly (see Figure 7.3).

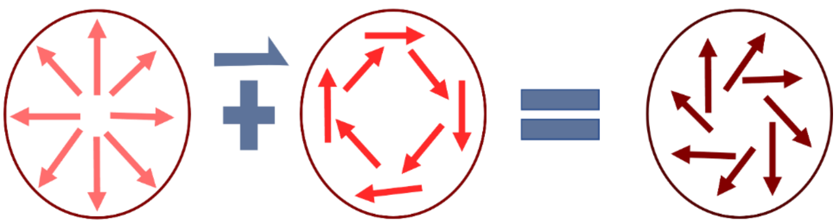


Figure 7.3. Example of the optic flow stimuli used in this experiment, spiral motion is a combination of radial expansion and clockwise rotation.

For spiral motion, on each trial the reference direction was set at 315° which indicated that the reference would rotate towards the centre, in an anticlockwise direction, with the “tightness” of the spiral defined exactly halfway between flat rotation and flat contraction. The “test” interval included a spiral that either moved the same direction or was “tighter” or “less tight” at one of three levels either side of the reference direction. As before, the difference between the directions was determined by the step size required for the observer to be able to complete the task (see

Table *7.3*). On all trials observers were asked to indicate which interval contained the dots with the "tightest" (most rotated) direction.

Table 7.3. Table showing how different step sizes in difference between presented direction (°) led to different presentations of test directions for the spiral task.

Step size	**More vertical directions**			**Reference direction**	**More horizontal directions**		
4 °	327 °	323°	319 °	315°	311 °	307 °	303 °
6 °	333 °	327°	321 °		309 °	303 °	297 °
8 °	339 °	331°	323 °		307 °	299 °	291 °
10 °	345 °	335 °	325 °		305 °	295 °	285 °

The observers' performances were transformed and presented using psychometric curve, to extract the JND values. All these procedures were designed and performed using MATLAB coded task in psychtoolbox, similar to the way that was used in speed calculations in Chapter 5.

7.2.2 Apparatus

The experimental equipment used was thoroughly outlined in Chapter 2 of the research.

7.2.3 Stimuli and behavioural experimental procedure:

This experimental methodology involved conducting 2IFC behavioural experiments to assess observers' ability to differentiate between local (translational) and global (spiral) motion directions. The MOCS was applied, where the stimulus magnitude for each trial was randomly chosen from a predetermined set. In performance-based experiments, the range of stimuli is typically selected to include the expected threshold value, allowing for a range of performance levels from challenging (near chance) to easy (near 100% correct) (Schwartz, 2006, Aaen-Stockdale, 2008, Gescheider, 2013). By fitting the resulting data with an appropriate psychometric function, precise estimates of the threshold and other parameters, such as slope sensitivity, can be obtained (Figure 7.4). This approach ensures accurate measurement of observers' discrimination abilities in motion direction tasks.

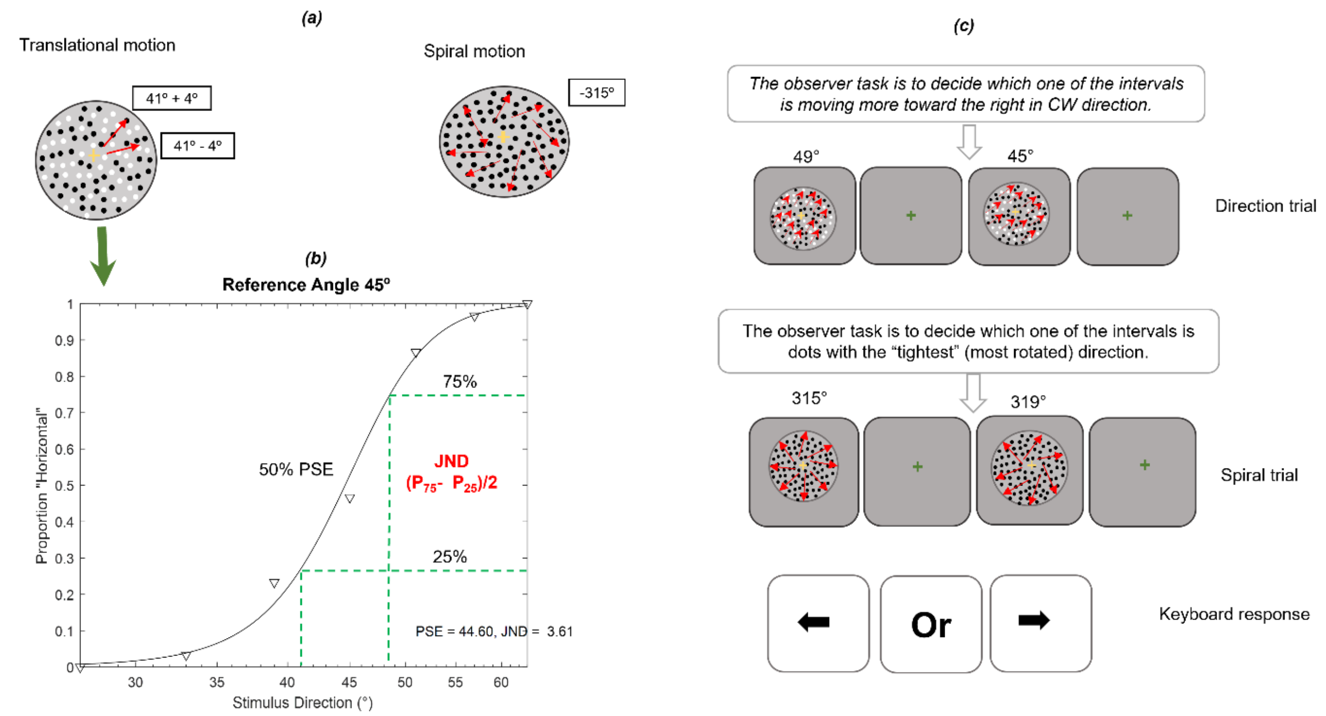


Figure 7.4. A schematic illustration of motion direction experimental procedure at step size of 4°. (a) a psychometric curve, in psychophysics a term that is used for calculating the difference between thresholds called the just noticeable difference (JND) or difference threshold and it refers to the smallest detectable difference between a starting and a secondary level of a specific sensory stimulus (Naseri and Grant, 2012). Figure (a) represents PSE, JND, UL (75%), LL (25%), values and their calculations for two intervals 2 IFC experiment with different directions were created ± 41° (b), the observers were asked to decide which one of the intervals is more toward the right in CW direction (c).

The JND values for individuals who participated in these experiments are detailed in Table 7.4 for translational and radial motion patterns.

Table 7.4. The individual JND values for translational motion pattern

	Translational motion Direction					**Radial motion** Spiral			
ID	**Baseline**	**HFA**	**HFB**	**HFBB**	**ID**	**Baseline**	**HFA**	**HFB**	**HFBB**
SC 1	3.35	3.03	3.23	2.94	SC 1	3.68	4.74	5.37	4.51
SC 7	3.68	7.10	5.12	5.50	SC 5	3.09	3.16	3.19	4.13
SC 9	4.08	5.03	4.31	4.43	SC 16	7.66	7.49	8	9.14
SC 11	6.92	5.52	5.23	4.13	SC 25	5.03	4.64	4.32	10.02
SC 14	4.39	3.88	4.32	3.50	SA 2	8.61	6.79	6.75	6.31
SC 16	3.64	3.46	2.60	3.15	SA 3	4.74	4.54	5.01	5.12
SC 22	5.11	3.69	4.08	4.72					
SC 23	3.61	3.77	2.85	2.90					
SC 25	2.76	3.83	4.10	4.33					
SA 1	3.00	2.75	3.41	2.77					

SA 2	5.18	6.45	4.04	4.47					
SA 3	2.09	2.18	2.10	2.01					
Average	*3.98*	*4.22*	*3.78*	*3.74*	*Average*	*5.47*	*5.23*	*5.44*	*6.54*
SD	*1.29*	*1.50*	*0.97*	*1.01*	*SD*	*2.20*	*1.61*	*1.72*	*2.49*
SE	*0.37*	*0.43*	*0.28*	*0.29*	*SE*	*0.90*	*0.66*	*0.70*	*1.01*

A random key press started the run, and a response was required for each trial to trigger the next one to appear. Before beginning the task, observers were presented with an orange central fixation cross on a homogenous grey background (Figure 7.4).

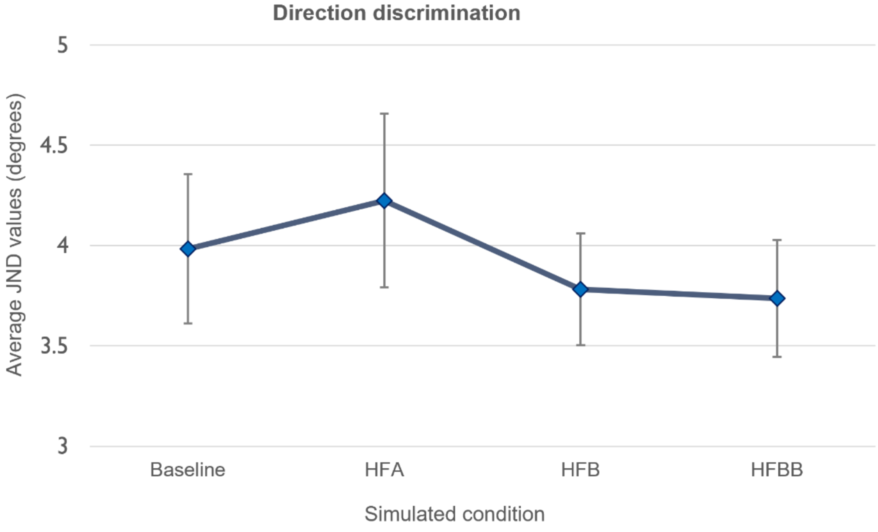
Within a single run lasting approximately 6 minutes, observers saw 15 repeats of each 'level' of the test stimulus (total 105 trials), and this was repeated twice in order to obtain a total of 30 repeats for each level. Observers in the "simulated" group, completed this paradigm for four levels of simulation: baseline, mild, moderate, and severe using the light scatter filters described in Chapter 4.

7.3 Results

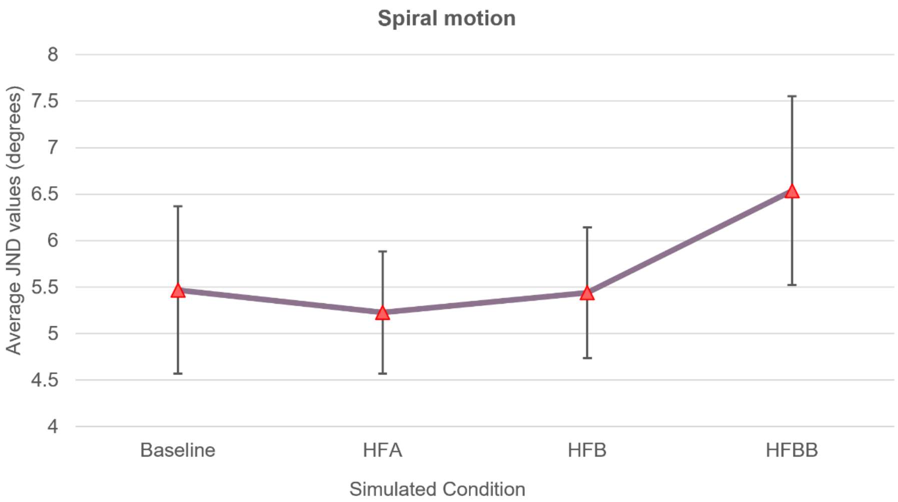
The task in this experiment required observers to determine whether a standard or comparison (reference interval) RDK interval had a more CW perceived directional motion (Figure 7.4). The collected data were expressed as JND values for each simulated condition (see Table 7.4), representing the angular difference at which observers judged the average direction of the comparison RDK as more CW relative to the standard (reference interval). Logistic fits were applied to these data to estimate the average direction of the comparison RDK that matched the perceived direction of the standard (see Methods). The dots in the standard RDK moved in a shared direction (i.e., the vector average, median, and modal directions were identical), randomly selected on each trial from a range centred around a reference angle of 45°(detailed in Table 7.2).

The JND for translational dot directions were sampled discretely from a psychometric function curve and illustrated in Figure 7.5 -a, for the sequential experimental procedure simulating cataract condition in non-cataract observers. In general, thresholds decreased as the signal patch became extended in the direction of motion, suggesting improved sensitivity with increased spatial integration. This trend aligns with previous findings that spatial summation enhances motion perception under conditions of reduced contrast sensitivity (Smith and Ledgeway, 2001, Grzywacz and Merwine, 2003).

(a)



(b)



(c)

	ANOVA test results		
Measures	df	F	*p*
Direction discrimination	(3,33)	1.164	0.332
Spiral motion	(3,15)	1.378	0.297

Figure 7.5. Direction Discrimination and Spiral Motion Thresholds Figure 7.5 summarises the average JND values for the four simulated conditions across groups 1 and 2: Panel (a): Direction discrimination thresholds and standard errors are plotted as a function of oblique motion direction and degree of decreased contrast sensitivity for 12 observers under simulated cataract conditions. Panel (b): Spiral motion thresholds and standard errors are plotted as a function of spiral motion direction and degree of decreased contrast sensitivity for six observers in the simulated cataract group. Panel (c): Results of repeated-measures ANOVA tests showing the mean observer performance for both direction and spiral motion experiments, as depicted in Figure 7.5-a and Figure 7.5-b.

A repeated-measures ANOVA revealed no significant main effects of simulated scatter on direction discrimination for either translational motion (p = 0.332) or spiral motion (p = 0.297). Similarly, the F-statistics in Figure 7.5 -c, did not indicate any overall significant differences between sample means. To further examine pairwise comparisons within the ANOVA data, a post hoc Tukey's Honestly Significant Difference (HSD) test was conducted. The results of the Tukey's HSD test (Table 7.5) also failed to identify any significant differences between pairs of means for either direction discrimination or spiral motion tasks.

Table 7.5. The results of the post hoc Tukey's HSD test for observers' performance under simulation. The results display pairs of mean performances across four simulated conditions as for motion discrimination experiments including the directional and spiral motion patterns.

	Tukey HSD p-value					
Pairwise Comparisons	**Baseline vs HFA**	**Baseline vs HFB**	**Baseline vs HFBB**	**HFA vs HFB**	**HFA vs HFBB**	**HFB vs HFBB**
Direction discrimination	0.962	0.977	0.959	0.808	0.759	1.000
Spiral motion	0.997	0.997	0.799	0.998	0.684	0.787

Post Hoc Tukey's HSD Test Table 7.5 presents the results of the post hoc Tukey's HSD test for observer performance under simulated conditions. The table includes pairwise comparisons of mean performances across the four simulated conditions for both motion discrimination experiments (directional and spiral motion patterns). None of the pairwise comparisons reached statistical significance (p > 0.05 for all comparisons). For example, direction discrimination the pairwise comparisons yielded p-values ranging from 0.759 to 1.000. Also, in spiral motion, the pairwise comparisons yielded p-values ranging from 0.684 to 0.998. These findings suggest that while some trends may exist, they could not be definitively proven due to high variability and lack of statistical power.

Overall, the motion direction experiments outlined in this chapter do not provide conclusive evidence regarding the effect of reduced media opacity (simulated using cataract filters) on motion perception. These results are consistent with prior studies highlighting the complexity of dissociating sensory deficits from higher-level processing impairments under simulated visual degradation (Snowden and Kavanagh, 2006, Yang et al., 2009b).

7.4 Discussion

The findings from the current direction discrimination experiment indicate no meaningful impact of altered viewing media (e.g., simulated filters) on an observer's ability to recognise directional patterns or effectively differentiate between various levels of motion direction across various media contrasts. These results suggest that motion direction perception may not rely equally on all motion patterns, instead appears to be constrained predominantly to oblique translational patterns in this experimental context.

For both experiments, the decreased thresholds for signal patches in the motion direction tests did not reveal a significant main effect of simulated scatter on direction discrimination for either translational motion or global spiral motion. However, a notable trend emerged: spiral motion thresholds appeared to increase as light scatter severity worsened. This observation aligns with previous studies by Anderson and Siegel (1999) and Burr (2000), which demonstrated that observers' ability to recognise alterations in motion patterns depends on the specific type of motion being tested (e.g., spiral vs. translational motion) (Anderson and Siegel, 1999, Burr, 2000).

Anderson and Siegel (1999) examined the behaviour of monkeys in response to different motion types and found a higher selectivity for radial and spiral motion compared to translational motion. Specifically, over half of the neurons showed a preference for radial and spiral motion, whereas only about one-fifth responded strongly to translational motion. Similarly, in the current experiment, observers displayed greater selectivity for spiral motion compared to translational motion. However, a key distinction lies in the direction of translational motion used: Anderson and Siegel employed horizontal translational motion, whereas the present study used oblique translational motion. This difference in experimental design may explain why the current results diverge from their findings.

According to Matthews and Qian (1999) and Burr and Thompson (2011), motions along cardinal directions are often perceived as faster and more distinct than those along oblique axes. This suggests that the perceived speed and clarity of motion stimuli are influenced by their directional orientation. For example, stimuli moving along cardinal axes tend to create greater perceptual clarity compared to those moving along oblique axes (Matthews and Qian, 1999, Burr and Thompson, 2011). In contrast, some studies have detected an increased preference for oblique axes in directional experiments involving variations in speed intervals (Burr and Thompson, 2011). The current study used a single oblique reference direction (45°) at a consistent speed, which may contribute to recognising the phenomenon of "motion repulsion."

Motion repulsion refers to the preference of individuals to overestimate the angle between directions in apparent motion, particularly within the range of approximately 30° to 40° (Treue et al., 2000). In their experiment, Treue et al. (2000) observed deviations from their model, relating these differences to potential perceptual errors in motion repulsion. While the current study did not obviously test motion repulsion, the data suggest that further analysis is necessary to interpret its role in directional motion perception under simulated cataract conditions.

In general, motion experiments are designed to assess choice-related activities, where decisions depend on specific stimulus characteristics such as speed, coherence, direction, or depth (Nienborg et al., 2012, Matthews and Qian, 1999, Burr, 2000). In the present experiment, observers were tasked with identifying the most oblique direction of motion in a 2IFC paradigm. Although memory can influence perceptual decision-making, particularly in tasks requiring differentiation between newly presented stimuli and stored representations (Hussar and Pasternak, 2013), the short inter-stimulus interval (<2 s) in this study likely minimised memory effects.

The human visual system must distinguish between object motion in the world and the corresponding retinal images. This challenge has led to the development of theories such as the direction illusion (DI), which explains how simultaneous presentation of two sets of displays with different directions can bias perception (Chen et al., 2014). Similarly, inexperienced observers often perceive the luminance of motion direction as a combined representation resulting from interactions between two kinetic gratings, perceiving them as either coherent movement or two sliding gratings (Adelson and Movshon, 1982).

