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Exploring new ways of examining age-related eye conditions in England

Thesis for PhD in Optometry and Vision Science
Date of submission: 30/08/2026

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School of Health and Medical Sciences.

Declaration

The work contained in this thesis was completed by the candidate, Mehal Rathore, under the supervision of Professor David P Crabb and Dr Pete R Jones. It has not been submitted for any other degrees, either now or in the past. All the experimental work has been either published or submitted for publication in peer-reviewed academic journals, as required for the PhD programme by prospective publications. All sources of information have been acknowledged, and references have been given. The university librarian of City St. George's, University of London, is permitted to allow the thesis to be copied in whole or in part without further reference to the author. This permission covers only single copies made for study purposes, subject to normal conditions of acknowledgement.



Mehal Rathore

(30/08/2026)

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Thesis Abstract

This programme of work comprises five studies exploring new ways of examining age-related eye conditions in England.

The first study in this thesis estimated the impact of neighbourhood deprivation on the time of presentation of advanced visual field loss to the hospital eye services. It showed that glaucoma severity at presentation to English HES is associated with levels of multiple deprivation. However, the likelihood of rapid VF progression during follow-up was not found to be associated with IMD, hinting at equity of glaucoma care and outcomes once patients are in English HES. The disparities identified in this study provide the broader context to empirically assess novel approaches to testing, as explored in the forthcoming studies.

My second study assessed the feasibility of using "wasted" waiting time to perform self-administered contrast sensitivity assessments on glaucoma patients within the waiting area. Potential environmental confounds and patient feedback were recorded. Vision self-assessments took 2.5-3.0 minutes to complete each time, and most patients (97%) completed the test. Both tests were highly acceptable to most patients and suggested that the approach may enable additional data collection, potentially improving patient management, clinic flow, and/or improving patient satisfaction.

My third study assessed the use of head-mounted visual field glasses to monitor visual fields in glaucoma patients from their home environment, and to assess normally sighted adults in simulated home-like environments. All patients completed the tests, and the results showed reasonable correlation with the HFA MD (r=0.78, P=0.008). The results suggested the test may provide a feasible way to monitor glaucoma patients though unanswered questions and opportunities for further improvement were identified.

My fourth study evaluated the *resilience* of novel contrast sensitivity tests to different environmental conditions encountered in a home setting. Normally sighted individuals (n=107) performed two contrast sensitivity tests, Spotchecks and PopCSF, in a simulated home-like environment. Illumination and seating position showed no impact on the test performance, suggesting that regular home-like environmental factors may not substantially impede home-based testing.

The fifth and final study in this thesis reported the views, expectations, and concerns of patients living with glaucoma and age-related macular degeneration regarding vision home-monitoring. The participants graded six home-monitoring devices and rated them highly for usability. However, several practical improvements were suggested. The results suggest that patients view vision home-monitoring as being likely beneficial but have significant concerns about its potential implementation.

Collectively, these five studies suggest that novel visual function assessments can be feasibly administered outside traditional clinical settings, though not without some important limitations. Possible future work is suggested in the discussion to address these limitations.

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2. Rathore, M., Reddingius, P. F., Campbell, P., Crabb, D. P., & Jones, P. R. (2025). Eyecatcher 3.0–Validating the Use of "Smart Glasses" as a Low-Cost, Portable Method of Assessing Visual Fields. *Translational Vision Science & Technology*, *14*(8), 7-7.
3. Reddingius, P. F., Rathore, M., Crabb, D. P., & Jones, P. R. (2026). Assessing the resilience of portable vision tests to an uncontrolled home environment. *PeerJ*, *14*, e20657.
4. Dave, S., Rathore, M., Campbell, P., Edgar, D. F., Crabb, D. P., Callaghan, T., & Jones, P. R. (2024). Views and opinions of patients with glaucoma and age-related macular degeneration on vision home-monitoring: a UK-based focus group study. *BMJ open*, *14*(7), e080619.

Manuscript under review:

1. "Making better use of patients' time: Feasibility of performing self-administered vision assessments in waiting rooms"
   Authors: Mehal Rathore, Panagiota Founti, Blessy Rethi, Retno Wulandari, Aneela Raja, Andrew Scott, Hari Jayaram, David P Crabb, and Pete R Jones.

Abbreviations

AMD	Age-related macular degeneration
AREDS	Age-Related Eye Disease Study
AUROC	Area under the receiver operating characteristic curve
CI	Confidence interval
CS	Contrast sensitivity
CSF	Contrast sensitivity function
dB	Decibel
dB_{SPL}	Decibels sound pressure level
EMR	Electronic medical record
ETDRS	Early Treatment Diabetic Retinopathy Study
FACT	Functional acuity contrast sensitivity tests
HES	Hospital Eye Services
HFA	Humphrey Visual Field
IMD	Index of Multiple Deprivation
IRAS	Integrated Research Application System
logCS	Logarithm of contrast sensitivity
logMAR	Logarithm of the minimum angle of resolution
LSOA	Lower-layer Super Output Area
MD	Mean deviation
MRF	Melbourne Rapid Fields Test
NHS	National Health Service
NICE	National Institute for Health and Care Excellence
POAG	Primary open-angle glaucoma
PR	Pelli-Robson Contrast Sensitivity Test
PSD	Pattern standard deviation
SAP	Standard automated perimetry
SC	Spotchecks contrast sensitivity test
SD	Standard deviation
SE	Standard error
SES	Socioeconomic status
SITA	Swedish Interactive Thresholding Algorithm
SNR	Signal-to-noise ratio

SUS	System Usability Scale
TAGS	Treatment of Advanced Glaucoma Study
VA	Visual acuity
VCST	Vision Contrast Test System
VF	Visual field
VF-7	Visual Function -7 Questionnaire
VR	Virtual reality

Definitions and contextual information

Key term	Definition
Visual Function	Measurements of visual acuity, contrast sensitivity, visual field, colour, depth and motion perception, etc., that quantify a person's ability to perform a given perceptual task.
Psychophysical Test	A measure of a person's perceptual abilities based on behavioural responses to controlled changes in a physical stimulus.
Feasibility	The practical ability of a visual function test to generate clinically meaningful data in real-world patient populations.
Usability	The extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use. Throughout this thesis, feasibility and usability are often used interchangeably.
Implementation	In this context, implementation is the ability to apply the suggested techniques to be administered and executed in a clinical setting.
Age-related eye disease	Eye conditions that become more prevalent with age. In this thesis, the primary focus is on glaucoma with supporting work related to age-related macular degeneration (AMD) and cataract. Beyond these conditions, diabetic eye disease/diabetic retinopathy is another common sight-threatening age-related eye disease; however, none of the research done in this thesis addresses that condition.

Glaucoma	A neurodegenerative disorder of the optic nerve head. It is often, but not always, associated with increased intraocular pressure. (Nitta et al., 2019).
Age-related Macular Degeneration (AMD)	An age-associated degenerative condition that primarily affects the macula and therefore primarily threatens central vision (Hageman et al., 2008).
England (the context)	All the research conducted in this thesis was performed in England. Both "necessity" and "feasibility" are discussed based on their success in an English health care system.
Deprivation	A state of observable and demonstrable disadvantage relative to the local community or the wider society or nation to which an individual, family or group belongs (Townsend, 1987). People are "deprived" if they lack other types of resources to meet their needs, not just income.
Index of Multiple Deprivation (IMD)	A score given to a geographical neighbourhood based computed as the sum of multiple "domains of deprivation": income (22.5%), employment (22.5%), health deprivation and disability (13.5%), education, skills, and training (13.5%), crime (9.3%), barriers to housing and services (9.3%), and living environment (9.3%).(The English Index of Multiple Deprivation (IMD) 2015-Guidance, n.d.).
Home-monitoring	The longitudinal assessment of visual function by patients outside of the traditional clinical settings, typically unsupervised, and using portable tools which aim to detect a change in patients' vision from the baseline clinical measurement.

Contrast Sensitivity	A measure of a person's ability to detect a relative difference in luminance between two-or-more adjacent surfaces.
Visual Field	The spatial extent visible to an individual during steady fixation. It can be visualised as a "hill of vision" surrounded by "sea of blindness" (National Academies of Sciences, 2025).
Standard Automated Perimetry (SAP) a.k.a. static automatic threshold perimetry	A psychophysical procedure for mapping the visual field. It quantifies the minimum threshold in differential-luminance necessary to detect the presence of a static white light stimulus of constant size in various locations of the visual field (Jampel et al., 2011).

Chapter 1. Introduction

This thesis examines the need for and feasibility of new approaches to visual function testing in age-related eye diseases in England, with a particular focus on glaucoma. In this chapter, I explain the motivation behind this work and outline the structure of the document.

1.1 Thesis motivation: The clinical challenge

England is currently facing an ageing population and the clinical challenges that accompany it (Raymond et al., 2021). Two of the leading causes of age-related visual impairment in England are glaucoma and age-related macular degeneration (AMD). Both impose a significant burden on the healthcare system.

In glaucoma, a major age-related condition, detection is largely opportunistic and mainly led by community optometrists. Diagnosis is complicated by the fact that the condition is often asymptomatic in its early stages. Delays in detection leave a profoundly negative impact on a patient's life due to the irreversible nature of the disease.

AMD also requires early detection and timely treatment, particularly in the transition to neovascular (wet) AMD, where delays can lead to irreversible vision loss. As such, the condition requires frequent monitoring and repeated interventions in the form of intravitreal injections, which places a substantial burden on the patients and the healthcare system. Furthermore, as the country grapples with an increasing ageing population and a subsequent increase in AMD prevalence, there has been a significant increase in hospital footfalls, adding to the challenges of the hospital. As of 2005/2006, AMD-related hospital activities were around 10,000 episodes per year, which increased to 75,000 (7.5x increase in two decades) episodes in 2014, and this number is expected to keep increasing steadily (Age-Related Macular Degeneration NICE Guideline, 2018).

The challenges of these age-related conditions converge on a common theme: delays in diagnosis and treatment negatively impact both the patient and the efficiency of the healthcare system. These concerns surrounding the management of age-related eye conditions underscore the growing demand for eye care services, leading to the central

argument of this thesis. The increasing disease burden, compounded by limited healthcare capacity, has created the need to explore new technological solutions that address the shortage of human resources while supporting patients as much as possible. The current challenges facing the system extend beyond establishing that a new test is theoretically superior. The test must also be capable of being delivered within existing clinical capacity, without disrupting clinical flow. **Figure 1.1** illustrates the conceptual chain connecting these elements: rising disease burden increases demand on an already limited healthcare workforce, which in turn prompts interest in technological solutions to extend capacity.

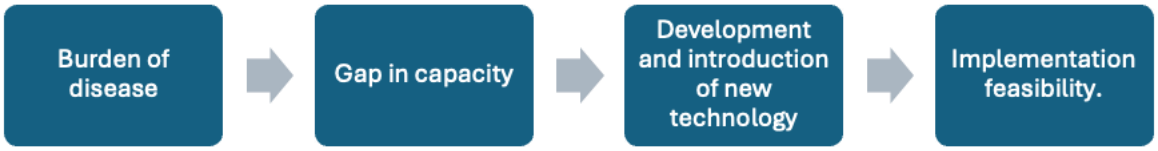


Figure 1.1. Conceptual framework depicting the connection between disease burden, gap in capacity, development of new technology and implementation feasibility.

The main argument of this thesis is that exploring and investigating new methods to assess visual function for age-related eye diseases is both necessary and feasible in England. Firstly, I aim to highlight this necessity by reporting the current status of eye care in the country with respect to certain age-related eye diseases, specifically glaucoma. Second, I aim to empirically test the feasibility of using alternative approaches to test vision in patients. In this thesis, new ways of testing refer to testing approaches that differ from conventional hospital/clinic-based assessments by any of the following:

(i) Testing protocol,

(ii) Testing in different physical settings, like a home or waiting room, instead of a clinical room,
(iii) Using a different stimulus/ response format,
(iv) Size and form factor,
(v) Output style, and
(vi) Use cases that could be intended for screening, diagnosis, and monitoring of eye disease.

The next section of this introduction provides an overview of the existing approaches to vision testing. Throughout the thesis, I focus on two critical visual functions: visual field and contrast sensitivity. This section also explains the rationale behind using these visual functions to assess age-related eye conditions in novel vision tests.

1.1.1 Contrast sensitivity testing

Contrast sensitivity (CS) is a measure of a person's ability to detect a relative difference in luminance between two or more adjacent surfaces. Peak CS (3 to 6 cycles per degree in humans (Robson, 1966)) is crucial for mobility, driving, and other activities of daily living (Richman et al., 2013). It's also important for postural stability (Lord & Dayhew, 2001), as falls have been associated with poor CS. Although visual acuity (as measured at high contrast [100%]) is the standard method of assessing visual function, evidence has suggested that contrast sensitivity may also be a good indicator of everyday functional ability (Xiong et al., 2020). Certain conditions, such as central serous chorioretinopathy, optic neuritis, posterior subcapsular cataracts, early AMD and DR, and some instances of amblyopia, for example, are also associated with CS changes before high-contrast VA, making it a potentially valuable asset to assist with diagnosis and patient monitoring (Pelli & Bex, 2013; Vingopoulos et al., 2023; Xiong et al., 2020).

Specifically in glaucoma, contrast sensitivity (CS), early changes in CS have been reported in glaucoma patients (Hawkins et al., 2003; Ichhpujani et al., 2020; Fatehi et al., 2017; Jammal et al., 2020; Lord & Dayhew, 2001; Xiong et al., 2020; Herrero-Gracia et al., 2025; Li et al., 2021). CS has also been proposed as a functional endpoint in glaucoma clinical trials, including in the context of neuroprotection research, where standard automated perimetry has been argued to have insufficient sensitivity for detecting early functional change (Evans et al., 2003; Fang et al., 2020; Guo et al., 2014)), providing evidence that contrast sensitivity

could be included in the battery of tests for glaucoma patients to improve sensitivity. Visual field testing, by design, is also an indirect measure of contrast sensitivity itself; however, it works primarily well for understanding the application of CS testing in glaucoma patients. In addition, regular VF testing could further inform patient management or assessment. In addition, there is evidence that contrast sensitivity has a good correlation with glaucomatous visual field damage despite the patients maintaining good visual acuity, explaining how some patients may have worse functional symptoms even when visual acuity is preserved until the later stages (Hawkins et al., 2003). In addition to visual fields, contrast sensitivity changes are associated with decreased structural thickness, making it a valuable functional vision indicator in glaucoma. CS changes at near have shown a better association with visual field sensitivity changes than CS measurements taken at distance (Jang & Lee, 2023). The paper also showed how correlations between CS and VF sensitivity were likely to be influenced by distance, suggesting near-based CS tests may be a better indicator in glaucoma.