The current study aimed to examine the impact of altering visual contrast on the perceived physical direction of global motion under simulated cataract conditions. The results indicate that the ability to distinguish direction decreases as transparency decreases, corresponding to an in the opaqueness of the simulating filters. This finding supports the notion that contrast influences the perception of speed, amplitude, and direction (Anstis, 2004). Thus, the link between reduced contrast sensitivity and impaired direction discrimination provides valuable insights into how degraded visual environments affect motion perception.

The experiments revealed a new phenomenon involving the perceived direction of randomly displayed dots creating spiral and oblique patterns. Specifically, a translational pattern with a higher average perceived speed was created when motion vectors were arranged into a translational and global motion pattern. This finding suggests that spiral motion—embodied by both translation and rotation—may be more challenging for humans to perceive than oblique motion. Additionally, motion discrimination appears to be proportionally affected by reduced media transparency (increasing blur), with spiral motion showing greater sensitivity than translational motion. While this deficit may be associated with the presence of cataracts, broader investigation is needed to confirm this relationship. Despite the lack of statistical significance in the final results, it is important to highlight that the current experiment introduced several novel features compared to previous studies. Notably, it incorporated a wider range of directional angular patterns and four environmental media conditions (simulated filters). From this perspective, the direction motion experiment represents a distinct behavioural approach that integrates multiple features (speed, contrast, direction). However, the inclusion of additional observers would strengthen the robustness of the conclusions.

Chapter 8 Investigating the Effect of Light Scatter on Motion Coherence Thresholds

8.1 Introduction

To facilitate secure navigation and understanding of the surrounding environment, the brain processes visual information from moving objects and their reflected images. These images often present complex motion patterns, such as contraction (inward motion) and expansion (outward motion), which are projected onto the retina (Snowden and Milne, 1997, Burr et al., 1998, Burr et al., 2001). The perception of orientational motion extends beyond the mere movement of objects in the environment, it also includes their position, velocity, and orientation (Morrone et al., 1999, Snowden and Milne, 1997). Building upon the initial experiments outlined in Chapters 5, 6, and 7, this experiment investigates how perceptual variations in radial motion influence judgmental abilities using coherence paradigms (Morrone et al., 1999, Burr et al., 2001).

Research indicates that the ageing process significantly affects the perceptual abilities of older individuals, particularly motion perception, with older individuals exhibiting increased visual thresholds and reduced sensitivity to motion (Pilz et al., 2017, Betts et al., 2007). While the precise mechanisms underlying this decline remain unclear (Pilz et al., 2017), neurophysiological studies suggest that these changes may be linked to alterations in orientation-selective neurons within cortical areas V1 and V2, as well as the middle temporal (MT) area (Betts et al., 2007, Bennett et al., 2007a).

Basically, this decline is likely due to neural rather than optical factors. For example, age-related changes in neural processing efficiency and selectivity within the visual cortex could impair the ability to integrate global motion signals effectively. These findings feature the importance of examining how neural mechanisms contribute to motion perception under conditions of simulated visual degradation, such as those induced by cataracts or other forms of light scatter.

To study these questions, a threshold experimental procedure is used to investigate the minimum number of signal dots required to accurately judge the radial motion direction threshold—whether expanding or contracting (Morrone et al., 1999, Burr et al., 2001, Legge and Campbell, 1981). The procedure used a motion noise paradigm, in which coherent signal dots were embedded within a field of randomly moving "noise" dots. This approach allowed to examine whether the addition of coherent motion interferes with the processing of global motion signals (Morrone et al., 1999, Burr et al., 2001).

The primary aim of this experiment was twofold: first, to determine the effect of scatter on observers' ability to accurately distinguish between coherent movements and uncorrelated movements; and second, to investigate how discriminability in the spatial frequency content of the two types of movements impacts the perception of coherent motion. By addressing these objectives, the study seeks to provide insights into the mechanisms underlying radial motion perception and its susceptibility to visual degradation.

8.2 Methodology

The procedural framework of this experiment was designed to investigate the impact of a coherent global motion stimuli on radial motion extraction under varying levels of simulated filters applied. Specifically, the study examined the relationship between the severity of simulated filters and the percentage coherence of signal dots required for observers to determine the direction of radial motion (expansion vs. contraction).

8.2.1 Observers

Seven observers participated in the radial motion coherence experiment. Their ages ranged from 20 to 39 years, with detailed clinical and demographic data provided in Table 8.1. All observers were free from ocular pathological diseases or neurological conditions that could affect attention or perception. Vision data, including corrected distance visual acuity (DVA), corrected near visual acuity (NVA), and contrast sensitivity (CS), were recorded for each observer. These values were based on the best-corrected visual acuity (BCVA) of the eye used during the behavioural experiment.

Table 8.1. Summarises the clinical and demographic characteristics of the observers, grouped by age (<30 years and ≥30 years). Gender information is abbreviated as M (male) and F (female).

	Motion coherence Simulated group	
Experimental groups	< 30 years	≥ 30 years
Number of observers (Gender)	5 (2 F, 3 M)	2 (1F, 1M)
Age (Average ± SE)	24.60 ± 1.40	34.50 ± 4.50
DVA @ 3m in log MAR (Average ± SE)	-0.11 ± 0.01	-0.15 ± 0.05
NVA @ 40 cm in log MAR (Average ± SE)	-0.15 ± 0.04	-0.15 ± 0.05
CS **@1m** (Average ± SE)	1.94± 0.04	2.10 ± 0.15

For all observers, vision recordings were calculated as the acuity readings of the BCVA for the eye used in the behavioural experiment. The coherence levels (proportion of signal dots) presented to each observer varied across trials, ranging from 0.05 to 0.5 in steps of 0.075 (i.e., 0.05, 0.125, 0.2, 0.275, 0.35, 0.425, 0.5). These levels were randomly selected to maintain a uniform level of difficulty throughout observers, based on their performance during an introductory demo test. In each trial, observers had to identify whether the signal dots were moving toward the centre (contracting) or away from the centre (expanding) (Figure 8.1).

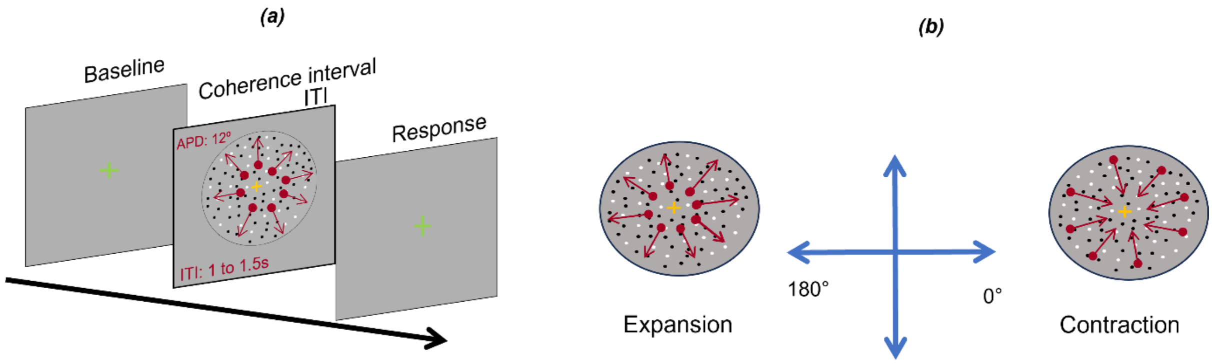


Figure 8.1. Schematic illustration of the stimuli used in the radial coherence motion task. (a) The overall procedure for the coherence motion task, where 500 randomly positioned dots moved in radial coherent motion (outward vs. inward). (b) On each trial, observers judged whether the stimulus was expanding or contracting.

The threshold corresponds to the lowest proportion of signal dots required to determine the global radial motion direction (inward or outward). This can be conceptualised as achieving a specific signal-to-noise ratio, where the signal represents the number of motion vectors aligned with the global motion direction, and the noise represents the number of motion vectors in random directions (Figure 8.1).

8.2.2 Stimuli and experimental procedure:

This experimental framework used a 2IFC paradigm to determine observers' ability to discriminate coherent motion direction. For a detailed review of this approach, see Chapter 2.

The stimuli were generated using MATLAB Psychtoolbox (2020) software and displayed on a Lenovo ThinkVision L1900PA monitor with a resolution of 1,440 × 900 pixels (horizontal × vertical) and a refresh rate of 60 Hz.

Trials were performed monocularly, with the non-tested eye occluded using an eye patch. Observers were secured in position using a chin rest and forehead rest to minimise head movement. Simulation lenses, corresponding to different scatter conditions (as described in Chapter 2), were held in place with a clamp system to ensure stable positioning.

The stimuli were RDKs, as illustrated in Figure 8.2. The RDKs were presented within a 6° aperture and were viewed centrally from a fixed distance of 57 cm. Each RDK consisted central circular display containing 500 black and white dots moving against a uniform grey background with a luminance of 50 cd/m². the dots moved at a constant speed of 8°/sec for a duration of 250 ms, with each dot having a diameter of 0.2 degrees. The overall dot density within the was maintained at 0.69 dots/deg². The dots had a limited lifetime of 20 frames, after which they were extinguished and repositioned randomly within the aperture. Throughout the experiment, the spatial arrangement, background brightness, displacement, radius, dot density, size, and brightness were kept constant.

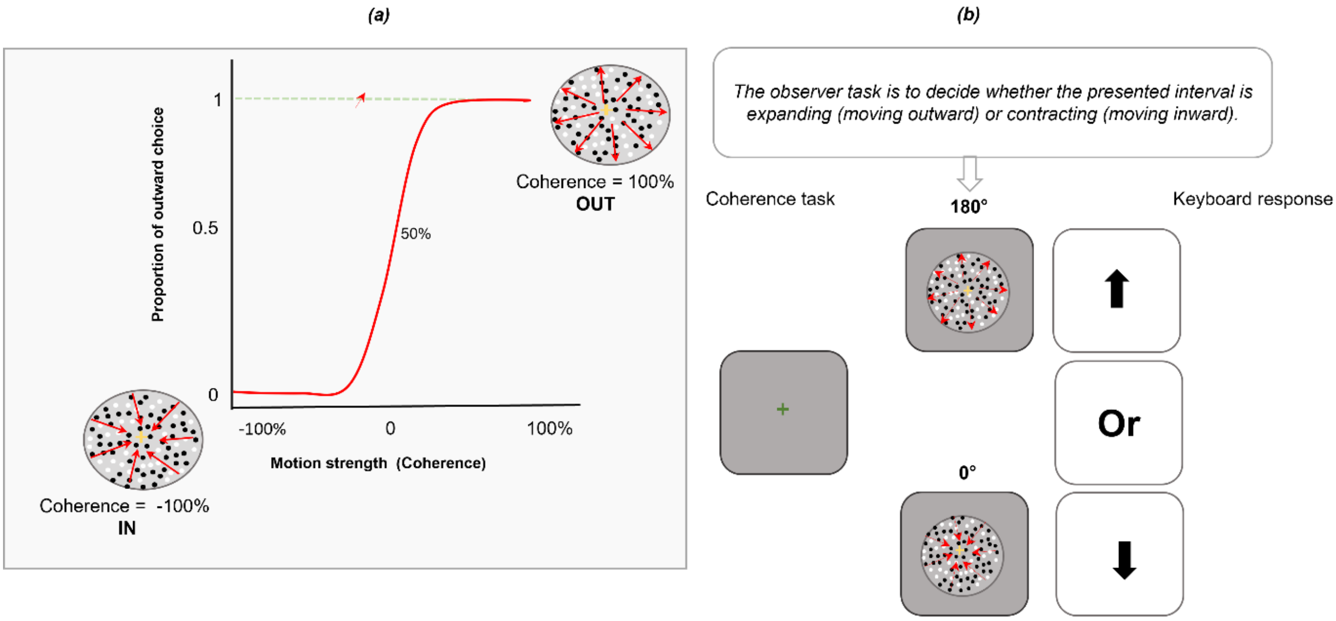


Figure 8.2. Illustration of radial motion paradigm: the left panel (a)shows a psychometric curve used to calculate the just noticeable difference (JND). It shows the relationship between motion strength (coherence) and the proportion of outward choices, demonstrating how increasing coherence influences perception. at 100% coherence, all dots move outward, while at -100% coherence, all dots move inward. The right panel (b) illustrates the experimental setup, where participants observe radial motion pattern with varying levels of coherence and make judgement about the direction of motion, the task includes discriminating between coherence outward and inward motion amidst random noise.

Each session consisted of 105 trials, divided into seven coherence levels presented randomly. For the simulated groups, coherence levels ranged from 0.05 to 0.5. Each coherence level included 15 trials, and the direction of motion (inward or outward) was randomly selected for each trial (Figure 8.2).

The individual JND values for observers participating in the radial motion coherence experiment are detailed in Table 8.2.

Table 8.2. The individual JND values for radial coherence motion pattern

	Radial coherence motion			
ID	**Baseline**	**HFA**	**HFB**	**HFBB**
SC 1	5	18	5	21
SC 5	11	5	5	11
SC 11	46	32	20	41
SC 16	35	21	38	32
SC 23	25	43	29	23
SC 25	20	31	26	20
SA 2	31	33	29	20

Average	*24.71*	*26.14*	*21.71*	*24.00*
SD	*14.13*	*12.44*	*12.59*	*9.70*
SEM	*5.34*	*4.70*	*4.76*	*3.66*

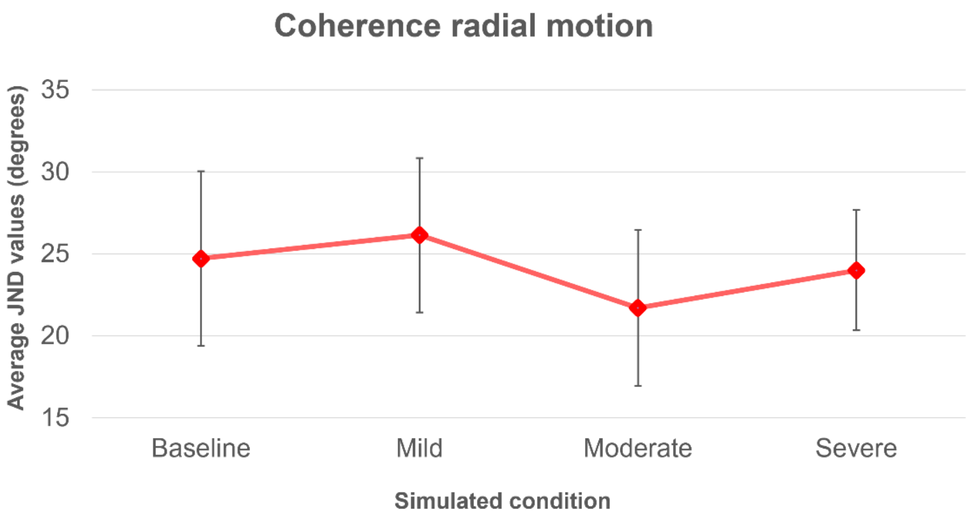
The decision to perform the task monocularly aligns with the experimental design used in previous chapters (Chapters 5, 6, and 7). Monocular testing ensures consistency in the data by eliminating potential binocular interactions, such as fusion or rivalry, which could confound the results.

8.3 Results

The collected data for each condition were expressed as the average coherence threshold for each light scatter condition. The dots in the standard RDK travelled in a common direction, with coherence levels randomly selected on each trial from a range of 5% to 50%.

Thresholds for all four simulated conditions (baseline, mild, moderate, and severe scatter) are illustrated in Figure 8.3. The number of signal dots required to correctly perceive the global motion direction is plotted for each condition, with error bars indicating one standard error of the mean. Markedly, the pattern of results remained consistent across all seven observers.

(a)



(b)

	ANOVA test results		
Measures	df	F	*p*
	(3,18)	0.370	0.737

Figure 8.3. (a) Average JND values for radial coherence motion thresholds and standard errors plotted as a function of radial coherence motion and degree of decreased contrast sensitivity for seven observers under simulated cataract conditions. (b) Results of ANOVA tests showing the mean observer performance in the radial coherence motion experiment, corresponding to the data presented in (a).

Observers' task in all four conditions (no filter, mild, moderate, and severe scatter) was to detect the global-motion signal direction—expanding versus contracting. The results revealed that altering the clarity of the environment (via simulated filters) had no significant effect on the extraction of the global-motion signal direction ($p = 0.737$). The thresholds for correct responses remained consistent across all conditions, with 15 trials per coherence level for each condition. Additionally, the JND values (Table 8.2) calculated for the extracted global motion direction (contracting at 0° vs. expanding at 180°) showed no significant differences among the simulated observer groups.

Regarding correct responses across different coherence percentage levels under simulated conditions, the accuracy of observers' decisions did not vary significantly across the simulated scatter conditions. A repeated-measures ANOVA confirmed that there was no substantial effect of coherent motion perception under simulated filters. Furthermore, the F-statistics in Figure 8.3-b did not indicate any overall significant differences between sample means. To further examine pairwise comparisons within the ANOVA data, a post hoc Tukey's Honestly Significant Difference (HSD) test was conducted. As shown in Table 8.3, the Tukey's HSD test also failed to identify any significant differences between pairs of means for the radial coherence motion task.

Table 8.3. The results of the post hoc Tukey's HSD test for observer performance under simulated conditions. The table displays pairwise comparisons of mean performances across the four simulated conditions for the radial coherence motion task. None of the pairwise comparisons reached statistical significance ($p > 0.05$ for all comparisons).

	Tukey HSD p-value					
Pairwise Comparisons	Baseline vs HFA	Baseline vs HFB	Baseline vs HFBB	HFA vs HFB	HFA vs HFBB	HFB vs HFBB
Coherence radial motion	0.9963	0.9679	0.9995	0.9064	0.9878	0.9853

These findings suggest that while some minor variations in performance may exist, they are not statistically significant. Overall, the results indicate that simulated scatter conditions do not substantially impair observers' ability to discriminate changes in radial coherence motion patterns.

The ability of observers to discriminate changes in coherence motion direction varied as a function of the coherence test level. Observers performed best at identifying the motion direction (expanding vs. contracting) at higher coherence levels (>0.5), achieving an average accuracy of 88% (±0.02). In contrast, accuracy dropped slightly for coherence levels between 0.2 and 0.4, with an average correct response rate of 76% (±0.04). These results align with previous studies suggesting that higher coherence levels enhance the salience of global motion signals, making them easier to detect (Naseri and Grant, 2012).