Despite its potential advantages, CS is not routinely assessed in most practices. One of the first works to evaluate the regular use of CS tests in 1998 investigated the use of CS tests in optometry practices and reported that only 16% of the 75 sampled optometrists used it regularly (Latham, 1998). Of those who did not regularly carry out CS tests (84%) cited that they either did not have equipment readily available, equipment was too expensive, were unsure of how to interpret the results or felt they did not gain any new information from that test (Latham, 1998). This study (Latham, 1998) highlighted the lack of awareness and the inability to use the visual function test to its full potential. The study also suggested that CS testing would/could be most effective when applied to specific subsections of the population, including geriatric patients who are more at risk of glaucoma or cataract. A more recent 2024 questionnaire-based study evaluating the use of CS tests by orthoptists in the UK reported that only 85% of surveyed orthoptists used CS testing in the clinic. However, they also noted that only 32% were unsure about the application of CS tests, highlighting the variability across practices in the UK. (Jones et al., 2024).

Contrast sensitivity in adults is typically measured using optotypes or gratings. The tests that use letter charts are the Pelli-Robson Letter chart, the Bailey-Lovie chart, and Regan's low contrast chart (Grosvenor, 2007). Some common grating-based contrast assessments include

the Functional acuity contrast test (FACT), Arden grating plates, Vision contrast test systems (VCTS), Tech Chart, Melobourna Edge test, Cambridge Low contrast grating, Vector vision CSV-1000, and monitor B-VAT II and B-VAT II SG (Grosvenor, 2007). Among the above-mentioned, the **Pelli-Robson chart** has the widest clinical reach (Ichhpujani et al., 2020; Richman et al., 2015) in adults. It uses Sloan letters of constant size, with contrast levels ranging from 100% to 0.56%, arranged in 16 triplets across 8 lines. Typically wall-mounted and measuring 60 x 85 cm, the chart is used monocularly at a distance of 1 m, in an area with an external illumination of 85 cd/m². Although the test is simple to administer, it requires a standardised clinical environment (particularly lighting) and depends on the patient's ability to identify letters. It also lacks portability and, despite its clinical relevance, is not a mandatory test in all clinics (Dorr et al., 2017). The results from the Pelli-Robson assessment are also influenced by reflections and the fading of the charts over time (Richman et al., 2013).

The concern surrounding additional equipment is important to address, as these charts need space to be performed and stored, and require active engagement from the clinician. Similar to other eye charts, they are also vulnerable to wear and tear, but it becomes more crucial here because they tend to be less effective as the charts become dirtier and may not give accurate results. However, when used effectively, it can provide more information in certain cohorts that may not be subtle enough to be picked up by high-contrast visual acuity or not as vague and subjective as patient history. Methods that are both convenient to the clinician and patient may help increase the usage of this key visual function metric.



Figure 1.2. Pelli Robson CS chart. (Dakin & Turnbull, 2016)

Portable contrast sensitivity tests --- either digital or printed --- may address some challenges associated with conventional measures such as the Pelli-Robson letter chart. Among these popular printed alternatives are the Illinois Eye and Ear Noise CS test (IEEN-CS) (Essig et al., 2021), the Mars letter contrast sensitivity test (Dougherty et al., 2005) and more recently the Spotchecks CS test (Precision Vision, Woodstock, IL, USA). The Spotchecks (Precision Vision, Woodstock, IL, USA) is a commercially available disposable pen-and-paper-based method designed for near-distance assessment. Its non-letter-based format is easily administrable to both children and adults (Anderson et al., 2023). This test has been used in several studies within this thesis and will be discussed in further detail in Chapters 3, 5 and 6 (specifically subsections 3.2.7, 5.2.4, and 6.2.2).

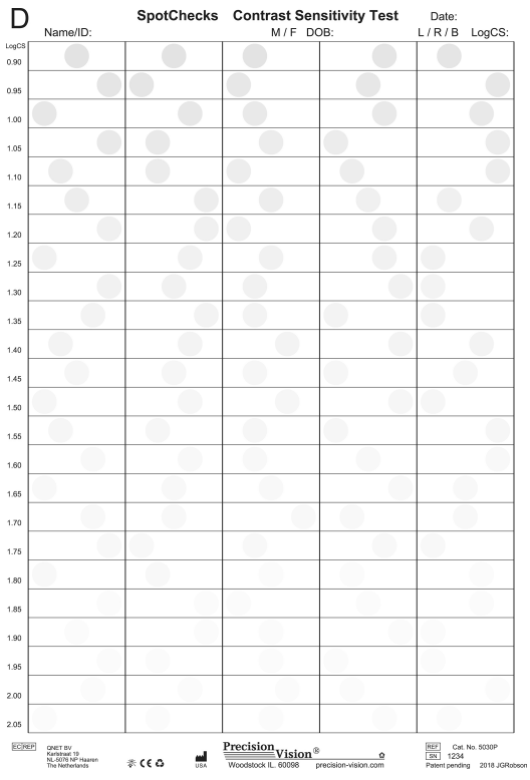


Figure 1.3. Spotchecks contrast sensitivity test. Image source:(Anderson et al.,2023)

Digital tests such as qCSF and PopCSF evaluate contrast across various spatial frequencies, overcoming the challenges of ceiling/floor effects and poor repeatability in traditional printed CS tests used in the clinic. Although not portable, the qCSF Manifold is a popular digital test that has been used to evaluate contrast sensitivity in retinal disorders such as age-related macular degeneration (Anders et al., 2023), diabetic retinopathy, retinal vein occlusion, retinal detachment and central serous chorioretinopathy (Vingopoulos et al., 2023). This test is performed at a distance of 20 feet using an LED screen with high-definition resolution. The test uses Sloan letters with 19 possible spatial frequencies. The patients respond verbally, and the examiner records the responses separately. The responses are then used to construct a contrast sensitivity function curve (Vingopoulos et al., 2023).

The PopCSF test (Irida Health, London, UK) is another test that measures the CSF through a portable handheld device. It is a gamified digital CS test that uses moving Gabor patches to estimate the contrast sensitivity function. These “floating” Gabor patches move around the screen, and the participant is instructed to click on them as and when they are seen. As shown in **Figure 1.4**, the contrast sensitivity function is estimated in this test by estimating the peak contrast sensitivity (G_{max}), the spatial frequency associated with peak contrast

sensitivity (F_{max}), and the slope of the high-spatial frequency drop (β). This test runs on an Apple iPad Pro (11-inch, 2nd generation, Apple Inc, Cupertino, CA, USA) and is designed to be used at maximum brightness. The test is performed at 50 cm. Like Spotchecks, this test has been used extensively in my work and will be discussed in greater detail in Chapters 3, 5 and 6 (specifically 3.2.6, 5.2.5, and 6.2.2).

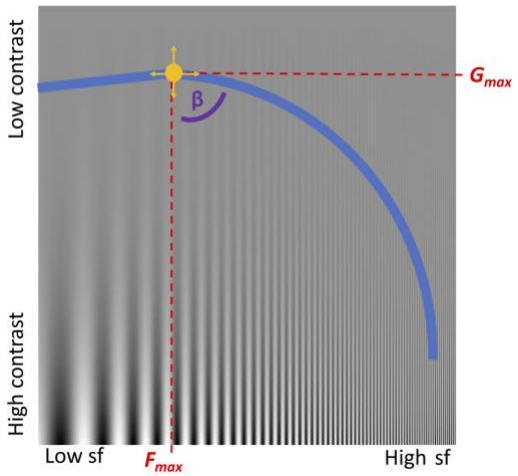


Figure 1.4. The parameters measured by the PopCSF test to estimate the CSF. The yellow point represents the point of intersection between G_{max} (the point of peak contrast sensitivity) and F_{max} (its corresponding spatial frequency). The angle β represents the decline of the CSF once the peak has been reached.

1.1.2 Visual Field Testing

Visual field testing is a critical diagnostic tool for conditions such as glaucoma, where it remains the primary method for the functional assessment of disease progression. Consequently, glaucoma management necessitates regular, in-person visual field assessment. Within the UK, most UK tertiary sites assess the visual field using the Humphrey field analyser (HFA; Carl Zeiss Meditec Ltd., California, USA, **Figure 1.5**). While the HFA enables assessment of multiple locations on the visual field; however, it presents several practical limitations. Although the test procedure is straightforward, requiring only a button-press response from the user, it has several drawbacks: it is expensive and time-intensive; it is sensitive to variations in patient attention and fatigue; it requires trained personnel for

administration and interpretation; and its limited portability restricts use primarily to clinical settings (Wang, 2025).

To address some of these challenges, research has increasingly turned towards smaller, easier-to-administer tablet-based and head-mounted devices. These options do need some procedural discipline, but do not require the same level of attention and postural discipline needed to maintain a fixed working distance in the HFA.

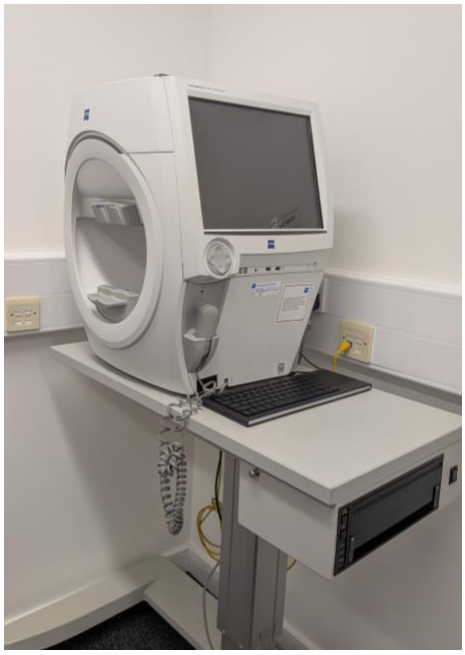


Figure 1.5. Humphrey Field Analyser (HFA).

1.1.3 Alternative and portable types of perimeters

Portable perimeters can be divided into tablet-based and head-mounted variants. Tablet-based options benefit from simpler and more readily available hardware. However, they require careful control of viewing distance and ambient illumination. These confounds can potentially be obviated by head-mounted devices. Headsets limit or prevent any external light from entering their field of view. The headset screen moves in alignment with the patient's head movements, allowing them to do the tests in their preferred position while sitting (Ma et al., 2022; Phu et al., 2024).

With the rising popularity of telemedicine, there are several visual field perimeters using head-mounted technologies. A systematic review by Selvan et al (2023) summarises the work of 64 studies describing 36 unique VR-based perimetry devices, highlighting the

growing popularity of this intervention. The systematic review concluded that VR headsets provide notable benefits over the gold standard SAP, especially in terms of accessibility and comfort; however, there was a lack of studies that validate the use of these headsets across different disease progressions and conditions, which limits their usability (Selvan et al., 2024). The Eyecatcher device used in this thesis does not use a full VR headset but a lighter pair of smartglasses.

The benefits of measuring perimetry and contrast sensitivity are well-documented; however, the challenges of the currently available clinical tests often limit their usage to specialised practice. This indicates the need for more accessible technology in the day-to-day diagnosis and management of age-related eye conditions to support the growing needs of the modern-day patient and practitioner.

The challenges of these age-related conditions converge on a common theme: delays in diagnosis and treatment negatively impact both the patient and the efficiency of the healthcare system. These concerns surrounding the management of age-related eye conditions underscore the growing demand for eye care services, leading to the central argument of this thesis. The increasing disease burden, compounded by limited healthcare capacity, has created the need to explore new technological solutions that address the shortage of human resources while supporting patients as much as possible. The current challenges facing the system extend beyond establishing that a new test is theoretically superior. The test must also be capable of being delivered within existing clinical capacity, without disrupting clinical flow. The flow chart below illustrates the conceptual chain connecting these elements: rising disease burden increases demand on an already limited healthcare workforce, which in turn prompts interest in technological solutions to extend capacity.

1.2 Thesis Overview

This thesis brings together research from five studies exploring the feasibility of developing and evaluating novel tests of visual function for age-related eye disease in England. The majority of these studies primarily focus on glaucoma, with supporting work in AMD.

The first study (Chapter 2) of the thesis focuses primarily on evaluating the need for alternative and new approaches. This is achieved by examining the impact of multiple deprivation on the diagnosis and management of glaucoma.

Having addressed the necessity in the previous chapter, Chapters 3 and 4, examine the feasibility of performing new tests of visual function through experiments involving real patients.

During this research, two major concerns arose: the resilience of these novel tests across different light environments and the patient acceptability of such alternative out-of-clinic testing strategies. Therefore, Chapters 5 and 6 focus on the resilience and acceptability of these tests, indicating the factors that are important for the success of their real-world implementation.

Finally, in Chapter 7, I discuss the key findings and limitations of the present work and outline directions for future research.

Chapter 2. Measures of multiple deprivation and visual field loss in glaucoma clinics in England: lessons from big data

One of the key themes of the overall programme of work is the need for alternative approaches to monitoring age-related eye conditions. The study presented in this chapter aligns with this theme by examining just one issue surrounding access to and utilisation of glaucoma care within Hospital Eye Services (HES) in England, i.e., neighbourhood multiple deprivation. The study aims to examine the association between multiple deprivation and late diagnosis and rapid worsening of glaucoma in patients in the English HES by using a method of retrospective analysis of data. A version of this study, prepared to journal specifications, was published in the Journal Eye in May 2023 (Rathore et al. 2023). Parts of this work have been presented as an invited symposium talk at the European Vision and Eye Research (EVER) Conference, Valencia (October 2023), oral presentations at the City St George's Doctoral Conference, London (June 2023), the Macular Society, London (July 2023), Glaucoma UK, London (January 2023), the British Congress of Optometry and Vision Science, Birmingham (September 2022), the Imaging and Perimetry Society Meeting, Berkeley (August 2022, virtual), and the VERI-Crabb Lab Symposium, Cambridge (April 2022) and as a poster at the Women in Vision UK Annual Meeting (June 2022, awarded Best Poster Presentation).