8.4 Discussion:

The observations from the experiments outlined above are limited in scope and do not allow for definitive conclusions regarding the impact of light scatter in simulated cataract conditions. The lack of a significant effect of simulated scatter on coherent motion perception can be related to several factors. First, the human visual system is highly strong in extracting global motion signals even under reduced visual conditions. This strength may arise from neural mechanisms in cortical areas such as V1, V2, and MT, which are specialised for integrating local motion signals into a coherent global percept (Burr et al., 2001, Morrone et al., 1999). Second, the experimental design ensured that the spatial and temporal properties of the stimuli (e.g., dot density, lifetime, and aperture size) were kept constant across conditions, minimising potential confounds that could have influenced performance. Finally, the high coherence levels used in the experiment (particularly >0.5) likely provided sufficient signal-to-noise ratios for observers to reliably detect the global motion direction, even under simulated scatter conditions. These factors collectively explain why simulated scatter did not significantly impact observers' ability to extract the global-motion signal direction.

However, the findings suggest that the motion coherence task is influenced, at least in part, by the different types of visual motion properties being measured—specifically, radial motion direction versus noise sensitivity (Beardsley and Vaina, 2005, Burr et al., 2001). The motion coherence task estimates direction sensitivity among adjacent motion systems that respond to similar motions, whereas the motion model coherence task quantifies external noise sensitivity between detached or contrasting motion mechanisms, such as in coherent motion experiments involving expansion versus contraction (Beardsley and Vaina, 2005, Morrone et al., 1999).

In comparison to the natural environment, optic flow contains not only an individual's self-motion but also lateral retinal motion and the local coherent motion of objects within the visual field (Beardsley and Vaina, 2005, Morrone et al., 1999, Burr et al., 2001), Furthermore, dynamic visual scenes are rarely isolated; they are often crowded and cluttered with surrounding objects' motion that may have no relation to an individual's self-motion. This complexity highlights the importance of identifying slight changes in global motion patterns as a means of segregating visual scenes based on motion (Bravo, 1998, Burr et al., 2001, Morrone et al., 1999).

Humans' visual system is highly sensitive to motion and possesses the ability to discern subtle variations in spatial frequencies within certain thresholds (Legge and Campbell, 1981). The success of this experiment centres on the observer's capacity to effectively distinguish between "coherent" or mutual motion and uncorrelated motions (referred to as noise dots) (Pilz et al., 2017, Morrone et al., 1999, Burr et al., 2001). Additionally, the discernibility of coherent motion is influenced by variations in the spatial frequency components of single moving intervals (Mowafy et al., 1990, Morrone et al., 1999, Pilz et al., 2017).

In conclusion, coherent motion provides information about global motion in a way that reveals distinct techniques for analysing the perceived direction of coherently moving dots forming patterns of blooming inward or outward motion. The results of this experiment did not yield a definitive conclusion regarding the correlation between coherent motion perception and reduced media transparency. Nontheless, additional research is necessary to validate this relationship and explore its underlying mechanisms

Chapter 9 **Motion Perception in Age-Related Cataract Patients: A Comprehensive Case Study Across Behavioural Tasks**

9.1 Introduction

The ability to perceive motion is a fundamental aspect of visual processing, enabling individuals to navigate their surroundings safely and interact effectively within a dynamic environment. This complex visual function highlights countless daily activities, from walking and driving to avoiding obstacles and social interactions. Despite its definite importance, motion perception remains underexplored in clinical evaluations of visual impairment, particularly in the context of age-related cataracts. Examining the perception of moving stimuli among cataract patients is fundamental for understanding the specific difficulties they face. Furthermore, such investigations are necessary for the developing of targeted interventions that can significantly improve their quality of life.

Age-related cataracts, characterised by the progressive opacification of the eye's lens, represent a leading cause of visual impairment among the elderly population (Pascolini and Mariotti, 2012, Klein et al., 2009). This condition significantly impacts different aspects of vision, including contrast sensitivity, visual acuity and light scatter, each of which plays an important role in motion perception. Understanding the relationship between cataracts and motion perception is essential from both scientific and humanitarian perspectives, with the prospective to transform patient care and therapeutic strategies.

Motion perception is a complex process that relies on an intricate network of neural pathways within the visual system. Key areas involved in this process include the primary visual cortex (V1), the middle temporal area (MT/V5+), and the medial superior temporal area (MST). These regions are responsible for higher-order processing, enabling the brain to interpret motion, speed, and direction (Born and Bradley, 2005, Burr and Thompson, 2011). These areas combine information across multiple dimensions, including contrast sensitivity, spatial resolution, and temporal resolution, to build a coherent representation of the dynamic world. However, in individuals with age-related cataracts, each of these components becomes vulnerable to degradation, disrupting the delicate balance required for accurate motion perception.

The impact of cataracts on motion perception manifests is evident through several yet interconnected mechanisms:

1. Reduced Contrast Sensitivity:
   Cataracts reduce the eye's ability to detect differences in luminance between objects and their backgrounds, resulting in blurred vision and difficulty identifying moving objects against low-contrast environments (Elliott et al., 1989, Elliott et al., 1990, Pelli et al., 2006). For example, an individual with cataracts may find it difficult to identify a pedestrian crossing the road on a foggy morning or notice an approaching vehicle in dim lighting conditions. Such impairments not only

diminish functional vision but also increase the risk of accidents and misjudgements in dynamic settings.

2. Reduced Spatial Resolution:
   Cataracts impair edge detection, making it difficult to track the movement of objects with accuracy. This loss of spatial resolution complicates tasks that require accurate interpretation of motion, such as following a ball during sports or navigating crowded spaces (Legge and Campbell, 1981, Snowden and Kavanagh, 2006).
3. Impaired Temporal Resolution:
   Individuals with cataracts often experience difficulties in perceiving fast movements or distinguishing between continuous frames of motion. This can lead to problems in dynamic environments, such as judging the speed of vehicles or reacting to sudden changes in motion (Allen et al., 2010, Yang et al., 2009b).
4. Increased Glare and Light Scatter:
   Cataract presence increases glare and light scatter, reducing the ability to detect motion in brightly illuminated environments or during nighttime conditions. This can put significant obstacles for activities such as driving at sunset or in direct sunlight (van den Berg et al., 2009, Sample et al., 1988).

The combined effects of cataracts and the natural processes of ageing lead to a decrease in motion perception. Many studies have documented how advancing age reduces the ability to perceive speed and direction. For example, older adults often require higher speeds to accurately judge the velocity of moving objects (Allen et al., 2010, Snowden and Kavanagh, 2006). Similarly, interpreting slight directional changes becomes increasingly difficult with age (Ball and Sekuler, 1986, Trick and Silverman, 1991, Yang et al., 2009a). These age-related declines are driven by physiological and neurological changes, including reduced neural processing efficiency, increased light scatter within the ocular media, and reduced contrast sensitivity (Thompson et al., 2006, Snowden and Kavanagh, 2006).

The observed decline in motion perception with age can be related to several physiological and neurological changes. There is evidence of reduced neural processing efficiency in older adults, which affects their ability to detect motion and discriminate between subtle directional changes (Yang et al., 2009b, Trick and Silverman, 1991). Additionally, increased light scatter within the eye, caused by conditions such as cataracts or changes in the ocular media, distorts the retinal image, making it harder for older individuals to notice fine details, including directional cues (Snowden and Kavanagh, 2006). As well, age-related reductions in contrast sensitivity further impair the ability to distinguish objects and their motion, as lower contrast levels reduce the visibility of directional information (Thompson et al., 2006).

The interaction between cataracts and the natural ageing process raises important questions about how these factors collectively impact motion perception. For individuals with cataracts, impaired motion perception can significantly affect their ability to navigate their surroundings safely. For example, they may struggle to crossroads, avoid obstacles, or engage in activities that require precise visual-motor coordination. Understanding these relations is essential for developing interventions that address the unique needs of cataract patients and empower them to regain their independence and quality of life.

This chapter aims to explore the effects of age-related cataracts on motion perception. By examining these factors in detail, the study seeks to explain the challenges faced by cataract patients and pave the way for innovative solutions that enhance their ability to navigate the dynamic world around them.

9.2 Methodology

9.2.1 Overview of the Study

This chapter presents in-depth a case study investigating motion perception in individuals with age-related cataracts—a critical yet underexplored area of visual neuroscience. Building upon the experimental framework established in Chapter 5– Chapter 8, this study introduces specific adjustments adapted to address the unique challenges posed by cataract-related visual impairments. The primary objective was to evaluate global motion perception across four central areas: speed, predictability, directionality, and radial coherence. To achieve this, a motion threshold paradigm was implemented to determine the minimum proportion of signal dots required for accurate identification of global motion tasks. Higher thresholds were indicative of reduced performance, reflecting reduced sensitivity to global motion—a hallmark of cataract-induced deficits.

9.2.2 Observers:

Prior to data collection, comprehensive assessments of ocular health, cataract severity, and clinical vision parameters were accurately conducted, as detailed in Chapter 2. These assessments confirmed that all participants met the inclusion criteria and provided a healthy foundation for subsequent analyses. The experimental procedure involved four distinct motion experiments—speed discrimination, speed prediction, direction discrimination, and radial coherence—summarised schematically in Figure 9.1.

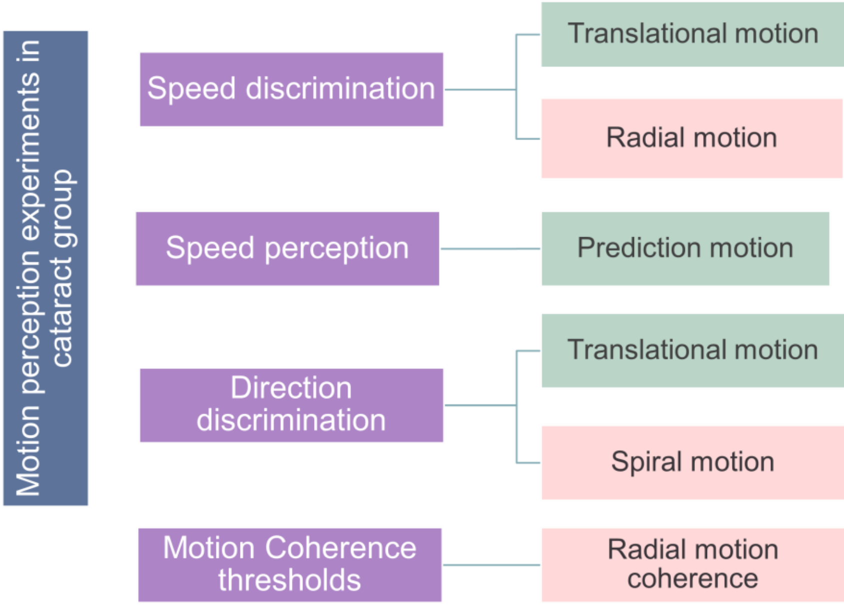


Figure 9.1. Provides a schematic representation of the classification of motion experiments conducted with age-related cataract patients. These experiments collectively examined motion perception, resulting in a total of six unique experimental conditions.

Two observers with age-related cataracts participated in the behavioural motion experiments. Their ages ranged from 51 to 70 years, with a median age of 60.5 years. Clinical and demographic data for the observers are presented in Table 9.1, including corrected distance visual acuity (DVA), corrected near visual acuity (NVA), contrast sensitivity (CS), and gender information (M – male; F – female). Notably, neither observer demonstrated ocular pathological conditions or neurological disorders that could influence attention or perception, ensuring the integrity of the findings.

Table 9.1. Summarises the clinical and demographic data for the observers, highlighting key metrics such as DVA, NVA, and CS. Gender information is abbreviated (M – male; F – female).

	Cataract group >50 years
Number of observers (Gender)	2 (2 F) * 3 eyes
Age (Average ± SE)	60.50 ± 9.50
DVA @ 3m in log MAR (Average ± SE)	0.00 ± 0.14
NVA @ 40 cm in log MAR (Average ± SE)	0.04 ±0.20
CS **@1m** (Average ± SE)	1.50 ±0.00

To account for the limited sample size, the number of eyes rather than individuals was considered. One observer had binocular cataract, necessitating independent testing of both eyes, while the second observer presented with early monocular cataract. This approach resulted in a total of three eyes being assessed, maximising the statistical power of the study while modifying individual variability.

9.2.3 Stimuli and behavioural experimental procedure:

9.2.3.1 Apparatus

The experimental equipment is described in detail in Chapter 2, ensuring consistency with prior experiments while including refinements specific to cataract-related impairments.

9.2.3.2 Design and procedure

The experimental design mirrored that used in Chapter 5– Chapter 8, with one notable distinction: observers in this study used their natural eyes without intervening filters. This variation allowed for the assessment of real-world cataract effects, providing ecologically valid insights into motion perception. However, due to the visual impairments associated with cataracts, adjustments were made to step sizes in certain tasks to ensure consistent levels of difficulty across participants.

9.2.3.2.1 Speed Discrimination

Observers in the cataract group required larger step sizes in experiments assessing speed discrimination, reflecting the increased challenge posed by degraded visual input. During these experiments, two intervals were presented on each trial: one representing the reference speed (3°/sec for slow, 8°/sec for fast) and the other presenting a test speed at one of seven levels around the reference speed (see

Table *5.2*). The difference between speed levels was determined by the step size required for the observer to distinguish between the intervals. Most observers required a step size between 15–20, balancing individual differences while maintaining task difficulty based on demo-test responses.

On each trial, observers were asked to indicate which interval contained the dots with the fastest speed. The JND values for cataract observers were calculated using logistic functions fitted to response data, as detailed in Chapter 5. These values are summarised in for translational and radial motion patterns in Table 9.2.

Table 9.2. Summarises the average performance of the cataract group across translational and radial motion tasks. Data are presented as averages with standard errors (SE).

	Cat01 RE	**Cat01 LE**	**Cat02 RE**	Average (SE)
Translational motion				
Slow	0.55	0.54	0.39	0.50 (0.05)
Fast	0.17	0.30	0.20	0.22 (0.04)
Radial motion				
Slow	0.20	0.44	0.52	0.39 (0.10)
Fast	0.29	0.17	0.17	0.21 (0.04)

9.2.3.2.2 Speed Prediction

The speed prediction task was conducted using the same speed levels as those applied to the simulated group in Chapter 6, ensuring comparability across conditions. Two eyes (right eyes of both observers) were included in this experiment.

The task involved determining the precise moment when a moving white dot reached its target (a white bar). After a random delay, the dot appeared and moved horizontally at one of three reference speeds (2.5°/s, 5°/s, or 10°/s) before disappearing behind an occlusion. Observers were instructed to press a key when they estimated the dot had reached the target. The average errors in perceived speed are summarised in Table 9.3.

Table 9.3. Presents the average error in perceived speed for the cataract group under slow, moderate, and fast conditions

		Cat01 RE	Cat02 RE	Average (SE)
Speed prediction	Slow	6.90	0.83	3.87 (3.03)
	Moderate	3.15	0.11	1.63 (1.52)
	Fast	2.71	0.77	1.74 (0.97)

9.2.3.2.3 Direction discrimination

Direction discrimination followed the procedures outlined in Chapter 7. Observers completed two directional discrimination tasks: translational and spiral. In each experiment, they were presented with two intervals: one displaying a reference direction (45° up to the right for translational and 315° for the spiral) and the other presenting a test direction deviating by one of three levels on either side of the reference. Step sizes ranged from 4° to 8°, depending on individual capabilities.

Observers identified the interval containing dots moving in the most horizontal direction. The JND values for translational and spiral motion tasks are detailed in Table 9.4.

Table 9.4. Summarises the average performance of the cataract group in translational and spiral motion tasks, with data expressed as averages with standard errors (SE).

	Cat01 RE	Cat01 LE	Cat02 RE	Average (SE)
Translational	6.38	7.08	4.24	5.9 (0.85)
Spiral	60	42	48	50 (5.29)

9.2.3.2.4 Motion coherence thresholds

The motion coherence task was performed similarly to Chapter 8, with adjustments to accommodate cataract-related impairments. One observer participated using their right eye. The coherence step size was increased from 0.05–0.5 to 0.2–0.8 to account for reduced sensitivity. The JND values for coherent motion are presented in Table 9.5.

Table 9.5. Shows the individual JND values for radial coherence in one eye of a cataract observer.

	Cat01 RE
Coherent motion (Radial)	48

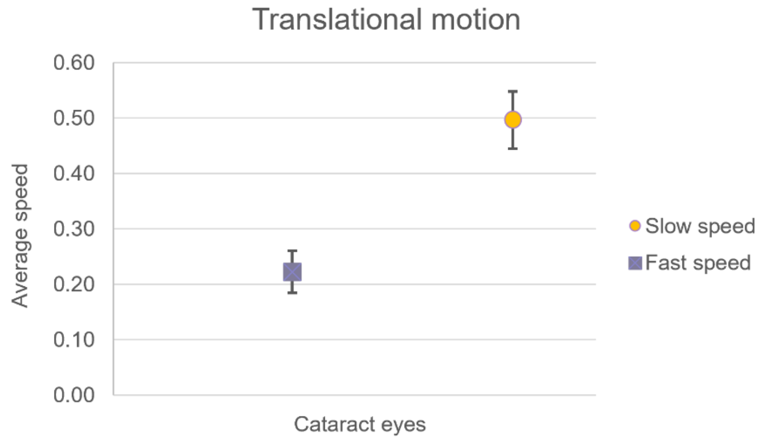
9.3 Results

9.3.1 Speed Discrimination

The results of the speed discrimination task revealed a variability in performance among cataract-affected eyes, underscoring the profound impact of cataracts on motion perception. For translational motion, the average JND values were 0.50 (±0.05 SE) for slow speeds and 0.22 (±0.04 SE) for fast speeds (Table 9.2). Similarly, radial motion produced JND values of 0.39 (±0.10 SE) for slow speeds and 0.21 (±0.04 SE) for fast speeds. These findings suggest that cataracts disproportionately impair the ability to discriminate slower speeds—a phenomenon likely associated with reduced contrast sensitivity and increased light scatter, both hallmarks of age-related cataracts.

Figures 9.2 and 9.3 illustrates these impairments with remarkable clarity, demonstrating that cataracts significantly elevate speed thresholds for both translational and radial motion. Particularly, translational motion shown increased sensitivity to visual contrast and distortion severity compared to radial motion. This divergence highlights the intricate interaction between optical degradation and higher-level perceptual processing.