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Author Contributions:

Rathore: Data analysis, preparation of the original manuscript draft, editing the final manuscript, and management of the submission process.

Shweikh: Study design, data interpretation support, and manuscript revisions.

Kelly: Study design and data analysis.

Crabb: Study design, data analysis, manuscript writing, acquired funding, and supervised the project.

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visual field loss in glaucoma clinics in England: lessons from big data. *Eye* **37**, 3615–3620 (2023). DOI: https://doi.org/10.1038/s41433-023-02567-z

Abstract

A total of 602,439 visual fields (VFs) were previously extracted from five regionally different glaucoma clinics in England. Mean Deviation (MD) worse than −12 dB was used as a surrogate definition for advanced VF loss at diagnosis in patients with ≥2 reliable VF records. MD loss worse than -1 dB per year was used to define rapid VF progression in patients with ≥6 VFs. Patient data were stratified into deciles of the Index of Multiple Deprivation (IMD) from residential postcodes. Results indicated there was an association between IMD and advanced VF loss at diagnosis in 44,956 patients, with 18% (293/1608) and 11% (771/6929) in the most and least deprived IMD decile, respectively. Age-corrected odds ratio (OR) for having advanced VF loss at entry into HES was 1.42 (95% confidence interval [CI] 1.21–1.67) and 0.75 (95% CI: 0.66–0.85) in the most and least deprived IMD decile, respectively (reference = fifth decile). In 15,094 patients with follow-up data (median [interquartile range] of 6.9 [4.5, 10.0] years), the proportion having rapid VF progression did not differ across the IMD spectrum. In conclusion, this study showed that large-scale VF data from clinics indicate that glaucoma severity at presentation to English HES is associated with levels of multiple deprivation. We found no evidence to suggest the likelihood of having rapid VF progression during follow-up is associated with IMD; this hints at equity of glaucoma care and outcomes once patients are in English HES.

2.1 Introduction

If glaucoma is not detected early enough or is not well managed, then the subsequent visual field (VF) loss can adversely affect a patient's vision-related quality of life. Late presentation of glaucoma, when a patient already has advanced VF loss at diagnosis, is a major risk factor for subsequent loss of vision (Kastner & King, 2020; Saunders et al., 2013). Primary open-angle glaucoma, the most common form of the condition, is mostly asymptomatic in its early stages, and early detection relies on a person having regular eye examinations. The vast majority of glaucoma referrals to hospital eye services (HES) in England are generated by examinations at community optometrists (Davey et al., 2011; Harper et al., 2020; Sheldrick et al., 1994). Yet, people with lower socioeconomic status, lower educational attainment, and less awareness of eye disease are probably less likely to engage with primary healthcare services for this "opportunistic" eye health screening, recommended to be done at least once every two years (Prior et al., 2013).

Poor socioeconomic status (SES) is related to poorer health. This association is very well established, and it exists even in relatively prosperous parts of the world. Eye health is not an exception to this rule, and this is well described in a recent comprehensive systematic review (Lane et al., 2018). The specific association between the late presentation of glaucoma and SES is recognised. For example, more than 20 years ago, Fraser and colleagues demonstrated that people exposed to higher levels of multiple deprivation were more likely to have late presentation of glaucoma at HES in England (Fraser et al., 2001). Further evidence has emerged to corroborate this association in England (Sukumar et al., 2009), Scotland (Ng et al., 2010), and in other parts of the world (Buys & Jin, 2013; Gogate et al., 2011). An up-to-date examination of this association, in a larger number of patients from different parts of England, would be useful, and this is one of the main ideas of this study.

Aside from its use in clinical management, an electronic medical record (EMR) allows for the collection of clinical data from large patient populations. In turn, these data can be used for identifying trends in disease worsening and treatment response on a large scale (Kelly et al., 2019). Linking these 'big data' to other public health data, like those developed for measuring a person's SES, opens up interesting areas of research, and our study serves as an example of this. One such data set is the index of multiple deprivation (IMD), which is the

most widely used English measure of SES at the small area (postcode) level, aimed at assisting policymakers. IMD is based on seven metrics: income, employment, education, health, crime, living environment, and access to housing and services (Smith, n.d.). IMD data has been widely used previously to show that deprivation is a significant factor in the prevalence or presentation of a number of specific eye conditions (Bourkiza et al., 2020; Goverdhan et al., 2011; Moussa et al., 2021).

The purpose of this study is to present large-scale multicentre data on a measure of glaucoma severity at presentation to HES in England and to see how this varies across the SES spectrum as measured by IMD. In addition, nothing is known about the effect of multiple deprivation on glaucoma management outcomes in patients receiving long-term treatment from HES in England. We therefore test the novel hypothesis that rates of VF progression (as a measure of glaucoma worsening) in diagnosed patients in HES in England vary with a patient's level of multiple deprivation.

2.2 Methods

2.2.1 Overview of the study

This study is a retrospective analysis of large-scale data extracted from EMRs as described elsewhere (Kelly et al., 2019, 2020; Liu et al., 2019). In short, data recorded between April 2000 and March 2015 were extracted and anonymised from the Medisoft EMR (Medisoft, Leeds, UK) at five regionally different National Health Service (NHS) Hospital Trust glaucoma clinics in England. These clinics provide secondary eye care to people referred by primary care providers, mainly community optometrists. Each centre is the only NHS provider of glaucoma care to their local population, and relatively few patients switch between providers or access care privately. The original data extraction was commissioned by the Healthcare Quality Improvement Partnership, overseen by the Royal College of Ophthalmologists, as the National Ophthalmology Database Audit provider. Data were securely held on a university database. The study adhered to the Declaration of Helsinki and the General Data Protection Regulation of the European Union. Subsequent analyses of the data were approved by a research ethics committee of City, University of London, with one condition being that the five NHS centres were anonymised.

2.2.2 Data extraction

The original data extraction yielded 602 439 separate VF records from 73 994 people. These data also included age (years) and a minimum data set of other clinical records. At the source, the EMR includes data on residential addresses as standard. Each postcode was identified and allocated to the IMD score for that area (LSOA; lower layer super output area) based on the English Indices of Deprivation 2015 (https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015). The IMD score was calculated based on the first four postcode digits. Notably, the LSOA conversion was done at the source to avoid the transfer of patient-identifiable data, and postcodes were never extracted. The English IMD 2015 uses the LSOAs defined in the 2011 census, with the evaluation of deprivation being primarily based on data taken from 2012 to 2013. Merging and matching the VF data to the available IMD data yielded complete records from 69 587 people.

Only VFs recorded by adults (≥18 years) on the Humphrey Field Analyser (HFA; Carl Zeiss Meditec, California, USA) using a Goldmann size III stimulus with a 24-2 test pattern acquired with the Swedish Interactive Testing Algorithm (SITA Fast or SITA standard) were included. Information about their refractive correction was not available and therefore not analysed. We excluded all unreliable VF records using the criterion of a percentage of false-positive errors ≥15%. No exclusion criteria were applied based on fixation losses or false-negative errors as recommended by previous research (Chauhan et al., 2008; Yohannan et al., 2017).