(a)



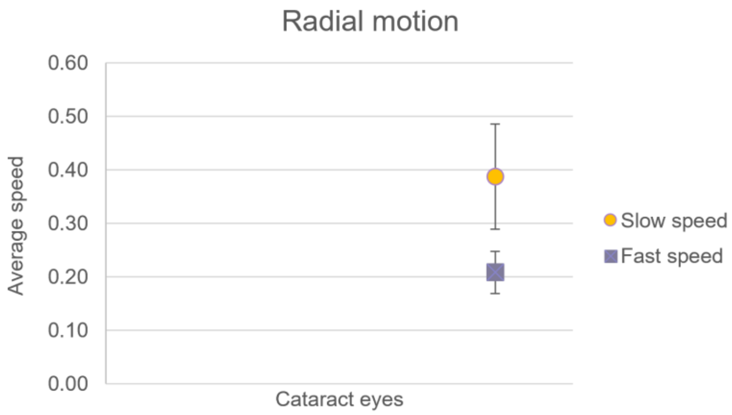
(b)

	T – statistic	P- value
TM Slow	10	<0.001
TM Fast	5.5	<0.001

Figure 9.2. (a) Line graph showing the average Weber JND data for translational motion patterns in 3 eyes of two cataract patients. Error bars represent the standard error of the mean (SEM). (b) Below the graph, the t- test results are presented, showing the p-values for each condition.

Figure 9.2 presents a line graph representing the average Weber JND data for translational motion patterns across three eyes of two cataract patients. Error bars represent the standard error of the mean (SE), while associated t-test results confirm statistical significance ($p < 0.001$ for fast speeds; $p < 0.05$ for slow speeds). Similarly, Figure 9.3 shows radial motion thresholds, revealing that faster radial motion ("RM Fast") was comparatively greater ($p \leq 0.001$), whereas slower radial motion ("RM Slow") was more susceptible to distortions ($p < 0.05$).

(a)



(b)

	T – statistic	P- value
RM Slow	3.9	<0.05
RM Fast	5.25	<0.001

Figure 9.3. (a) Line graph showing the average Weber JND data for radial motion patterns in 3 eyes of two cataract patients. Error bars represent the standard error of the mean (SEM). (b) Below the graph, the t- test results are presented, showing the p-values for each condition.

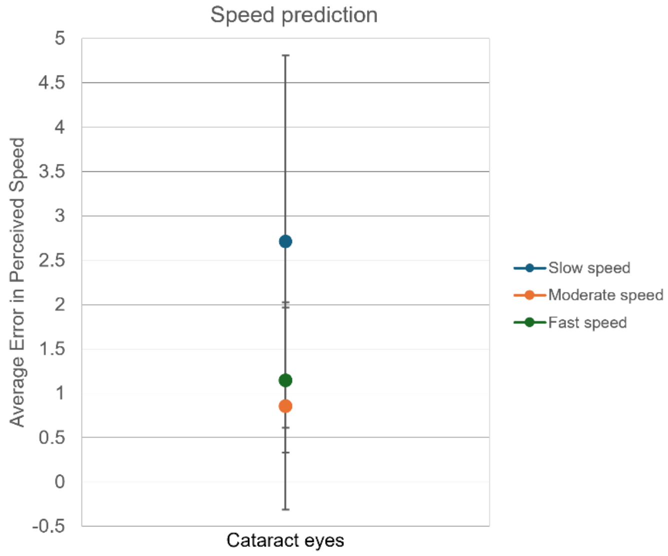
Collectively, these findings underscore the obvious impact of cataracts on translational and radial motion perception, particularly at faster speeds. Translational motion appeared as markedly more sensitive to visual contrast and distortion severity than radial motion, emphasising its vulnerability to cataract-induced impairments.

9.3.2 Speed Prediction

In the speed prediction task, observers revealed moderate accuracy in estimating TTC. The average error in perceived speed ranged from 1.63 (±1.52 SE) for moderate speeds to 3.87 (±3.03 SE) for slow speeds (Table 9.3).

Figure 9.4 reveals that speed prediction tasks did not produce statistically significant results, likely due to high variability (large SE). This variability is further illustrated by the tendency of observers to overestimate TTC, perceiving objects as slower than they actually were—particularly under conditions of increased light scatter and at faster speeds. Such overestimation reflects the degraded reliability of motion signals in cataract-affected eyes, where impaired contrast sensitivity and increased light scatter disrupt the precise encoding of velocity information.

(a)



(b)

	T – statistic	P- value
Speed prediction (Slow)	1.28	>0.05
Speed prediction (Moderate)	1.07	>0.05
Speed prediction (Fast)	1.80	>0.05

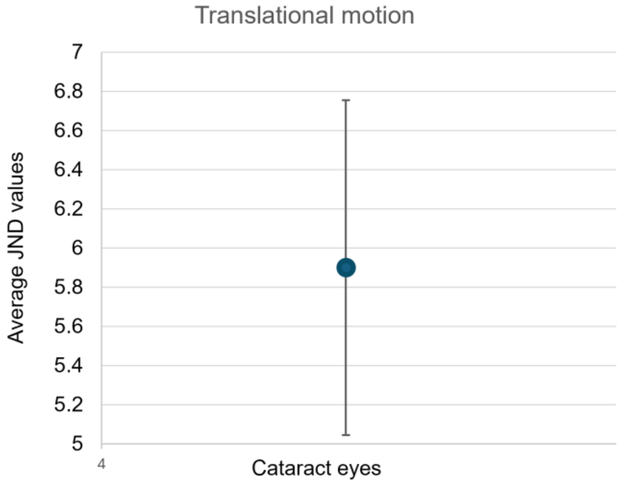
Figure 9.4. A scatter plots shows the averages for the average error in perceived speed (Vp) relative to actual speed (deg/ sec) for each condition in control group participants in the right section of the chart, the left section demonstrates responses in 3 eyes of cataract observers. Error in Vp was calculated by determining the average Vp and subtracting it from related reference for the predicted motion conditions.

The capacity to accurately estimate TTC depends on the proper functioning of motion prediction mechanisms, which rely heavily on healthy ocular media and optimal cognitive function. Both factors deteriorate with age, impairing the challenges faced by cataract patients. This trend became increasingly pronounced under higher levels of light scatter and at faster speeds, suggesting that individual differences in sensitivity to contrast reduction may contribute to the observed variability. These findings underscore the profound difficulties of motion perception under visually degraded conditions, offering critical insights into the functional limitations imposed by cataracts.

9.3.3 Direction Discrimination

The direction discrimination task yielded markedly higher thresholds for cataract-affected eyes compared to simulated groups in previous chapters. For translational motion, the average JND was 5.9 (±0.85 SE), while for spiral motion, it increased to 50 (±5.29 SE) (Table 9.4). These findings indicate that cataracts severely impair the ability to discriminate subtle directional changes, particularly in complex motion patterns such as spirals. Figures 9.5 and 9.6 summarise these results, highlighting the significant impact of cataracts on motion direction identification.

(a)



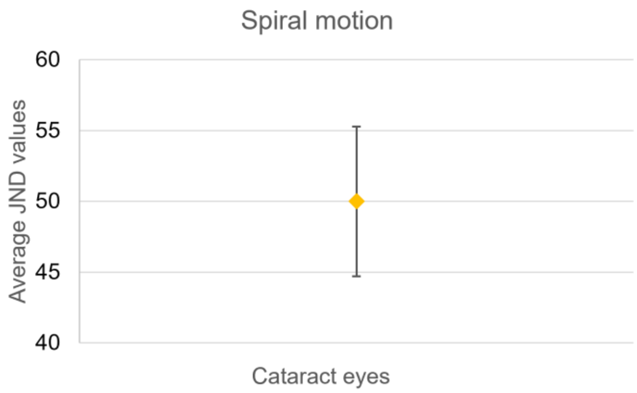
(b)

	T – statistic	P- value
Translational direction	6.94	<0.001

Figure 9.5. Illustrates The average JND values for three eyes of two cataract observers (a). Direction discrimination data thresholds and standard errors are plotted as a relation of oblique direction motion and degree of decreased contrast sensitivity. (b) The T- test results showing the mean of observers' performance in direction in above figure (a).

Figure 9.5 illustrates the average JND values for translational motion, revealing a strong relationship between oblique direction motion and decreased contrast sensitivity. Similarly, Figure 9.6 illustrates the remarkable elevation in thresholds for spiral motion, with t-tests confirming a significant main effect of cataracts on spiral motion discrimination ($p < 0.001$).

(a)



(b)

	T – statistic	P- value
Spiral motion	9.45	<0.001

Figure 9.6 The average JND values for three eyes of two cataract observers. Spiral motion discrimination data thresholds and standard errors are plotted as a relation of oblique direction motion and degree of decreased contrast sensitivity. (b) The T- test results showing the mean of observers' performance in direction in above figure (a).

These findings collectively underscore the profound impact of cataracts on direction identification, particularly in tasks requiring fine-grained spatial and temporal integration. The obvious difference between translational and spiral motion thresholds suggests that cataracts disproportionately affect complex motion patterns, likely due to their dependence on higher-order cortical processing.

9.3.4 Motion Coherence

In the motion coherence task, the single cataract-affected observer demonstrated a JND value of 48 for radial motion (Table 9.5). This finding underscores the substantial impact of cataracts on the ability to extract coherent motion signals from noise, likely attributable to increased light scatter and reduced contrast sensitivity.

Figure 9.7 illustrates the number of signal dots required for the observer to correctly perceive the global motion direction, highlighting the challenges faced by cataract patients in integrating motion signals across the visual field. Although the limited sample size prevents formal statistical analysis, this result aligns with prior research indicating that cataract-related deficits in motion perception may stem from both optical degradation and neural ageing processes (Pilz et al., 2017).

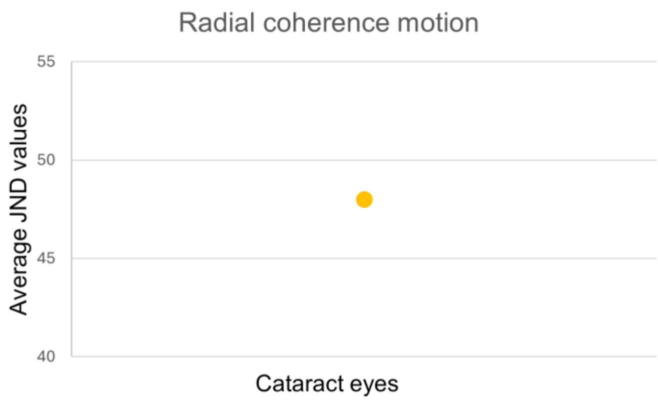


Figure 9.7 Illustrates the number of signal dots required to correctly perceive the global motion direction is plotted the right eye of one cataract observer.

Specifically, the elevated JND value observed at this point suggests that cataracts impair the visual system's capacity to process subtle motion cues embedded within noisy environments. This impairment is consistent with the hypothesis that degraded retinal input disrupts higher-order motion processing mechanisms, particularly those dependent on contrast sensitivity and temporal resolution.

9.4 Discussion

The findings from this case study provide convincing evidence that age-related cataracts significantly impair motion perception across multiple dimensions, including translational motion, radial motion, and direction discrimination. These results not only align with existing literature but also extend the understanding of how cataracts disrupt global motion processing. By examining two observers with age-related cataracts, a significant difference is uncovered from null hypothesis in most conditions (Table 9.6). However, speed prediction tasks failed to demonstrate a significant results due to high variability (large standard errors), underscoring the challenges faced by cataract patients in accurately estimating TTC. Additionally, while statistical analysis was impossible for radial coherence motion due to the inclusion of only one observer, preliminary comparisons suggest potential significance, warranting further investigation.

Table 9.6. Detailing the t statistics for all behavioural experiments applied on cataract observers.

Condition	Mean JND	SE	T- statistic	P- value	Significance?
Translational motion (Slow)	0.50	0.05	10.0	$p < 0.001$	Yes
Translational motion (Fast)	0.22	0.04	5.5	$p < 0.001$	Yes
Radial motion (Slow)	0.39	0.10	3.9	$p < 0.05$	Yes
Radial motion (Fast)	0.21	0.04	5.25	$p < 0.001$	Yes
Speed prediction (Slow)	3.87	3.03	1.28	$p > 0.05$	No
Speed prediction (Moderate)	1.63	2.52	1.07	$p > 0.05$	No
Speed prediction (Fast)	1.74	0.97	1.80	$p > 0.05$	No
Direction (Translational)	5.90	0.85	6.94	$p < 0.001$	Yes

Direction (Spiral)	50	5.29	9.45	*p* <0.001	Yes

The lack of significance in speed prediction tasks likely stems from the inherent variability in cataract-related impairments. Factors such as individual differences in contrast sensitivity, light scatter, and cognitive load may contribute to inconsistent performance. Furthermore, the small sample size limited the power of statistical analyses, particularly in tasks requiring finer perceptual judgments.

One critical question this study required to address is whether the observed deficits in motion perception are attributable to age-related changes or cataract-specific impairments. The two cataract patients demonstrated lower overall translational motion discrimination, with JND values worse than those observed in the most severe simulated distortions across all conditions. While these results suggest that cataracts worsen motion perception deficits, it remains unclear whether these impairments are entirely cataract-driven or compounded by age-related neural decline. To separate these effects, future studies should include larger samples of both cataract patients and age-matched controls without cataracts. This approach would allow researchers to isolate the specific contributions of optical impairments versus neural ageing processes. For instance, prior work by Pilz et al. (2017) highlights the interplay between optical degradation and neural plasticity, suggesting that cataract-related deficits may persist even after surgical intervention due to irreversible changes in cortical processing.

This study also examined the broader impact of age on motion perception, revealing significant differences between younger and older observers, particularly at specific speeds and contrasts. These findings confirm earlier reports by Ball and Sekuler (1986), Trick and Silverman (1991), Wojciechowski et al. (1995), and Bennett et al. (2007), who identified age-related declines in motion perception. For example, Snowden and Kavanagh (2006) reported age-related differences only at speeds ≤1°/sec, while Atchley and Andersen (1998) found impairments in older adults' central vision at 4.8°/sec but not at higher speeds. In contrast, Gilmore et al. (1992) did not report overall differences between age groups, highlighting inconsistencies in the literature (Table 9.7).

Table 9.7. Previous studies and their relation between global translational motion and ageing.

Dots speed (°/sec)	**Found a difference between young and old age groups**	**Dots speed (°/sec)**	**No difference between young and old age groups**
3 & 8	Current study	3.9	(Gilmore et al., 1992)
10	(Ball and Sekuler, 1986)		
5.8	(Trick and Silverman, 1991)		
28	(Wojciechowski et al., 1995)		
4.8 & 22	(Atchley and Andersen, 1998a)		
0.5 – 4	(Snowden and Kavanagh, 2006)		
6	(Bennett et al., 2007a)		
6.6 & 18.6	(Billino et al., 2008)		

5.6	(Allen et al., 2010)

By systematically examining the interplay of speed, contrast, and simulated distortions across age groups, this study contributes to resolving these discrepancies. Notably, the current findings emphasise the role of contrast in modulating motion perception—an observation consistent with Allen et al. (2010), who found age-related differences only under low-contrast conditions. These insights underscore the importance of considering both stimulus parameters and individual differences when assessing motion perception in aging populations.

The deficits observed in cataract patients extend beyond general age-related declines, including several domain-specific impairments that significantly disrupt visual processing. These impairments include:

1. Speed Detection: Delayed reaction times to moving stimuli indicate slower motion detection, particularly at lower speeds. The current study revealed higher JND values for slow translational (0.50 ± 0.05 SE) and radial motion (0.39 ± 0.10 SE) in cataract patients, likely due to reduced contrast sensitivity and increased light scatter. These findings resonate with those of Atchley and Andersen (1998), who identified age-related impairments in central vision at 4.8°/sec but not at higher speeds. Collectively, these results suggest that cataracts increase age-related deficits in speed perception, particularly under reduced visual conditions.
2. Motion Direction Discrimination: Cataract patients show marked difficulties in detecting slight directional changes. This deficit reflects reduced sensitivity to motion signals, which may be related to increased light scatter and reduced contrast sensitivity (Pilz et al., 2017). The current study confirms these findings, with higher JND values for both translational (5.9 ± 0.85 SE) and spiral motion (50 ± 5.29 SE) tasks in cataract patients compared to cataract simulated groups in earlier chapters. These results align with previous work by Snowden and Kavanagh (2006), who reported age-related differences in direction discrimination at speeds ≤1°/sec, suggesting that cataracts impair pre-existing neural ageing effects.
3. Motion Coherence: Cataract patients demonstrate significant challenges in integrating motion signals across the visual field, delaying the perception of coherent global motion. In this study, one observer shown a JND value of 48 for radial coherence, underscoring the difficulty in extracting coherent motion signals from noise. This finding is consistent with Gilmore et al. (1992), who highlighted the role of contrast sensitivity in motion coherence tasks, and further supports the notion that cataracts disproportionately affect tasks requiring fine-grained spatial and temporal integration (Gilmore et al., 1992).

The deficits in motion perception observed in cataract patients have profound effects for daily functioning, extending beyond laboratory settings to real-world scenarios. These impairments demonstrate in critical aspects such as driving, mobility, and routine activities, showing the need for interventions that address both static and dynamic aspects of vision.

- Driving: Cataract patients may struggle to detect moving vehicles, pedestrians, or changes in lane position, risking road safety. This study's findings on impaired speed detection and motion coherence align with prior research highlighting the importance of motion perception in driving tasks (Wood et al., 2009). For example, Wood et al. demonstrated that reduced contrast sensitivity and delayed reaction times significantly increase accident risks among older drivers. By impairing the ability to accurately perceive motion, cataracts impair these risks, necessitating targeted interventions to restore dynamic visual function.
- Mobility: Impaired ability to assess the movement of obstacles increases the risk of falls and reduces independence, particularly among elderly individuals. This study's results on reduced peripheral motion detection corroborate findings by Lord et al. (2003), who identified poor motion perception as a key predictor of fall risk in older adults.
- Sports and Routine Activities: Tasks requiring motion tracking, such as catching a ball or reaching for objects, become difficult for cataract patients. As Lisberger (2010) notes, motion perception is integral to sensory-motor integration, enabling precise actions like grasping and reaching. Given that approximately two-thirds of our sensory information comes through vision (Qin et al., 2022), disruptions in motion perception significantly impact quality of life. This focuses the need for interventions that restore not only visual acuity, yet also dynamic aspects of vision, such as contrast sensitivity and motion coherence.

While this study provides valuable insights, several limitations must be acknowledged. First, the small sample size—two cataract patients and three eyes—limits the generalisability of the findings. Including more genuine cataract cases would strengthen the validity of the conclusions. Second, the absence of age-matched controls without cataracts prevents definitive statements about the relative contributions of ageing versus cataracts to motion perception deficits.

By linking the gap between basic science and clinical practice, this study contributes to a deeper understanding of how cataracts impair motion perception and highlights the importance of addressing these deficits to enhance safety, independence, and overall quality of life for ageing individuals. Future research should explore the efficacy of rehabilitative interventions, such as perceptual training and adaptive technologies, in mitigating residual deficits post-surgery.

Chapter 10 **General Discussion**

The preceding chapters of this thesis have systematically explored the impact of light scatter on motion perception, with a particular focus on radial, translational, and spiral motion patterns. This examination included an in-depth analysis of alterations in media transparency influence motion discrimination sensitivity, as well as the broader implications for visual processing under degraded conditions. Through a combination of MATLAB-based psychophysical experiments and simulated filters, this study ends in a case study examining motion perception in genuine cataract patients. This final chapter shows the key findings, contextualises them within existing literature, and proposes avenues for future research to expand upon these insights. The findings collectively underscore the complex interplay between reduced contrast sensitivity, increased light scatter, and age-related neural changes in shaping the perceptual challenges faced by individuals with cataracts.

10.1 Summary of findings

The study began by contextualising cataract-induced impairments through an online survey targeting eye care professionals and patients. Results highlighted three primary domains of visual dysfunction: mobility, discrimination, and near tasks. Mobility tasks, such as driving and walking, rely heavily on peripheral retinal processing, while near tasks like reading depend on central retinal function. Notably, 40% of surveyed patients reported difficulties detecting motion in animated videos, emphasizing the profound impact of cataracts on dynamic vision. This aligns with prior literature indicating that cataracts primarily manifest through increased blur and diminished contrast sensitivity, which disproportionately affect motion perception compared to static vision.

Chapter 4 further explored of simulated cataract conditions on motion perception using optical filters to replicate light scatter, glare, and blur. The results demonstrated significant declines in CS and VA across all spatial frequencies, consistent with earlier studies (Wood et al., 2010, Long and Zavod, 2002, Wood et al., 2009). These findings highlight the profound effect of degraded media contrast on visual function, particularly in older adults, who show reduced sensitivity to motion tasks under such conditions (Anderson et al., 2000, Pluháček et al., 2022). The observed impairments in motion perception provide critical insights into the challenges faced by individuals with cataracts and serve as a foundation for examining specific deficits in speed discrimination.

Speed discrimination experiments (Chapter 5) shown differential sensitivity among motion types to visual degradation. For translational motion, no statistically significant differences were observed at slow or fast speeds, suggesting minimal impact from simulated distortions. However, radial motion showed increased sensitivity to visual impairments, particularly at slower speeds, where thresholds increased significantly under moderate and severe distortion levels. These results highlight the vulnerability of radial motion to contrast and distortion challenges, extending prior literature on motion perception to the context of cataract-induced impairments.

Speed prediction tasks (Chapter 6) further underscored the role of reduced contrast and attentional demands in motion processing. Performance across three distinct speed patterns (2.5°/sec, 5°/sec, and 10°/sec) deteriorated with increasing simulation severity, and perceived speed was increasingly underestimated as both filter severity and speed levels rose. This aligns with prior research linking decreased contrast to impaired motion prediction and highlights the importance of attentional processes in accurately estimating motion.

Direction discrimination experiments (Chapter 7) provided additional insights into the complexity of disconnecting sensory deficits from higher-level processing impairments. Observers demonstrated greater difficulty distinguishing oblique translational patterns compared to other motion types, suggesting that direction perception may be controlled by specific stimulus characteristics rather than purely velocity-based responses. While the findings did not conclusively establish the impact of reduced media opacity on motion perception, they reinforced the intricate relationship between sensory input and cognitive processing under simulated visual degradation.

Radial coherence experiment Chapter 8) challenged establishing assumptions about the relationship between media contrast and radial motion perception. In contrast to earlier studies, the current findings revealed relative stability in threshold levels for expanding versus contracting optic flow patterns across varying media contrasts. This unexpected outcome highlights the need for further investigation into the mechanisms underlying radial motion perception and its resilience to certain forms of visual degradation.

The case study examining genuine cataract patients Chapter 9) provided convincing evidence of the profound impact of age-related cataracts on motion perception. Across multiple dimensions—including translational motion, radial motion, and direction discrimination—cataract patients demonstrated significant impairments. Speed prediction tasks, however, yielded inconclusive results due to high variability, underscoring the challenges faced by cataract patients in accurately estimating TTC. Similarly, preliminary comparisons for radial coherence motion suggest potential significance, warranting further investigation despite the limitations imposed by sample size.

Collectively, these findings highlight the multifaceted impact of cataracts on motion perception, incorporating both optical and neural deficits. Reduced contrast sensitivity, increased light scatter, and age-related changes in neural processing create a complex interaction of impairments that disrupt dynamic visual tasks. Importantly, the results suggest that addressing optical impairments—such as through cataract surgery—may mitigate some of these deficits, proposing hope for improved functional vision and quality of life in ageing populations. Research indicates that surgical interventions restore contrast sensitivity, spatial resolution, and the ability to detect moving objects, leading to enhanced mobility, safety, and independence.

In conclusion, this thesis bridges basic science and clinical practice by showing the profound impact of age-related cataracts on motion perception. Thru incorporating psychophysical methodologies with real-world applications, the study provides actionable insights for improving interventions and enhancing patient outcomes. Adopting a multidisciplinary approach will be essential to addressing both the optical and perceptual challenges faced by individuals with cataracts. These efforts hold the potential to transform patient care and empower ageing individuals to navigate their environments with confidence and independence

10.2 Optical Influences on Motion Perception

This study aimed to explore how reduced media transparency affects motion perception—a vital skill for navigating dynamic environments. Understanding how observers track moving objects and respond behaviourally is central to this study, as it sheds light on the broader relationship between optical degradation and perceptual processing. This ability is not only essential for everyday tasks like driving and walking, however, it provides critical insights into how visual impairments, such as those caused by cataracts, disrupt dynamic vision. Reduced VA, caused by reduced media transparency from simulated filters, impacts motion perception offering insights into how degraded contrast sensitivity disrupts sensory processing and related visual functions. The results highlight the importance of considering motion perception in both experimental and clinical contexts, particularly when studying cataract populations.

In a related study, Braddick et al. (2007) reported substantial effects on both form and motion thresholds, however only at higher levels of blur (specifically with +7D and +10D lenses). Their findings suggest that intense optical blur disproportionately affects motion coherence thresholds (Braddick et al., 2007). Similarly, Zwicker et al. (2006) proposed that optical blur neither enhances nor impedes motion processing, indicating that motion perception remains relatively unaffected under certain conditions. However, their experimental setup—simulating optical blur with positive lenses ranging from 0.75 to 3.50 dioptres—was limited to slow, vertical translational motion with dot speeds varying from 1.26 to 0.039°/sec. Additionally, their experiments were conducted under diffuse lighting conditions (mesopic) to minimise glare (Zwicker et al., 2006). While informative, these earlier studies fall short of replicating real-world conditions. In contrast, the current study achieves more ecologically valid results by using photographic simulated filters and maintaining dim room illumination to eliminate interference from reflected light, thereby capturing the full effect of simulated filters.

In the context of spatial frequency and dot displacement, the presence of blur—resulting in a visual acuity of 3.56 cycles per degree (c/8) or lower—was associated with an increase in the spatial limit, suggesting heightened sensitivity. Cleary and Braddick (1990) demonstrated that removing high spatial frequencies from stimuli elevated the upper spatial limit, highlighting the complex interaction between blur and motion perception (Cleary and Braddick, 1990). Building on this, Barton et al. (1996) examined the influence of optical blur on the perception of global coherent motion in RDKs. Their findings revealed that optical blur significantly impaired the ability to discriminate motion direction in RDKs, which involve a broad spectrum of spatial frequencies. Notably, they observed a non-monotonic relationship between blur and motion perception: for small displacements (<16°), blur impeded motion perception, whereas for larger displacements, it appeared to enhance it. These insights align with the current study's findings, pointing out the nuanced effects of blur on motion perception (Barton et al., 1996a).

Consistent with current results outlined in this thesis Burton et al. (2015) observed that the spatial frequencies associated with global form and motion discrimination increased with the induction of blur. Prior to applying blur, these frequencies were similar, suggesting a relationship between blur and the perception of form and motion. Importantly, their findings indicate that while high spatial frequencies contribute to the detection of global motion within stimuli, they are not essential for this process (Burton et al., 2015). Although this study provides valuable insights into global motion perception, the current thesis adopts a broader approach, focusing exclusively on various speed perception patterns without including form-based stimuli.

Light scattering, a consequence of blur in the eye, significantly degrades vision quality—an effect worsened by ageing and conditions such as cataracts. Chapter 4 showed that the simulated filters effectively replicated this phenomenon, providing a strong framework for understanding its implications. To quantify the impact of light scattering on the ocular lens, this thesis developed a statistical model parameterising degraded vision using filters during motion tasks. The effectiveness of this model was validated through behavioural experiments conducted using a specialised setup, enabling precise control over speed and direction across varying levels of light scattering. These experiments not only validate the model's utility but also lay the groundwork for future visual research, offering a controlled means to explore the effects of light scattering on motion perception.

The results suggest that optical blur resulting from cataract development influences motion sensitivity, although this influence is not directly mediated by CS or VA unless VA is significantly reduced. This conclusion is supported by data from simulation groups presented in Chapter 4, which confirm qualitative deterioration in CS. Collectively, these findings highlight the intricate relationship between optical blur, contrast sensitivity, and motion perception, offering a deeper understanding of how cataracts disrupt dynamic visual processing.

10.2.1 Effect of Light Scatter on Motion Perception

The precise characterisation of individual differences in motion perception under varying light transmission conditions—ranging from 100% (natural, unfiltered vision) to approximately 62% (using an HFBB filter)—offers a unique opportunity to investigate how specific filters influence neural responses associated with retinal directional locations. This approach not only facilitates a deeper understanding of peripheral retinal responses to light scattering but also highlights the critical role of the peripheral retina in motion perception. Unlike the central retina, which is primarily responsible for tasks requiring high spatial resolution, such as reading or recognising fine details, the peripheral retina plays a dominant role in detecting and interpreting dynamic visual stimuli, particularly motion (Hutchinson et al., 2012, Atchley and Andersen, 1998b). By isolating the effects of light scatter on peripheral motion perception, this study provides valuable insights into how degraded visual input disrupts the processing of moving stimuli.

While central light scattering may not serve as an optimal model for all types of cataracts, it holds particular relevance for nuclear cataracts (NC), which are the most prevalent type, accounting for approximately 31.19% of cases in older populations (NICE, 2022). In contrast, cortical cataracts (CC) and posterior subcapsular cataracts (PSC), representing 24.78% and 7.29% of cases respectively (NICE, 2022), exhibit distinct characteristics that may not align perfectly with this framework. For instance, CC and PSC are more likely to induce glare and visual distortions that vary with changes in viewing angle, making them better suited for analysis through alternative methods, such as angular-dependent light scattering assessments. These distinctions highlight the importance of adapting experimental designs to the specific optical properties of different cataract types, ensuring that findings remain both accurate and clinically relevant.

Furthermore, the observed age-related differences among observers suggest a potential correlation between motion perception and advancing age. This relationship can be explained by two key factors identified in the literature. First, as individuals grow older, the internal additive noise within their motion perception neurons tends to increase, reducing the signal-to-noise ratio and impairing the ability to detect subtle motion cues (Betts et al., 2009). Second, age-related changes in channel bandwidth—combined with heightened internal noise—may further compromise motion perception by limiting the range of spatial frequencies that can be effectively processed (Bennett et al., 2007a). These findings underscore the complex interplay between optical degradation and neural ageing, highlighting the need for future research to account for these factors systematically.

To address these complexities, it is recommended that future studies include a control group including individuals without cataracts, as well as a larger sample of simulated observers aged over 30 years. Such an approach would enable researchers to disentangle the effects of age-related neural changes from those attributable to cataract-induced optical impairments. Additionally, expanding the sample size would enhance the statistical power of the findings, allowing for subgroup analyses based on cataract type, severity, and age. By adopting a multidimensional perspective that integrates optical, neural, and behavioural measures, future investigations can provide a more comprehensive understanding of how light scatter impacts motion perception across diverse populations.

In conclusion, the application of specific filters in motion experiments offers a promising avenue for exploring the neural and perceptual consequences of light scatter. By focusing on the peripheral retina's response to degraded visual input and considering the unique characteristics of different cataract types, this line of inquiry has the potential to bridge gaps in our understanding of motion perception deficits in aging populations. Moreover, addressing the dual impact of optical and neural factors will pave the way for targeted interventions aimed at mitigating the visual challenges faced by individuals with cataracts, ultimately enhancing their quality of life and functional independence.

10.2.2 Useful Field of View

An illustrative example of impaired vision and its impact on the perception of useful scenes within the visual field is particularly evident among older adults. These individuals often encounter significant challenges when performing daily activities, especially in unfamiliar or visually cluttered environments (Kline et al., 1992). Such difficulties extend beyond simple obstacle, as they can have profound implications for safety and independence. For example, evidence suggests that visual impairments contribute to an increased risk of falls and associated injuries (Felson et al., 1989), as well as heightened difficulties in driving and navigating traffic, leading to a higher incidence of accidents compared to younger individuals (Planek, 1972, Mackay, 1988, Chisholm et al., 2008). To address these concerns, researchers have developed innovative clinical tools, such as the measurement of the useful field of view (UFOV), to assess age-related visual difficulties and their functional consequences.

The concept of the useful field of view (UFOV) refers to the specific area within the visual field from which an individual can extract critical information about their surroundings without overtly shifting their gaze. Sekuler et al. (2000) established efforts to quantify UFOV in relation to ageing by assigning observers tasks designed to evaluate attentional performance across central, peripheral, and divided attention conditions. In their study, participants completed tasks requiring either focused attention on a central target, detection of peripheral stimuli, or simultaneous processing of both central and peripheral information—a condition referred to as divided attention. The findings revealed that older adults made significantly more errors than younger participants, with the most pronounced deficits observed during divided attention tasks, particularly those involving peripheral stimuli. This decline in UFOV with age underscores its potential role in explaining the difficulties older adults face in complex, dynamic environments.

The reduction in UFOV has far-reaching implications for daily life, particularly in activities that demand extensive attentional resources. For example, driving requires drivers to simultaneously observe central elements, such as traffic signals, while remaining cautious to peripheral hazards like pedestrians or approaching vehicles. A diminished UFOV compromises this ability, increasing the probability of accidents and reducing overall confidence in performing such tasks. Moreover, the challenges posed by a restricted UFOV are likely exacerbated in individuals with age-related cataracts, whose visual input is further degraded by reduced contrast sensitivity, increased light scatter, and blurred vision. These factors may compound the natural decline in UFOV, creating a dual burden of optical and neural impairments that disproportionately affect older adults.

Interestingly, recent research suggests that interventions targeting UFOV could mitigate some of these challenges. Cognitive training programs designed to enhance attentional capacity and expand the UFOV have shown promise in improving driving performance and reducing accident rates among older adults (Ball et al., 2010, Edwards et al., 2009). Such interventions could be particularly beneficial for individuals with cataracts, offering a complementary approach to surgical or corrective treatments. By combining cognitive rehabilitation with strategies to address optical impairments, it may be possible to restore not only static visual acuity but also the dynamic visual functions essential for safe and independent living.

Future research should explore the interplay between UFOV, cataracts, and other age-related changes in vision. For example, longitudinal studies could investigate whether cataract surgery leads to improvements in UFOV and related functional outcomes, such as driving safety and mobility. Additionally, integrating advanced imaging techniques, such as functional MRI, could provide deeper insights into how changes in UFOV reflect underlying neural adaptations. Understanding these mechanisms will be necessary for developing targeted interventions that address both the optical and perceptual challenges faced by ageing populations.

10.3 Futures Directions

The findings presented in this thesis provide valuable insights into the impact of cataracts on motion perception, however numerous avenues remain open for future exploration. These directions are designed not only to extend the understanding of the underlying mechanisms, however, also to broaden the applicability of the findings and develop practical interventions that can improve outcomes for individuals with visual impairments. The following sections outline specific areas for future research, highlighting methodological advancements, technological innovations, and interdisciplinary approaches.

10.3.1 Expanding Sample Sizes and Demographic Diversity

One critical area for future investigation is the inclusion of larger and more diverse participant pools. While the current study provides convincing evidence regarding the effects of cataracts on motion perception, the generalisability of these findings could be significantly enhanced by recruiting a broader range of participants. Specifically, expanding the sample size to include more genuine cataract patients would allow for subgroup analyses based on factors such as cataract severity, type, and location (Fraser et al., 2013). Increasing demographic diversity—by including a wider range of ages, genders, and individuals with varying ocular abnormalities—would generate more broad insights into how these factors interact with motion perception deficits (Elliott et al., 1996). Such efforts would ensure that the findings are representative of the broader population and applicable across different clinical contexts. Future studies could also explore the role of comorbid conditions (e.g., glaucoma or diabetic retinopathy) in shaping motion perception outcomes (Zhang et al., 2024).

10.3.2 Longitudinal Designs to Assess Reversibility and Neural Plasticity

A longitudinal research design represents another promising avenue for future exploration. By tracking changes in motion perception before and after cataract surgery, researchers could gain critical insights into the reversibility of perceptual deficits and the role of neural plasticity in recovery (Wan et al., 2020a). this approach could determine whether prolonged exposure to degraded visual input due to cataracts leads to permanent alterations in cortical processing or whether these changes are reversible following surgical intervention (Hess et al., 2007). Additionally, longitudinal studies could help identify the time course of recovery and the factors that influence post-surgical outcomes, such as age, pre-existing visual deficits, and rehabilitation strategies. This approach would not only advance the understanding of the neuroplasticity of the visual system, however update the development of targeted interventions to improve recovery (Betts et al., 2009).

10.3.3 Investigating Neural Mechanisms Using Functional Imaging

To further elucidate the interplay between optical degradation and cortical restructuring, future research should use advanced functional imaging techniques to investigate the neural correlates of motion perception in cataract patients. Techniques such as functional magnetic resonance imaging (fMRI) and magnetoencephalography (MEG) could provide detailed insights into how optical distortions caused by cataracts affect the processing of motion stimuli in higher-order visual areas, such as the middle temporal area (MT) and medial superior temporal area (MST) (Fischer et al., 2012, Koyama et al., 2005). Additionally, these techniques could determine whether prolonged exposure to light scatter leads to compensatory changes in the activity of these brain regions or whether surgical correction restores normal patterns of activation (Snowden and Kavanagh, 2006). Understanding these neural mechanisms would have significant implications for both basic science and clinical practice.

10.3.4 Developing Rehabilitation Strategies

Another important direction involves the development and testing of rehabilitation strategies aimed at mitigating residual deficits in motion perception following cataract surgery. Perceptual training programs, which involve repeated exposure to motion stimuli under controlled conditions, represent a promising approach to enhancing visual function in patients with impaired motion perception (Bennett et al., 2007a). These programs could be tailored to target specific deficits, such as reduced sensitivity to global motion or impaired discrimination of speed and direction and incorporate principles of gamification and adaptive learning algorithms to increase engagement and improve training outcomes (Turano and Wang, 1992). Future research would evaluate the efficacy of such interventions in improving the laboratory-based measures of motion perception and real-world functional outcomes, such as driving performance and mobility (Wan et al., 2020a)..