2.2.3 Cross-sectional analysis

For testing the hypothesis that presenting at HES with advanced VF loss is associated with SES, we defined our population as people who had had at least two separate visits to the clinic. Therefore, we excluded all those patients who had only one visit or one set of VF records, assuming most of these would have been false referrals from primary care. We used HFA mean deviation (MD) as a measure of the overall severity of a VF loss. MD is calculated relative to visually healthy peers, with more negative values indicating greater VF loss. The stage of VF loss at presentation was estimated by the MD in the worse eye (the one with the more negative MD) at the second VF examination. The second VF was used to mitigate the bias of the perimetry learning effect (Gardiner et al., 2008; Kelly et al., 2019). We chose the worse eye as a surrogate of the most 'detectable' level of VF loss at the stage of case finding in primary care. Patients with MD worse than −12 dB in this eye were defined as having advanced VF loss at presentation. This VF criterion has been widely used, including in health economic investigations of service delivery of glaucoma (Burr et al., 2007; Kelly et al., 2019). This criterion was most appropriate to use because of its simplicity and its independence from the individual data points on the pattern deviation plots.

2.2.4 Longitudinal analysis

For testing the hypothesis that patients in glaucoma clinics have rapid VF progression associated with lower SES, we then defined our population as patients with at least six visits to the clinic. These patients were simply a subset of those from the previous cross-sectional analysis. The speed (rate) of VF loss in these patients in clinics was determined by using ordinary linear regression of MD against the time of follow-up (dB/year); a standard method that is widely used (Chauhan et al., 2008; Kelly et al., 2019). The first VF examination in each

series was removed to account for the perimetry learning effect. We used all the patient's follow-up data, meaning that the rate of VF loss could be estimated more precisely, from more than six records and over longer periods where available. Again, we only used one eye per patient, the one with the more negative (worse) MD at the second (baseline) VF examination. Patients with a rate of loss worse than −1 dB/year in this eye were defined as having rapid VF progression; this criterion has been widely used in previous studies (Baril et al., 2017; Chauhan et al., 2014; Wright, Konstantakopoulou, et al., 2020). Likewise, previous studies have used five or more visual field reports to quantify progression rates. (Baril et al., 2017, Chauhan et al.,2014) . We particularly chose six, as the first report was eliminated from the analysis to account for the perimetric learning effect.

2.2.5 Statistical analysis

Patients were stratified into their IMD deciles one to ten as described on https://www.gov.uk/government/statistics/english-indices-of-deprivation-2015. Decile 1 (IMD 1) corresponds to the most deprived group. We calculated summary statistics for MD (dB) at presentation and MD (dB) loss per year for patients stratified by decile of IMD. We also calculated the proportion of patients with the outcome of interest, that is, having advanced VF loss at presentation and having rapid VF progression, for each decile. We used age-corrected logistic regression to calculate an odds ratio (OR) for having each outcome of interest across all the deciles (the spectrum of SES) using the fifth IMD decile set as the reference group, as has been done previously (Denniston et al., 2019). Under the null hypothesis that the IMD is not associated with the outcomes of interest, we would expect the age-corrected ORs not to be statistically different from one. All statistical analyses were done using R statistical software (R Foundation for Statistical Computing, Vienna, Austria).

2.3 Results

2.3.1 Cross-sectional analysis

The inclusion criteria for the cross-sectional analysis yielded 44 956 patients. Data for these patients, stratified by IMD decile, are given in **Table 2.1**. Median age (years) is strikingly similar across all IMD deciles, but the median MD at presentation clearly varies across the IMD deciles, being worse in patients exposed to more deprivation. For example, the difference in median MD between those in the most and least deprived deciles is >1.5 dB; the magnitude of the effect is noteworthy. Moreover, 18% (293/1608) of patients had advanced VF loss at presentation in the most deprived IMD decile, whereas this value was 11% (771/6929) for those in the least deprived IMD decile. There was a clear pattern of association between IMD (across all deciles) and the likelihood of having advanced VF loss at diagnosis, as shown in **Figure 2.1 (A)**. For example, the age-corrected OR for having advanced VF loss at entry into HES was 1.41 (95% confidence interval [CI] 1.20 to 1.62) and 0.75 (95% CI: 0.67 to 0.85) in the most and least deprived IMD decile, respectively (relative to the fifth decile in all cases).

2.3.2 Longitudinal analysis

Inclusion criteria for the longitudinal (follow-up) analysis yielded 15 094 patients. These data were rich in length of follow-up (median [interquartile range] of 6.9 [4.5,10.0] years). So, for example, approximately one-quarter of these patients had at least ten years of follow-up data available for analysis, giving us confidence in the estimates of the rates of MD loss. Data for these patients, stratified by IMD decile, are given in **Table 2.2.** As with the cross-sectional sample, median age (years) is similar across all IMD deciles. The median rate of VF loss appears to be similar across all IMD deciles, and this is noteworthy. For example, the median rate of VF loss for those in the most (-0.16 dB/year) and least (-0.18 dB/year) deprived deciles were virtually the same. Whilst patients as a group in IMD 1 (most deprived) clearly have worse VF loss at baseline, they do not seem to be progressing more quickly, on average, than those in IMD 10 (least deprived). There was no evidence of an association between IMD and rapid VF progression at all, as noted in **Figure 2.1(B).** The proportion of patients with the attribute of having rapid VF progression was similar across the deciles. Moreover, even at the extremes of the SES spectrum, the age-corrected OR of 1.25 (95% CI:

0.89 to 1.74) and 0.86 (95% CI: 0.68 to 1.09) in the most and least deprived IMD deciles, respectively, do not significantly differ from the reference value of one (*P*=0.19 and *P*=0.21).

Table 2.1. Description of cross-sectional data - advanced visual field loss at presentation to clinic. (VF: visual field; n: number of patients; y: years; MD: mean deviation; IMD: index of multiple deprivation; IQR: interquartile range; or: age-corrected odd's ratio)

IMD Decile	n	Median (IQR) age (y)	Median (IQR) MD (dB)	% (n) advanced VF loss	OR (95% CI)	P-value
1	1608	68 (57, 77)	-4.32 (-9.00, -1.88)	18 (293)	1.41 (1.20 – 1.62)	<0.001
2	2708	68 (56, 77)	-3.88 (-8.56, -1.62)	17 (454)	1.29 (1.12 – 1.48)	<0.001
3	2306	69 (57, 77)	-3.91 (-8.17, -1.73)	16 (361)	1.15 (0.99 – 1.34)	0.07
4	3629	69 (59, 77)	-3.67 (-7.80, -1.50)	15 (537)	1.06 (0.92 – 1.21)	0.43
5	3361	69 (60, 77)	-3.24 (-7.39, -1.28)	14 (480)	1	
6	4768	69 (60, 78)	-3.29 (-7.52, -1.26)	15 (704)	1.03 (0.91 – 1.18)	0.66
7	5788	69 (59, 77)	-3.13 (-7.07, -1.15)	13 (762)	0.92 (0.81 – 1.04)	0.18
8	6246	69 (60, 77)	-2.89 (-6.50, -1.06)	12 (769)	0.84 (0.74 – 0.95)	0.007
9	7613	69 (60, 77)	-3.00 (-6.97, -1.09)	13 (988)	0.89 (0.79 – 1.00)	0.045
10	6929	69 (60, 77)	-2.77 (-6.29, -1.00)	11 (771)	0.75 (0.67 – 0.85)	<0.001

Total	44956	69 (59, 77)	-3.19 (-7.19, -1.22)	14 (6119)

Table 2.2. Description of follow-up data - rapid visual field progression whilst followed in clinic. (VF: visual field; n: number of patients; y: years; MD: mean deviation; IMD: index of multiple deprivation; IQR: interquartile range; OR: age-corrected odds ratio; CI: confidence interval.)