10.3.5 Real-World Applications and Ecological Validity

Extending the findings of this study to real-world scenarios represents another important area for future research. While laboratory-based experiments provide valuable insights into fundamental mechanisms, their ecological validity can be limited (Greenwood and Edwards, 2006). To address this gap, future studies could use ecologically valid paradigms, such as driving simulators or virtual reality (VR) environments, to examine how cataracts and their associated perceptual deficits impact dynamic, real-world tasks (Rodman and Albright, 1989). VR platforms could simulate complex motion stimuli, such as optic flow patterns encountered during navigation, enabling researchers to assess how individuals with cataracts perceive and respond to these cues in immersive settings (Fischer et al., 2012). Findings from such studies would enhance the understanding of the challenges faced by cataract patients in everyday life, in addition will update the design of safer environments and assistive technologies for visually impaired individuals (Salvi et al., 2006).

10.3.6 Exploring the Role of Light Scatter in Motion Perception

Further research is essential to explore the role of light scatter in motion perception, particularly in relation to speed, direction discrimination, and the spatial arrangement of stimulus targets. This investigation could deepen our understanding of how degraded visual input impacts both basic and higher-order perceptual functions (Allen et al., 2010, Bex et al., 1998). Below are key areas for exploration:

10.3.6.1 Complex Motion Stimuli

Extending current paradigms to include more complex motion stimuli represents another promising direction for future research. While this thesis primarily focuses on two-dimensional (2D) RDKs, incorporating three-dimensional (3D) motion stimuli or naturalistic movement patterns would provide a more authentic representation of real-world motion perception.
Advancements in technology have facilitated the use of computerised stimuli to manipulate RDKs in a more systematic manner (Ma et al., 2021, Parsey and Schmitter-Edgecombe, 2013). By adjusting parameters such as density, velocity, and direction, these stimuli can be customised to address specific research objectives. This capability has enabled controlled investigations into various dimensions of motion perception (Nishida, 2011), including speed, direction, coherence global motion, and translational motion, as well as how motion cues affect the perception of object shape (Barton, 2021).

In broad terms, motion is considered "complex" when it includes a global motion component. This discussion will focus on two forms of complex motion: radial (optic flow) and biological motion (b and e in Figure 10.1). Optic flow refers to the expanding, radial motion that occurs when an individual moves through their environment. It is created by forward motion and provides vital cues important for heading (personal direction) and navigation in space. To obtain the maximum practical benefits from this type of motion, it is necessary for motion sensitive brain area MST to be able to select what is relevant to the task and ignore unnecessary information (Fischer et al., 2012, Koyama et al., 2005). In contrast to this, biological motion is stimulated by the movement associated with that of a human figure (or something depicting motion of a human, Figure 10.1) and contributes to social interaction cues (Billino et al., 2008). Both types of motion can be investigated in laboratory settings using dot stimuli in the form of RDKs or point-light displays (PLDs).

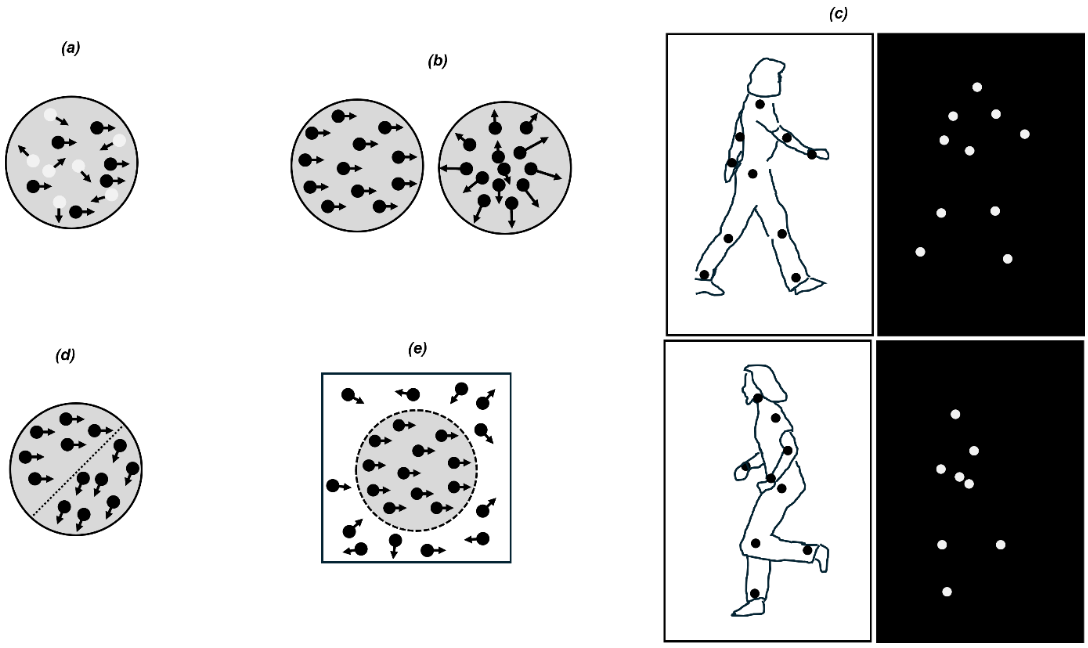


Figure 10.1. Illustrates examples of RDKs and shape perception through motion. (a) Global direction discrimination as an example of an experiment that was conducted in this thesis. involves a combination of signal dots moving in a specific direction (black dots) and noise dots moving randomly (white dots). The observer must analyse the entire display to determine the overall direction of motion, with the threshold indicating the level of noise they can handle. (b) Two examples of optic flow illustrate large displays that simulate how the environment moves across the retina as the observer navigates through it, including translating on the left side and radial (specifically, expanding) patterns on the right. (c) represents the point-light biological motion involves lights affixed to different parts of an object, The motion of these lights can create a strong perception of the animal or person and the activity they are engaged in. (d) motion segmentation divides the display into two sections, marked by an imaginary dotted line, where the dots on each side differ in some aspect of motion (in this case, direction). The observer indicates whether there is a motion boundary and its orientation. (e) images RDKs display motion in a specific area that contrasts with the background (for example, consistent rightward movement versus chaotic motion). Recognising this distinction enables the identification of a shape, such as a circle, represented by the unseen dotted line.

Radial motion in optic flow is processed in the medial superior temporal area (MST) of the brain (Fischer et al., 2012, Koyama et al., 2005). However, evidence suggests that the central heading component may be processed separately in V3A (Koyama et al., 2005, Braddick et al., 2000, Helfrich et al., 2013). Age-related studies indicate that older individuals are less likely to adjust their locomotion in response to changes in optic flow signals, suggesting altered perception of these signals (Berard et al., 2009).

Neurological conditions such as Alzheimer's and Parkinson's disease may impair optic flow processing even further (Kavcic et al., 2011, Putcha et al., 2014). However, findings on age-related radial motion impairments remain inconsistent. For example, Billino et al. (2008) found no evidence of deficits in heading perception, aligning with prior studies showing preserved radial motion perception (Atchley and Andersen, 1998a).

Biological motion, processed in the posterior superior temporal sulcus (STS) (Grezes et al., 2001, Battelli et al., 2003), has been studied using PLDs. Evidence on the effect of ageing is mixed: one study found no decline in biological motion perception (Norman et al., 2004), while another reported only a small (6%) decrease with age (Billino et al., 2008). More recent research indicates that identifying the direction of PLD walkers becomes more difficult with age when presented in noisy conditions (Pilz et al., 2017).

The perceptual process for 3D moving objects depends on both mathematical and physiological factors (Norman et al., 2013). Mathematically, the visual cortex perceives objects geometrically based on their shape, boundary, and contours as they move through space. Physiologically, perception relies on binocular disparity, shading, and texture highlights to interpret surfaces or 3D objects (Norman et al., 2013, Billino and Pilz, 2019). Clinically, this is evaluated by combining moving dots into 3D precepts, as shown in Figure 10.2 (Billino and Pilz, 2019). Ageing appears to preserve 3D motion perception but worsens the perception of motion-defined surfaces (Mateus et al., 2013, Billino and Pilz, 2019).

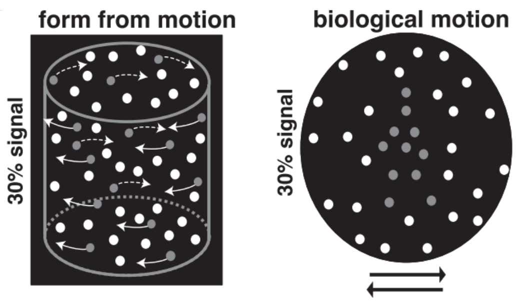


Figure 10.2. Illustrates a 3D form from motion. The dots designed to appear as if it is moving inside a transparent cylinder and attached to its surface, so the surface appears as a rotating cylinder from (Billino and Pilz, 2019).

Future experiments are necessary to explore the role that light scatter plays in motion perception functions, including speed and discrimination, in relation to the size, and spatial arrangement of stimulus targets (Betts et al., 2009). Implementation more complex motion tasks, such as biological motion (Troje, 2013), or three-dimensional motion stimuli (Glasauer and Merfeld, 2020) (Figure 10.2), may reveal whether light scatter impacts more higher-order perceptual processes. Although this thesis demonstrates that speed and direction of global motion stimuli can be attenuated under light scatter conditions, additional experiments could provide further confirming evidence. For example, the introduction of a dynamic segmentation cues, such as colour (Croner and Albright, 1997), to differentiate signal from noise dots would enhance the measurement of proportion discrimination functions.

10.3.6.2 Peripheral Motion Perception

Examining motion tasks across paracentral retinal areas would offer valuable insights into how light scatter influences peripheral motion perception. This is particularly relevant for tasks requiring wide-field visual processing, such as driving or sports (Atchley and Andersen, 1998b, Warren and Kurtz, 1992). Specific questions arise: Does light scatter disproportionately affect motion sensitivity in peripheral vision compared to central vision? And how do age-related changes in retinal function interact with light scatter to shape peripheral motion perception? Addressing these questions would help clarify the real-world implications of light scatter for individuals with cataracts or other ocular conditions. For instance, subsequent investigations may explore the impact of modifications to the physical characteristics of stimuli on our perception of motion, as well as the contributions of various regions of the retina (Betts et al., 2009, Ryan and Zanker, 2001).

The results from specific experiments discussed in this study reveal considerable differences among individuals regarding how perception affects motion sensitivity. A similar level of variability among subjects has been observed in motion perception tasks that use simulated filters. To reach conclusive understandings about the population, increasing of observers' demographics to include a wider range of ages, genders, and potential ocular abnormalities.

Visual perception fundamentally depends on motion as a key element presented in the dynamic environment we exist in. The analysis of visual stimuli derived from the surrounding context is crucial not only for the performance of daily activities but also for the appropriate motor responses of individuals (Nakayama, 1985, Contemori et al., 2023).

10.3.6.3 Enhancing Stimulus Design

Incorporating dynamic segmentation cues—such as colour or texture (Croner and Albright, 1997)—could significantly improve the measurement of proportion discrimination functions. By differentiating signal dots from noise dots more effectively, researchers could achieve more precise threshold measurements. For example, introduction of colour-based segmentation enhances the ability to discern coherent motion in noisy environments, while variations in dot density, velocity, and direction influence motion perception under conditions of light scatter. Advancements in computerised stimuli (Ma et al., 2021, Parsey and Schmitter-Edgecombe, 2013) provide opportunities to systematically manipulate RDKs and address these questions with greater experimental control.

10.3.6.4 Variability Across Individuals

Finally, the findings presented in this thesis highlight considerable variability among individuals regarding how light scatter affects motion sensitivity. To draw definitive conclusions about the broader population, future studies should increase the diversity of observers by including a wider range of ages, genders, and individuals with varying ocular abnormalities. Additionally, exploring the impact of simulated filters on motion perception tasks to identify shared and unique mechanisms across different patient groups. Such efforts would ensure that the results are representative and applicable to clinical contexts. These studies would not only enhance our understanding of the mechanisms underlying complex motion perception but also facilitate more precise and realistic threshold measurements.

10.3.7 Investigating Binocularity and Ocular Dominance

Future research should also explore the impact of binocularity on motion perception, particularly in individuals with monocular cataracts or other ocular conditions. While this study primarily focuses on the dominant eye, neglecting the potential contributions of the non-dominant eye may limit the understanding of how binocular interactions influence global motion processing. For instance, comparing the performance between individuals with monocular versus binocular cataracts could reveal whether binocular disparity enhances the perception of coherent motion or improves direction discrimination in global motion experiments. Drawing parallels between cataracts and other conditions that impair binocular function, such as amblyopia, could provide insights into the neural substrates of binocular processing. Understanding these mechanisms would have significant implications for both basic science and clinical practice, particularly in developing interventions to restore binocular function in visually impaired individuals.

Binocularity plays an essential role in processing global motion, as proved by its importance in everyday tasks like driving, which often requires binocular vision assessment. Research has shown that binocular disparity significantly enhances the perception of coherent motion within plaid displays and facilitates the detection of specific directional cues, thereby improving global motion discrimination (Greenwood and Edwards, 2006, Rodman and Albright, 1989). A compelling comparison can be drawn between cataracts and amblyopia, despite their distinct pathophysiological mechanisms. Both conditions often lead to dependence on one eye—either the healthier eye in cataract patients or the dominant eye in amblyopia—and impair binocular function during development. Literature reviews highlight that disorders such as unilateral amblyopia exhibit atypical global motion processing in both the affected and fellow fixing eyes, indicating dysfunction at a site responsible for binocular processing (Giaschi et al., 1992, Ho et al., 2005, Simmers et al., 2003). Hess et al.(2007) further reported that the advantages of binocularity in global motion perception are primarily linked to contrast rather than motion integration processes (Hess et al., 2007). However, the degree to which binocularity enhances global motion perception and the specific level at which this advantage occurs remain unclear at this time.

This study focused entirely on the dominant eye, potentially overlooking the influence of the non-dominant eye and binocular interactions on motion perception. Future research combining both eyes could uncover significant individual differences in motion perception tasks. Additionally, studies with larger sample sizes are necessary to draw definitive conclusions about the general population and to better understand the role of binocularity in motion perception under simulated and real-world conditions.

10.3.8 Examining Motion Perception in Other Ocular Pathologies

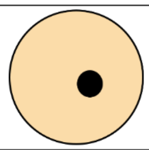
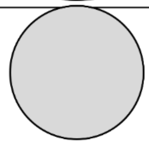
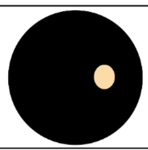
Motion perception deficits are not solely associated with the presence of cataracts. rather, extend to a broader spectrum of ocular pathologies and anomalies. Conditions such as glaucoma, diabetic retinopathy, and retinitis pigmentosa also significantly impact motion perception by affecting different components of the visual pathway.

Glaucoma, for example, damage of magnocellular pathway or the ganglion cells responsible for motion processing (Anderson and O'brien, 1997). It is noteworthy that glaucoma often remains undetected until approximately 20 to 40% of ganglion cells have degraded (Shabana et al., 2003). Given the irreversible nature of glaucomatous damage, developing behavioural and psychophysical experiments to assess and classify the extent of damage in both early and anticipated later stages is significant (Anderson and O'brien, 1997, Shabana et al., 2003).

Similarly, diabetic retinopathy (DR)—a leading cause of blindness and visual impairment among adults—has been linked to altered motion sensitivity. Zhang et al. (2024) found that type 2 diabetic patients demonstrate increased motion sensitivity, specifically for second-order high spatial frequencies, making it a strong predictor of DR presence (Zhang et al., 2024). Retinitis pigmentosa (RP), a hereditary retinal disease, also impairs motion perception. RP patients experience night vision loss and photoreceptor degeneration, leading to elevated motion thresholds and abnormal foveal processing (Turano and Wang, 1992, Grover et al., 1996, Hamel et al., 2000).

Future research could use RDK paradigms to systematically assess the impact of these conditions on motion perception aspects such as speed, direction, and coherence. Developing simulated filters that mimic the visual distortions associated with these pathologies would facilitate comparisons across patient groups and provide insights into shared and unique mechanisms underlying their perceptual deficits. Table 10.1 outlines proposed simulated filters for common ocular degenerative changes.

Table 10.1. Proposed simulated filters in most common ocular degenerative changes

Ocular condition	**Simulated filter**
Macular degeneration	
Retinal detachment.	
Cataract	
Glaucoma	
Diabetic retinopathy	
Retinitis pigmentosa	
Colour code: ■: *Affected area, blind area.* □: *Preserved visual area.* □: *Lenticular opacification*	

Additionally, age-related degenerative changes further impact motion perception. Ageing leads to declines in contrast sensitivity, visual acuity, and dark adaptation, profoundly affecting daily activities and quality of life (Salvi et al., 2006). Degenerative changes in the posterior eye, including reduced neural cells in the outer nuclear layer, thinning of the internal limiting membrane, and vascular alterations, impair the initial processing of visual signals (Gartner and Henkind, 1981, Jackson et al., 2002, Grossniklaus et al., 2013). These changes diminish blood supply over time, potentially leading to choroidal atrophy or retinal pigment epithelium dysfunction (Dorey et al., 1989, Curcio et al., 2001).

The onset of monocular cataracts may also disrupt binocular function, adversely affecting ocular movements such as saccades and smooth pursuit (Bernth-Petersen, 1981, Brown, 1993). Research indicates that even minimal motion signals can provoke eye movements in response to random dot stimuli (Kosnik et al., 1985, Watamaniuk and Heinen, 1999). Variations in ocular muscle movements between younger and older individuals could influence behavioural experiment outcomes, suggesting that age-related differences in eye movements may contribute to observed motion perception deficits (Bennett et al., 2007a).

In summary, addressing the combined impact of age-related and degenerative changes on motion perception is required. Investigating how retinal and visual cortex changes interact with conditions like cataracts, glaucoma, and diabetic retinopathy could provide valuable insights into the mechanisms underlying visual decline. These findings could inform the development of adapted interventions aimed at preserving visual function and enhancing independence in later life.

10.4 Study limitations

This study has provided valuable insights into motion perception in individuals with cataracts and other visual impairments. However, several limitations must be acknowledged to contextualise the findings and guide future research. These limitations stem from both external challenges beyond the researchers' control and methodological constraints inherent to the experimental design.

10.4.1 Limited Sample Size and Demographic Constraints

Limited Sample Size and Demographic Constraints One of the most significant limitations of this study was the restricted number of genuine cataract observers. Recruitment efforts were impeded by the challenges posed by the COVID-19 pandemic, resulting in a sample size of only two cataract patients. This limited cohort weakened the strength of the results and compromised the external validity of the outcomes. Specifically, the small sample size prevented subgroup analyses based on factors such as cataract type, severity, or location, which could have provided deeper insights into how these variables influence motion perception. Furthermore, the lack of demographic diversity—particularly in terms of age, gender, and ocular abnormalities—further constrained the generalisability of the findings to broader populations. To address these limitations, future studies should prioritize recruiting larger and more diverse participant groups. Including a wider range of cataract types (e.g., nuclear, cortical, posterior subcapsular) and severities would enable a more nuanced examination of their impact on motion perception. Additionally, incorporating a control group of age-matched healthy individuals would help distinguish age-related changes in motion perception from those specifically related to cataracts.
One of the most significant limitations of this study was the restricted number of genuine cataract observers. Due to the challenges posed by the COVID-19 pandemic, recruitment efforts were delayed, resulting in a sample size of only two cataract patients. This limited cohort weakened the strength of results and compromised the external validity of the outcomes. Specifically:

- The small sample size prevented subgroup analyses based on factors such as cataract type, severity, or location, which could have provided deeper insights into how these variables influence motion perception.
- The lack of demographic diversity—particularly in terms of age, gender, and ocular abnormalities—further constrained the generalisability of the findings to broader populations.

To address these limitations, future studies should prioritise recruiting larger and more diverse participant groups. Including a wider range of cataract types (e.g., nuclear, cortical, posterior subcapsular) and severities would enable a more featured examination of their impact on motion perception. Additionally, combining a control group of age-matched healthy individuals would help separate age-related changes in motion perception from those specifically related to cataracts.

10.4.2 Psychophysical Methodology and Experimental Design

The psychophysical method applied in this research, although carefully instructed, brought certain limitations that merit attention. The experiments required sustained attention and concentration over extended periods, with each trial lasting a minimum of 30 minutes to obtain reliable readings. This prolonged engagement likely contributed to observer fatigue, particularly among taller observers, who may have experienced greater discomfort due to ergonomic factors such as chair height and chin rest positioning. Gender differences in experimental duration were also observed, with male observers generally maintaining longer trials and taking shorter breaks compared to females. These factors may have influenced performance and introduced variability in the data. Additionally, some observers appeared to take part mainly for external incentives (e.g., vouchers), which resulted in reduced task engagement and inconsistent performance. Despite efforts to moderate these issues through clear instructions, preliminary tests, and adequate breaks, many observers required repeated trials, while others were excluded due to insufficient cooperation. Future studies could explore alternative motivational strategies or shorter, more engaging tasks to enhance observer compliance.

10.4.3 Stimulus Design and Chromaticity

The stimuli used in this study were predominantly monochromatic, featuring black and white dots against a grey background. While this design facilitated precise control over experimental variables, it may have overlooked the rich chromaticity present in natural environments and the differential contributions of cone photoreceptors to motion perception. For example, the absence of colour-based segmentation cues limited the ability to differentiate signal dots from noise dots effectively, potentially influencing the accuracy of proportion discrimination measurements. Including dynamic segmentation cues, such as colour or texture, could enhance the ecological validity of the experiments and provide a more authentic representation of real-world motion perception. Future research would explore the use of chromatic stimuli to better align experimental conditions with natural visual experiences. This method could enhance the generalisability of the results and enable a more comprehensive understanding of light scatter impact on motion perception across different spectral channels.

10.4.4 Monocular vs. Binocular Vision

Another limitation concerns the limited focus on monocular vision in certain experimental conditions. Occluding one eye during testing may disrupt the natural physiological processes underlying binocular vision, which plays a critical role in global motion perception. For example, binocular disparity significantly enhances the perception of coherent motion and facilitates direction discrimination, particularly in complex motion tasks such as optic flow (Greenwood and Edwards, 2006, Rodman and Albright, 1989). By neglecting the contributions of binocular interactions, this study may have underestimated the full extent of motion perception deficits in cataract patients. To address this gap, future studies should combine binocular vision paradigms and examine how cataracts affect the integration of information from both eyes. A larger sample of observers would also enable comparisons between individuals with monocular and binocular cataracts, providing insights into the neural substrates of binocular processing.

10.4.5 Statistical Power and External Validity

While the statistical analyses conducted in this study revealed significant effects, the small sample size and limited demographic diversity compromise the external validity of the findings. The inclusion of only two cataract patients did not provide a sufficient foundation for identifying strong effects on motion perception or establishing meaningful correlations between cataract characteristics (e.g., type, severity) and perceptual outcomes. Variability among observers, particularly in motion perception tasks involving simulated filters, underscores the need for larger and more representative samples to draw definitive conclusions about the population. Future research should aim to recruit a more extensive and diverse group of observers, including individuals with varying ocular conditions and demographic profiles. This would enhance the statistical power of the analyses and ensure that the findings are applicable across different clinical and real-world contexts.

10.4.6 Unresolved Questions and Ambiguities

Finally, certain ambiguities remain regarding the interpretation of the results. For instance, the observed differences in performance between speed experiments and those assessing direction or coherence may reflect variations in the experimental setup, such as the type of motion display or the control mechanisms employed. However, without further investigation, the exact nature of these discrepancies remains unclear. Additionally, the relationship between internal additive noise and age-related changes in motion perception requires additional exploration. Incorporating a control group of younger participants could help elucidate whether the observed effects are specific to ageing or cataracts. Addressing these unresolved questions will require more detailed and systematic investigations, leveraging advanced methodologies and technologies to refine our understanding of motion perception in visually impaired populations.

In summary, while this study has made significant paces in exploring the impact of cataracts on motion perception, several limitations highlight the need for further research. Expanding the sample size, diversifying the participant pool, refining stimulus design, and incorporating binocular vision paradigms represent critical steps toward addressing these gaps. By building on the foundation laid by this work, future studies can deepen our understanding of the complex interplay between optical degradation, neural processing, and motion perception, ultimately informing the development of targeted interventions to improve outcomes for individuals with visual impairments.

Chapter 11 **General Conclusion**

This thesis provides a comprehensive exploration of the intricate relationship between age-related cataracts and motion perception, shedding light on the profound impact of reduced visual input on dynamic vision. By integrating psychophysical methodologies with real-world applications, the study examines specific qualities of motion stimuli—speed, prediction, coherence, and direction—to uncover how cataracts disrupt visual processing across multiple dimensions. Collectively, the findings reveal that age-related cataracts impair motion perception beyond static visual deficits, significantly affecting tasks reliant on dynamic vision. These results contribute to a deeper understanding of the interplay between optical degradation and neural processing, offering actionable insights for improving patient outcomes.

The findings align with prior literature indicating that cataracts manifest through increased blur and reduced contrast sensitivity, profoundly impacting daily activities such as driving, mobility, and near tasks. An online survey targeting eye care professionals and cataract patients highlighted three primary domains of visual impairment: mobility, discrimination, and near tasks. Mobility tasks, which rely on peripheral retinal processing, and near tasks, dependent on central retinal function, were both affected. Behavioural data corroborated these self-reported deficits, demonstrating deteriorated motion detection and discrimination across all spatial frequency thresholds, consistent with earlier studies (Elliott et al., 1996, Fraser et al., 2013). These findings highlight the challenges faced by individuals with cataracts, particularly in tasks requiring rapid interpretation of moving stimuli.

To simulate cataract conditions, optical filters were used to replicate light scatter, glare, and blur. The results revealed significant declines in CS and VA across all spatial frequencies, consistent with prior research (Wood et al., 2010, Long and Zavod, 2002, Wood et al., 2009). These impairments underscore the profound effect of degraded media contrast on visual function, particularly in older adults who exhibit reduced sensitivity to motion tasks under such conditions (Anderson et al., 2000, Pluháček et al., 2022).

Speed discrimination experiments revealed differential susceptibility among motion types to visual degradation. Translational motion demonstrated resilience to simulated distortions, with no statistically significant differences observed at slow ("TM Slow") or fast ("TM Fast") speeds. In contrast, radial motion exhibited heightened sensitivity to visual impairments, particularly at slower speeds ("RM Slow"), where thresholds increased significantly under moderate and severe distortion levels. These findings underscore the vulnerability of radial motion to contrast and distortion challenges, extending prior literature on motion perception to the context of cataract-induced impairments (Ball and Sekuler, 1986, Snowden and Kavanagh, 2006,Allen et al., 2010). The results suggest that different motion patterns are processed differently in the brain, with radial motion being more susceptible to optical degradation than translational motion.

Building on these insights, speed prediction tasks evaluated the ability to estimate the speed of a locally moving single object across varying simulation conditions. Two critical observations emerged: increasing simulation severity significantly impaired speed prediction accuracy. These results highlight the role of reduced contrast and attentional demands in predicting motion, aligning with prior research on media transparency and attentional (Allen et al., 2010, Anstis, 2004, Thompson et al., 2006, Betts et al., 2009).

Direction discrimination experiments provided additional insights into the complexity of dissociating sensory deficits from higher-level processing impairments. Observers demonstrated greater difficulty distinguishing oblique translational patterns compared to other motion types, suggesting that direction perception may be constrained by specific stimulus characteristics rather than purely velocity-based responses. While conclusive evidence regarding the effect of reduced media opacity on motion perception was not obtained, the findings highlight the complex relationship between sensory input and cognitive processing under simulated visual degradation (Snowden and Kavanagh, 2006, Yang et al., 2009a).

Radial coherence experiments challenged prevailing assumptions about the relationship between media contrast and radial motion perception. Contrary to earlier studies, the findings revealed relative stability in threshold levels for expanding versus contracting optic flow patterns across varying media contrasts.

Case studies involving genuine cataract patients provided compelling evidence of the profound impact of age-related cataracts on motion perception. Significant impairments were observed across multiple dimensions, including translational motion, radial motion, and direction discrimination. However, speed prediction tasks yielded inconclusive results due to high variability, highlighting the challenges faced by cataract patients in accurately estimating TTC. Preliminary comparisons for radial coherence motion suggest potential significance, warranting further investigation with larger sample sizes.

Reduced contrast sensitivity, increased light scatter, and age-related changes in neural processing create a complex interplay of impairments that disrupt dynamic visual tasks. Prior studies have shown that older adults exhibit declines in motion processing across various conditions (Anderson et al., 2000, Betts et al., 2009). Addressing optical impairments, such as those caused by cataracts, may mitigate some of these deficits, offering hope for improved functional vision and quality of life in ageing populations. Research indicates that surgical interventions restore contrast sensitivity, spatial resolution, and the ability to detect moving objects, leading to enhanced mobility, safety, and independence. From a neurological perspective, motion perception is closely linked to vestibular function and relies on the rapid response of magnocellular ganglion cells in the retina and striate cortex. Key brain regions involved include the middle temporal (MT), ventral intraparietal (VIP), and medial superior temporal (MST) areas, which form part of the extrastriata network responsible for motion and depth perception (Barton, 2021). Dysfunction in these networks can lead to conditions such as Bálint syndrome, characterised by disorientation and impaired spatial processing (Barton, 2021). These findings highlight the complex relationship between optical degradation and cortical reformation, highlighting the need for targeted interventions to mitigate perceptual deficits.

In summary, the collective findings of this thesis demonstrate that simulated cataract conditions significantly alter motion perception, with variations dependent on stimulus parameters. Observers performed better in radial motion tasks than translational ones, but older, cataractous adults shown marked deficits in discriminating spiral (vertical) motion compared to translational directions along the horizontal axis. Individual differences in performance underscore the importance of considering diverse observer characteristics when examining motion perception deficits. These findings hold significant clinical implications for interventions aimed at restoring functional vision in ageing populations. For instance, intraocular lens placement markedly improves the functional capacity of individuals with advanced cataracts (Wan et al., 2020a). Understanding the specific challenges faced by cataract patients—such as difficulties in driving, mobility, and near tasks—can inform the development of targeted rehabilitation strategies and assistive technologies.

While cataract surgery restores many aspects of motion perception, residual deficits influenced by factors such as neural plasticity and age-related considerations may persist, necessitating further research to improve interventions. Continued investigation of these complexities holds the possible to transform patient care and empower ageing individuals to navigate their environments with confidence and independence. These findings provide a foundation for future research on visual motion perception and its implications for individuals with cataracts and other ocular pathologies. By addressing the limitations identified in this study—such as small sample sizes and restricted demographic diversity—future investigations can build on these insights to develop targeted interventions aimed at improving visual outcomes and quality of life for visually impaired individuals. Moreover, the integration of advanced methodologies, such as functional imaging and virtual reality, could further explain the neural substrates underlying motion perception and inform the development of innovative diagnostic tools and therapeutic strategies.

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Appendices:

Appendix 1 – ClinQ

1. How would you describe your role?

2. How long have you been working in practice?

3. What area of the UK do you work in?

4. When thinking about cataract referrals, rate the following factors from 1-10 as most important consideration for referral (1) to least important consideration for referral (10).
- The patient’s measured visual acuity
- The patient’s reported quality of life
- The patient’s reported everyday visual experience
- Whether the patient is requesting surgery
- The patient’s access to support (e.g. carers/ family members)
- Whether the patient has bilateral (relative to unilateral) cataracts
- The risks of surgery for that particular patient (e.g. relating to their general health)
- The patient’s fear of leaving the cataracts any longer
- Whether the patient is a driver
- Potential for post-surgery improvement

5. If you have any other comments or considerations to add to the factors affecting referral decisions then please write them in the box below:

6. With reference to the factor you rated as “most important” – why do you consider this the most important factor?

7. Do you ever ask patients with cataracts “open” questions about their perceptual experience? For example, “how do you find your vision day-to-day?”

8. If you answered yes to the question above, what would you do with the information from the patient?

9. Do you ever ask patients with cataracts “closed” questions about their perceptual experience? For example, “do you still find your vision is ok for driving?”

10. If you answered yes to the question above, what would you do with the information from the patient?

11. In your experience, have patients with cataracts ever reported experiencing difficulties with motion-related tasks? These include: driving, being a passenger in a car, reading moving LED signs (e.g. on a train), avoiding obstacles when walking.

12. Please provide details about your answer to the above question.

13. How often would you say that a patient’s <u>reported</u> visual abilities appear to be worse than your clinical examination would suggest?
    Always Often Sometimes Rarely Never

Appendix 2 – ContQ

1. What is your age?

2. Do you currently have any eye-related issues that you see a healthcare professional about? If so, please describe briefly below.

3. Do you wear glasses or lenses to help you to see?

4. If you answered yes to the question above – if known, please provide your prescription for the left and right eye.

5. Please rate the following actions on a scale of 1-5 (1 - not at all, 5 - a great deal) with how much your ability to perform these activities has deteriorated over the past 2 years:
   Driving
   Reading
   Walking indoors (without tripping or bumping into things)
   Walking outside (without tripping or bumping into things)
   Enjoying being a passenger in a car
   Reading moving LED signs (e.g. on a bus/ train)
   Watching TV
   Using your mobile phone
   Doing video calls

6. Close your left eye for a moment. How would you rate the vision in your right eye on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

7. Now close your right eye for a moment. How would you rate the vision in your left eye on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

8. Now with both eyes open, how would you rate your overall vision on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

9. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
   https://youtu.be/PudzSa5Sj_A
   Vertical stripes moving left
   Vertical stripes moving right
   Horizontal stripes moving upwards
   Horizontal stripes moving downward
   Plain grey square
   Technical difficulties/ video wouldn't load

10. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
   https://youtu.be/IUR8qyQhDfg
   Vertical stripes moving left
   Vertical stripes moving right
   Horizontal stripes moving upwards
   Horizontal stripes moving downward
   Plain grey square
   Technical difficulties/ video wouldn't load

11. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
   https://youtu.be/xZfeuatIJqU
   Vertical stripes moving left
   Vertical stripes moving right

Horizontal stripes moving upwards
Horizontal stripes moving downward
Plain grey square
Technical difficulties/ video wouldn’t load

12. When you visit your optometrist, do they ask questions about your ability to perform day-to-day activities?

Appendix 3 – CatQ

1. What is your age?

2. Which eye is your cataract in? Left, right or both??

3. When were you first diagnosed? MM/YYYY (An estimated month and year is fine)

4. If known, what type of cataract do you have?

5. Have you been referred for cataract surgery? If so, when were you referred? MM/YYYY (An estimated month and year is fine)

6. Do you currently have any other eye-related issues that you see a healthcare professional about? If so, please describe briefly below.

7. Do you wear glasses or lenses to help you to see?

8. If you answered yes to the question above – if known, please provide your prescription for the left and right eye.

9. Please rate the following actions on a scale of 1-5 (1 - not at all, 5 - a great deal) with how much your ability to perform these activities has deteriorated since your cataract diagnosis:
   Driving
   Reading
   Walking indoors (without tripping or bumping into things)
   Walking outside (without tripping or bumping into things)
   Enjoying being a passenger in a car
   Reading moving LED signs (e.g. on a bus/ train)
   Watching TV
   Using your mobile phone
   Doing video calls

10. Close your left eye for a moment. How would you rate the vision in your right eye on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

11. Now close your right eye for a moment. How would you rate the vision in your left eye on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

12. Now with both eyes open, how would you rate your overall vision on a scale of 1-5 (1 – extremely poor, 5 – very clear)? (Please ensure you are wearing corrective glasses/ lenses if required)

13. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
    https://youtu.be/PudzSa5Sj_A
    Vertical stripes moving left
    Vertical stripes moving right
    Horizontal stripes moving upwards
    Horizontal stripes moving downward
    Plain grey square
    Technical difficulties/ video wouldn’t load

14. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
    https://youtu.be/IUR8qyQhDfg
    Vertical stripes moving left
    Vertical stripes moving right
    Horizontal stripes moving upwards
    Horizontal stripes moving downward
    Plain grey square
    Technical difficulties/ video wouldn’t load

15. When looking at the video below, which of the following options best describes their appearance? (video is embedded in real survey)
    https://youtu.be/xZfeuatIJqU
    Vertical stripes moving left
    Vertical stripes moving right
    Horizontal stripes moving upwards
    Horizontal stripes moving downward
    Plain grey square
    Technical difficulties/ video wouldn’t load

16. When you visit your optometrist, do they ask questions about your ability to perform day-to-day activities?

Appendix 4: Risk Assessment

RISK ELIMINATION & CONTROL
Process / Activity / Area / Equipment

Business/Site Name	Optometry, LHS, Aston University	Date	10-Jun-21	Dep	Optometry	RA Ref.		Issue 1

Describe Process/Activity/Equipment being assessed:
Computer-based tasks assessing visual perception

Materials/Substances/Resources used
PC, monitor, keyboard, cyclopentolate (1%), OCT

Are there clear work instructions/procedures: List document numbers below	Yes	No	**Is the process / activity included in the skills matrix:**	Yes	No	High risk if activity not in skills matrix, and user is not confident in abilities
			Are you confident in your abilties	Yes	No	

What is the operator's level of competency?	Highly skilled and experienced	Trained or highly expereiced	No training / some experience / supervised	Novice / inexperienced / unsupervised

TO INSERT RISK FIGURES FOR FREQUENCY PROBABILITY AND SEVERITY REFER TO THE TABLES BELOW

FREQUENCY		PROBABILITY	SEVERITY		
FA - Freq. of Exposure	**FB** - Duration of Exp	**PA** - Likelihood of injury	**SA**-Number exposed	**SB** - Who's Exposed	**SC** - Severity
1 Yearly	1 < 10 min's	1 Improbable	1 0 - 1	1 Operator	1 Insignificant
2 Monthly	2 10min - 1hr	2 Less likely	2 2 - 5	2 Contractor	2 Minor
3 Weekly	3 1 - 4hrs	3 Possible	3 6 - 20	3 Visitor	3 1-3 days off
4 Daily	4 4 - 8 hrs	4 Likely	4 21 - 100	4 All in vicinity	4 +3 days off
5 Continuously	5 Continuously	5 Certainty	5 >100	5 Public	5 Fatality

When choosing risk value for the 'F', 'P' or 'S' if you cannot distinguish between two values always choose the higher of the two.