IMD Decile	n	Median (IQR) age (y)	Median (IQR) No. VFs	Median (IQR) Follow-up (y)	Median (IQR) MD loss (dB/y)	% (n) Rapid VF progression	OR (95% CI)	P
1	488	68 (58, 78)	8 (6, 11)	7.3 (4.6, 10.5)	-0.16 (-0.56, 0.05)	0.13 (63)	1.25 (0.89 – 1.74)	0.19
2	796	68 (60, 76)	7 (6, 10)	6.9 (4.7, 9.9)	-0.15 (-0.54, 0.10)	0.11 (89)	1.01 (0.75 – 1.35)	0.96
3	745	69 (59, 76)	8 (6, 11)	6.9 (4.4, 10.2)	-0.16 (-0.52, 0.07)	0.10 (78)	0.93 (0.68 – 1.26)	0.64
4	1345	68 (60, 76)	8 (6, 11)	7.1 (4.5, 10.4)	-0.20 (-0.55, 0.04)	0.11 (152)	1.03 (0.79 – 1.33)	0.85
5	1104	69 (60, 76)	7 (6, 10)	7.0 (4.6, 9.9)	-0.18 (-0.50, 0.05)	0.11 (126)	1	-
6	1562	68 (60, 76)	7 (6, 10)	6.9 (4.5, 9.9)	-0.17 (-0.52, 0.03)	0.12 (180)	1.03 (0.80 – 1.32)	0.81
7	1850	68 (59, 75)	7 (6, 10)	6.8 (4.4, 9.8)	-0.16 (-0.46, 0.07)	0.10 (188)	0.95 (0.74 – 1.21)	0.68
8	2118	68 (60, 75)	7 (6, 10)	6.8 (4.4, 9.8)	-0.14 (-0.50, 0.06)	0.11 (226)	0.98 (0.78 – 1.25)	0.87
9	2591	69 (60, 76)	7 (6, 11)	6.8 (4.5, 9.8)	-0.18 (-0.54, 0.03)	0.11 (283)	0.97 (0.78 – 1.23)	0.82
10	2495	68 (60, 75)	7 (6, 10)	6.8 (4.4, 10.0)	-0.18 (-0.50, 0.05)	0.09 (236)	0.86 (0.68 – 1.09)	0.21
Total	15094	68 (60, 75)	7 (6, 10)	6.9 (4.5, 10.0)	-0.17 (-0.51, 0.05)	0.11 (1621)		

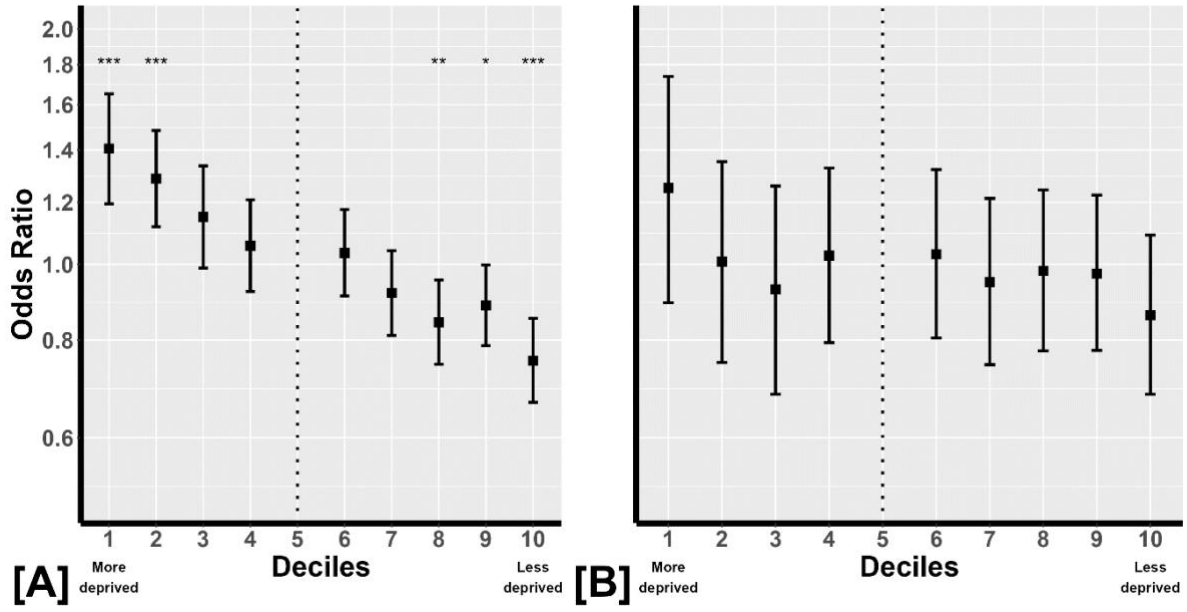


Figure 2.1. Graphical representation of the age-corrected odds ratio (OR) against each Index of Multiple Deprivation decile for advanced field loss at the time of presentation **(A)** and rapid VF progression **(B)**. **(A)** graphically shows the age-corrected odds ratio (OR) and corresponding 95% confidence intervals (bars) for having advanced visual field (VF) loss at presentation to clinic for each index of multiple deprivation (IMD) decile. (The most deprived being IMD decile 1 and the least deprived being IMD decile 10.) The asterisks indicate the level of statistical significance (<0.05, <0.01 and <0.001 for *, ** and *** respectively) for the age-corrected OR being different from the value for the reference fifth decile (dotted line). **Figure 2.1 (B)** is formatted in exactly the same way but shows the age-corrected OR and corresponding 95% confidence intervals (bars) for having rapid VF progression whilst followed in clinic for each IMD decile. In this case, none of the ORs are statistically different relative to the fifth decile (dotted line). Note the ORs are plotted on an appropriate log scale on the vertical axis.

2.4 Discussion

2.4.1 Summary of the study

By using retrospectively collected data from 44 956 patients from five regionally different HES glaucoma clinics across England, we show a clear association between late presentation of glaucoma and SES. More specifically, we show the likelihood of having advanced VF loss at the first visit to a glaucoma clinic to be much greater in people living in areas with higher multiple deprivation indices compared to peers from areas with lower multiple deprivation. We also demonstrated that rapid worsening of vision (using a surrogate of the rapid rate of

VF progression) in patients managed by HES across England is not associated with a patient's level of multiple deprivation.

2.4.2 Comparison with existing literature

Our results provide new knowledge on the relationship between a person's estimated level of multiple deprivation and their glaucoma patient journey in England. First, we have confirmed the reported link between the late presentation of glaucoma and deprivation; this was important because previous UK studies had small sample sizes confined to a particular geographical region (Fraser et al., 2001; Ng et al., 2010; Sukumar et al., 2009). Second, we present a novel finding using follow-up data from 15,904 glaucoma patients being managed within English HES, where we found no evidence of an association between rapid VF worsening and patients' IMD. More precisely, a patient from a more deprived area, compared to a peer from a less deprived area, is not more likely to lose VF rapidly in HES glaucoma clinics. Importantly, these data hint at an equity of glaucoma management and clinical care once patients are in HES in England. This finding is both novel and reassuring; it contradicts what others have found about the relationship between glaucoma outcomes and SES, albeit in different health systems in different countries (Elam et al., 2017; Halawa et al., 2022).