Not necessary	Up to assessor	Assess further	Assess further
1~110 I	11~20 L	21~60 M	> 60 H

No.	Hazard type	Control measures	F-A	F-B	F	P-A	P	S-A	S-B	S-C	S	Total risk=F.P.S (I / L / M / H)
1	Risk of eye strain or associated headaches when using the computer	Participants will be encouraged to take breaks when needed and will not be allowed to sit for more than an hour at a time.	1	3	2	1	1	4	3	1	2.667	5.3333
2	Possible risk of COVID infection if not careful in the building.	The building follows strict guidelines for COVID-19 safety and all equipment will be wiped between eash participant. Participants will be seen individually, with only one investigator, who will remain socially distanced with a mask on at all times.	1	3	2	1	1	4	4	4	4	8
3	Distress caused to participant due to brief dim flash of light caused by machines which take readings using IR or visible light.	Participants will be warned prior to testing of this side-effect and that it causes no harm to the eyes. Participants will be able to remain seated until they feel comfortable to leave. CE assessed instrumentation commercially marketed - keep to specified usage.	1	1	1	2	2	4	3	1	2.667	5.3333
4	Use of cyclopentolate to dilate and cycloplege eye	Adverse events with cyclopentolate are rare especially in young adults. All participants' eyes will be checked to monitor.	1	3	2	2	2	4	3	2	3	12
5												

RISK ELIMINATION & CONTROL
Process / Activity / Area / Equipment

Business/Site Name		Date		Dep		RA Ref. No.		Issue 1

ABNORMAL CONDITIONS

No.	Hazard type	Control measures	(F) Frequency F-A	F-B	F	(P) Probability P-A	P	(S) Severity S-A	S-B	S-C	S	Total risk=F.P.S I	L	M	H
1	Participant taken ill during examination/study period	If participant is taken ill during the examination or any other part of the study itself normal emergency procedures will be enforced. The designated first aider would be contacted and their advice followed. An ambulance can be called to the premises if required.	1	1	1	3	3	1	3	3	2.333	7			
2															
3															
4															
5															

EMERGENCY CONDITIONS

No.	Hazard type	Control measures	(F) Frequency F-A	F-B	F	(P) Probability P-A	P	(S) Severity S-A	S-B	S-C	S	Total risk=F.P.S I	L	M	H
1	Provisions in the event of an emergency/ fire alarm	In the case of an emergency the participant will be escorted to the safe assembly point by a member of the research team.	1	1	1	1	1	1	2	4	2.333	2.3333			
2															
3															
4															
5															

NO further assessment required

Further assessments required

Appendix 5: Participant Information Sheet

Investigating the Impact of Ageing and Cataracts on Visual Motion Perception Across the Visual Field

PARTICIPANT INFORMATION SHEET

Name of Chief Investigator: Dr Samantha Strong (s.strong2@aston.ac.uk)
Name of Co-investigator: Ayah Al-Rababah

Invitation

We would like to invite you to take part in a research study.

Before you decide if you would like to participate take time to read the following information carefully and, if you wish, discuss it with others such as your family, friends or colleagues.

Please ask a member of the research team, whose contact details can be found at the end of this information sheet, if there is anything that is not clear or if you would like more information before you make your decision.

What is the purpose of the study?

The objective of the study is to:

- Assess visual perception and how it might be affected by eye-related conditions e.g. cataracts

Why have I been chosen?

You are being invited because you have cataract ***or*** your vision can be compared to someone with cataracts ***or*** you are an optometrist who manages patients with cataract(s). Participants should have no known neurological or psychiatric conditions.

What will happen to me if I take part?

Participants will have their visual function assessed (acuity, contrast sensitivity) and then be asked to take part in a series of psychophysical experiments. These experiments will be designed to assess how well you perceive and detect moving objects. For all experiments you will be sat at a computer with your chin in a chin rest (to ensure a set distance away from the monitor). During each run you will be asked to maintain fixation on a cross in the centre of the screen and you will need to make a decision about a stimulus for example "press a button on the keyboard when you detect a moving stimulus" or "press a button on the keyboard to show which direction the stimulus was moving in".

There are nine experiments in total, which will be split over several 1-hour sessions. In order to sit for the whole experiment you will be required to attend 10 visits (totalling 10 hours). At the end of the study you will be paid £100 (£10 per hour) in Love2Shop vouchers for your time.

Do I have to take part?

No. It is up to you to decide whether or not you wish to take part. If you do decide to participate, you will be asked to sign and date a consent form. You will still be free to withdraw from the study at any time without giving a reason.

Are there any risks of taking part?

For this experiment you will need to visit a small lab space in the Vision Sciences Building. This means that for your own safety during the COVID-19 pandemic, you will be required to wear a face-mask and the experimenter will be sat at a distance away from you at all times. The lab will be cleaned between participant visits and a minimum of 30 minutes will be left between each visit.

What will happen if I don't want to carry on with the study?

If you feel uncomfortable about any aspect of the study, please let the researcher know straight away. She will discuss your concerns with you and may be able to help. You are free to withdraw from the study at any time. If you decide to withdraw, please tell the researcher.

We will not normally be able to use behavioural data from participants who withdraw from the study. Data that has already been collected will be destroyed if it cannot be used and will always be deleted at the participant's request.

What if there is a problem?

If you have a concern about any aspect of this study, please speak to the researchers who will do their best to answer your questions. You can contact Dr. Samantha Strong, who is leading this study (s.strong2@aston.ac.uk). If you remain unhappy and wish to complain formally, you can do this through the complaints procedure of Aston University.

Will my taking part be kept confidential?

Yes. A code will be attached to all the data you provide to maintain confidentiality.

Your personal data (name and contact details) will only be used if the researchers need to contact you to arrange study visits or collect data by phone. Analysis of your data will be undertaken using coded data.

The data we collect will be stored in a secure document store (paper records) or electronically on a secure encrypted mobile device, password protected computer server or secure cloud storage device.

To ensure the quality of the research, Aston University may need to access your data to check that the data has been recorded accurately. If this is required, your personal data will be treated as confidential by the individuals accessing your data.

What are the possible benefits of taking part?

While there are no direct benefits to you of taking part in this study, the data gained will help scientists better understand how cataract development affects visual perception, which is increasingly relevant.

What are the possible risks and burdens of taking part?

Whilst there are limited risks associated with this study, you would be required to attend 10 sessions in the Vision Sciences Building at Aston University. This means that you would need to adhere to the local COVID-19 guidance, and be able to wear a face mask whilst in the building. The experimenter will also adhere to local COVID-19 guidance for keeping an appropriate distance from you. Where possible all forms will be signed electronically and emailed to you to limit the amount of items you will need to come into contact with. Before you enter the lab and after you leave, the room will be cleaned.

The burden associated with this study is the time commitment because you will need to sit for up to 8 hours of experiment time, however this can be done over a period of a few months to suit your requirements, and you will be paid for your time.

What will happen to the results of the study?

The results of this study may be published in scientific journals and/or presented at conferences. If the results of the study are published, your identity will remain confidential.

A lay summary of the results of the study will be available for participants when the study has been completed and the researchers will ask if you would like to receive a copy.

Expenses and payments

All participants will be paid £10 (Love2Shop vouchers) an hour (total £80) for their time. Travel expenses can be discussed with the research team.

Who is funding the research?

The study is being funded by Aston University.

Who is organising this study and acting as data controller for the study?

Aston University is organising this study and acting as data controller for the study. You can find out more about how we use your information in Appendix A.

Who has reviewed the study?

This study was given a favourable ethical opinion by the Aston University Research Ethics Committee.

What if I have a concern about my participation in the study?

If you have any concerns about your participation in this study, please speak to the research team and they will do their best to answer your questions. Contact details can be found at the end of this information sheet.

If the research team are unable to address your concerns or you wish to make a complaint about how the study is being conducted you should contact the Aston University Research Integrity Office at research_governance@aston.ac.uk or telephone 0121 204 3000.

Research Team

Dr Samantha Strong (Lecturer, Optometry) – s.strong2@aston.ac.uk

Ayah Al-Rababah (PhD student, Optometry)

Thank you for taking time to read this information sheet. If you have any questions regarding the study please don't hesitate to ask one of the research team.

Aston University BIRMINGHAM UK

Aston University takes its obligations under data and privacy law seriously and complies with the General Data Protection Regulation ("GDPR") and the Data Protection Act 2018 ("DPA").

Aston University is the sponsor for this study based in the United Kingdom. We will be using information from you in order to undertake this study. Aston University will process your personal data in order to register you as a participant and to manage your participation in the study. It will process your personal data on the grounds that it is necessary for the performance of a task carried out in the public interest (GDPR Article 6(1)(e). Aston University may process special categories of data about you which includes details about your health. Aston University will process this data on the grounds that it is necessary for statistical or research purposes (GDPR Article 9(2)(j)). . Aston University will keep identifiable information about you for 6 years after the study has finished.

Your rights to access, change or move your information are limited, as we need to manage your information in specific ways in order for the research to be reliable and accurate. If you withdraw from the study, we will keep the information about you that we have already obtained. To safeguard your rights, we will use the minimum personally identifiable information possible.

You can find out more about how we use your information at www.aston.ac.uk/dataprotection or by contacting our Data Protection Officer at dp_officer@aston.ac.uk.

If you wish to raise a complaint on how we have handled your personal data, you can contact our Data Protection Officer who will investigate the matter. If you are not satisfied with our response or believe we are processing your personal data in a way that is not lawful you can complain to the Information Commissioner's Office (ICO).

Appendix 6: Consent Form

Investigating the Impact of Ageing and Cataracts on Visual Motion Perception Across the Visual Field

Consent Form

Name of Chief Investigator: Dr Samantha Strong (s.strong2@aston.ac.uk)
Name of Co-investigator: Ayah Al-Rababah

Please initial boxes

1.	I confirm that I have read and understand the Participant Information Sheet *(V1.0; 16/03/2021)* for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.	
2.	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason and without my legal rights being affected.	
3.	I agree to my personal data and data relating to me collected during the study being processed as described in the Participant Information Sheet.	
4.	I agree to my anonymised data being used by research teams for future research.	
5.	I agree to my personal data being processed for the purposes of inviting me to participate in future research projects. I understand that I may opt out of receiving these invitations at any time.	
6.	I agree to take part in this study.	

Name of participant   Date   Signature

Name of person receiving consent.   Date   Signature

Appendix 7: LOCS III grading protocol

Taken from PhenX Toolkit Supplemental Information, February 26, 2010

About the Measure	
Domain	Ocular
Measure	Lens Grading
Definition	A method of classifying the type and severity of opacification in the crystalline lens

About the Protocol	
Description of Protocol	The Lens Opacities Classification System, Version III (LOCS III) is a means of subjectively grading the type and severity of age-related cataract (ARC) *in vivo* by comparing a patient's cataract to a set of standard photographs that illustrate differing degrees of nuclear, cortical, and posterior subcapsular cataract formation.
Protocol text	LOCS III uses a standardized set of colored transparencies combined in a single 8.5" x 10" transparency to illustrate the various stages of cataract formation. In the LOCS III standard transparency there are six examples of nuclear cataract demonstrating increasing amounts of opacification (termed nuclear opalescence (NO)) and brunescence (termed nuclear color (NC)). The top row of standards is used to grade both NO and NC. Retroillumination images are used to illustrate the various stages of cortical (C), and posterior subcapsular (P) opacification. The middle row contains five examples of C cataract, and the bottom row contains five examples of P cataract. Each scale on LOCS III is a decimalized scale ranging from 0.1 (a completely clear or colorless lens) to 5.9 (upper value on the C and P scales indicating complete opacification of the cortex or posterior capsule) and 6.9 on the NO and NC scales (indicating advanced opacification and brunescence of the nucleus). When grading opacities at the slitlamp, the 8.5" x 10" transparency is placed on a small light box near the patient's shoulder and viewed while a slitlamp assessment of the patient's lens is underway. The ophthalmologist or optometrist should be able to view the lens and the LOCS III standards almost simultaneously by switching gaze from the eyepieces of the slitlamp to the LOCS III standards. LOCS III can be used to grade standardized slit and retroillumination images of the lens (film or digital) as well as cataracts observed in

	patients at the slitlamp during the course of a routine ocular examination. When performing LOCS III classification, the grader assesses the presence or absence and the severity of opacification in three major zones of the lens: the cortex, the nucleus, and the posterior subcapsular region. The LOCS III grade is a measure of that severity. When doing cataract classification, graders must be aware of their bias, either conscious or unconscious, that cataract is a unidirectional disease that steadily gets worse with age. Because of this bias, if one knows the baseline or any prior LOCS III grade, it is likely that the LOCS III grade assigned at a follow-up visit will be higher. To avoid this, a grader must not look at prior case report forms (CRFs) or try to ascertain the LOCS III grades assigned to a patient at an earlier visit. One must always start with a blank CRF and remain masked as to earlier LOCS III grades to avoid this observation bias. One will tend to grade higher than baseline, if one knows the earlier LOCS grade.
Participant	Adults aged 30 to 80 years old
Source	Chylack LT Jr, Instructions for applying the Lens Opacities Classification System, Version III (LOCS III) in grading human age-related cataracts, Revised 05/19/09. Chylack L.T. Jr, Wolfe J.K., Singer D.M., Leske M.C., Bullimore M.A., Bailey I.L., Friend J., McCarthy D., & Wu S.Y. (1993). The Lens Opacities Classification System III. The Longitudinal Study of Cataract Study Group**.** *Arch Ophthalmol*, 111(6), 831-6.
Language of Source	English
Personnel and Training Required	Web-interactive and web-self-administered certification/re-certification training programs have been developed that physicians, optometrists, and Ph.D.s can use to acquire skills in the application of the LOCS III system. These programs have been widely used by pharmaceutical companies under license agreements with the Brigham and Women's Hospital (BWH). The web-based LOCS III self-administered training programs consist of several recorded sessions and take approximately 4-5 hours to complete. The individual sessions are available "24/7" with passwords obtained from the BWH. A course of web-based training includes the following recorded sessions:

	1. The LOCS III WebEx Recording-Introduction This is a nine-minute recording that introduces the user to the WebEx Recorded Session and the WebEx Player - the program used to control the pace of the session. This Recorded Session is unnumbered. The user must take this session before accessing the other sessions. 2. The LOCS RETRO IMAGE ARTIFACTS This is an 18-minute recorded session that teaches the user how to identify artifacts present in Neitz-CTR retroillumination images. All LOCS III web-training and web-testing recordings use these images, so it is very important that the user know how to recognize these artifacts. 3. The LOCS III Self-Administered Training (Part 1) This is a one-hour session that introduces the user to the LOCS III grading system. 4. The LOCS III Self-Administered Training (Part 2) This is a half-hour practice-grading session for cortical and posterior subcapsular cataract. 5. The LOCS III Self-Administered Training (Part 3) This is a half-hour practice-grading session for nuclear cataract and nuclear color. 6. The LOCS III Self-Administered Certification Test (Part 4) This is a one-and-a-half-hour session that contains a brief review of LOCS III and a formal test of competence. It should not be taken until the user has completed the five sessions listed above. A License Agreement between user/sponsor and BWH is needed before the LOCS III Training Program may be used. Please contact Mr. Milorad Bursac (mbursac@partners.org) for more information about the web-based training and the licenses needed. Upon completing the LOCS III training on the web site, each student is required to take and pass a test of competence on this same web site. The tests assess the student's ability to grade lens opacification and nuclear color in sets of photo-images. Tests are labeled either "Certification Test" or "Recertification Test 01", "Recertification Test 02", etc. At the beginning of each Recertification Test there is a brief review of the rules of LOCS III grading. The completed test answer sheet is faxed to the Center for Ophthalmic Research at the BWH and is triple-graded by the Center. The individual test scores from each grader are reconciled and then a final test score is assigned. The lowest passing grade is a 70%. Dr. Chylack evaluates each test answer sheet and writes a note to the student indicating where there

	are problems and which additional material must be reviewed to correct them. If the student fails a test, a similar note is written which contains instructions for retaking the same web-based test. If the student fails the test twice, Dr. Chylack will set up a web-interactive training and grading session for the student. At the end of this review, Dr. Chylack will instruct the student to retake the recertification test. If the student fails this test, usually no further training or testing is indicated.
Equipment Needs	A License Agreement between user/sponsor and Brigham and Women's Hospital is needed before the LOCS III Training Program may be used. Please contact Mr. Milorad Bursac (mbursac@partners.org) for more information about the web-based training and the licenses needed. one LOCS III transparency (which contains the standard images) one set of instructions for using the LOCS III standards small light box Slit lamp
Protocol Type	Physical measurement
General References	Tan AC, Loon SC, Choi H, Thean L. (2008). Lens Opacities Classification System III: cataract grading variability between junior and senior staff at a Singapore hospital. *J Cataract Refract Surg,* 34(11):1948-52. Kirwan JF, Venter L, Stulting AA, Murdoch IE. (2003). LOCS III examination at the slit lamp, do settings matter? *Ophthalmic Epidemiol,* 10(4):259-66. Hall AB, Thompson JR, Deane JS, Rosenthal AR. (1997). LOCS III versus the Oxford Clinical Cataract Classification and Grading System for the assessment of nuclear, cortical and posterior subcapsular cataract. *Ophthalmic Epidemiol*, 4(4):179-94. Karbassi M, Khu PM, Singer DM, Chylack LT Jr. (1993). Evaluation of lens opacities classification system III applied at the slitlamp. *Optom Vis Sci,* 70(11):923-8.