Mean deviation, by nature of its design, is corrected for age. Several papers have reported that progression was considerably faster in older patients than younger patients (P=0.002) . Chauhan et al (2024), in their study on rates of glaucomatous visual field change in a large clinical population, show that routine-care progression is, in reality, quite slow when all patients with glaucoma across the spectrum are included, with a median decline of -0.05 dB/year across the included patients (n=2324). The study also highlighted how only 1.5% of all the included participants were catastrophic progressors (<-2 dB/year); however, the number of fast progressors progressively increased with every tertile of advancing age. The study also confirmed that worse mean deviation scores were associated with older age at the baseline assessment. Rao et al. (2015) state that rates of change in mean deviation were more negative (worse) in older patients, but the rates were less negative in eyes with more severe baseline VF loss (Rao et al., 2015). Another study assessed the impact of baseline age and mean deviation on rates of VF loss in 84,711 visual field reports. The paper reports that

for each additional year of baseline age, the odds of rapid progression were raised by a factor of 1.033 and the impact of age on the mean deviation rate was itself modified by baseline MD severity (Bommakanti et al., 2020).

Our results should be discussed in the context of other published studies considering the relationship between SES (multiple deprivation) and glaucoma detection and management, specifically in England. Fraser et al first reported evidence on the relationship between the late presentation of glaucoma and various indicators of deprivation in a case-control study across three centres (Fraser et al., 2001). Sukumar and colleagues also showed the association between levels of deprivation and presenting VF loss in a retrospective single-centre study of 113 patients (Sukumar et al., 2009). This general finding was corroborated in a sample of 126 patients in Scotland (Ng et al., 2010) and in another more recent study of 472 consecutive newly referred patients in Scotland (Wong et al., 2023). It has also been shown that people with self-reported glaucoma had higher levels of deprivation and lower income compared to other individuals in the UK Biobank cohort (Shweikh et al., 2015). There are examples of evidence for the association between the late presentation of glaucoma and measures of SES in other countries, but the effect is likely heavily dependent on the health system used and the general level of deprivation (Buys & Jin, 2013; Gogate et al., 2011; Jones et al., 2020; Kyari et al., 2016). The interested reader is directed to a recent systematic review by Lane and colleagues, which concluded with a call to policymakers to act on untangling the complex link between deprivation and late presentation of eye conditions (Lane et al., 2018). Most recently, King and colleagues reported on the effects of SES (as measured by IMD) on baseline values and outcomes from the Treatment of Advanced Glaucoma Study (TAGS) randomised controlled trial (King et al., 2023) (TAGS was primarily designed to determine whether primary medicine or primary surgery is more effective for patients presenting with advanced glaucoma). In 453 patients presenting with advanced VF loss, IMD was correlated with poorer self-reported visual function, poorer MD and visits to a community optometrist in the years preceding diagnosis. Interestingly, the TAGS investigators found no evidence that IMD was associated with the effect of the success of treatment at 24 months, which supports our finding that VF worsening may not be influenced by SES.

Explanations for the associations we report from our data are largely beyond this discussion, but we briefly speculate on some here. In England, late glaucoma presentation can be explained by delays at the patient level (e.g., less frequent attendance to optometrists) or delays at the healthcare provider level (Prior et al., 2013). Interestingly, results from a mapping study of optometrists in an area of Northern England support the theory that people with lower SES present late due to limited access to primary eye care services (Day et al., 2010). In contrast, reasons for delayed access to eye healthcare have been recently shown, in Northern Ireland, not to be linked to low income, for example (Wright, O'Reilly, et al., 2020). Moreover, others have shown no robust evidence of a direct association between SES and access to eye health services in the UK (Knight & Lindfield, 2015). Reasons underpinning poor access to regular eye testing with optometrists in England are likely complex and may include poor knowledge of eye health, fear, inertia, perceived costs, limited mobility, and access (Shickle et al., 2015; Shickle & Griffin, 2014). These explanations and others for the late presentation of advanced glaucoma have been recently reviewed (Kastner & King, 2020).

2.4.3 Strengths, limitations and future scope of the study

An obvious strength of our study is the vast number of patient records used to estimate our measures of interest. Moreover, the data were multicentre from regionally different clinics across England, although the sampling was not done systematically. Another strength of our study was maintaining the anonymity of the patient records; IMD requires postcode information, but the data linkage was undertaken at source within the HES EMR to avoid the transfer of patient-identifiable data. We also used established methods for assessing VF data, and our criteria for late presentation and rapid VF loss have been widely used in other studies. Our chosen method of analysis sensibly corrected for age, too, which is known to be associated with late presentation of VF loss and faster VF progression (Boodhna et al., 2015). The five NHS centres belonged to geographically different areas, which may help generalise the findings to a certain extent; however, no formal analysis was performed to identify differences between the sites. In the future, it would be valuable to learn the centre-specific effects of such centres that may influence our findings.

Our study had several limitations because it was retrospective and lacked information about the complete diagnoses of patients. We cannot be certain that a patient's first VF is truly their first one after diagnosis, because a person may have simply moved, for example. Yet with these large numbers of VF records, we expect any effect of these transfers to be small. Moreover, our surrogate for advanced VF loss, or rapid VF loss, could be affected by a patient having concomitant eye disease. Lack of clinical information restricts the level of certainty about the underlying diagnosis. Again, the size of our sample helps mitigate against this, and only including patients with VF loss being regularly seen in HES glaucoma clinics should exclude most cases of non-glaucoma diagnoses. We could not differentiate between different types of glaucoma in this study; interestingly, for example, it has been recently shown that deprivation is an important risk factor for patients presenting with acute angle-closure glaucoma (Saxby et al., 2022). We also acknowledge that our data reflected a skewed representation of the population in terms of deprivation (i.e., an overrepresentation of participants from the least-deprived decile). Although this imbalance would lead to wider confidence intervals for our results, they are offset by the large amount of data.

In our current study, we only adjust for age, but it would be interesting to learn about the other factors that likely contribute to deprivation – such as ethnicity, presence of co-morbidities, gender, geographical location and physical distance from the point of care. In addition, we also acknowledge that the IMD score was an area-level analysis and not an individual socio-economic deprivation indicator. LSOAs within themselves may have varying levels of deprivation that could have been underestimated by our analyses.

We also note that we were unable to factor in refractive error in the analyses, which may have influenced the MD level in the cross-sectional analyses. However, we do not expect this limitation to have impacted the longitudinal analyses due to the presence of multiple data points.

Our cross-sectional analysis prioritises the definitions of advanced glaucoma. Primarily due to the impact it has on vision and because of its straightforward criteria when using the HPA classification. In the future, with more data, it would be useful to compare the times of presentation of people with varying severities in people with varying levels of deprivation.

That information would provide insights into the health-seeking behaviour of the community and to help direct resources into prevention, detection and monitoring appropriately.

We also acknowledge the impact of the floor effect on the analysis. We expect it to affect the cross-sectional analysis less, as the definitions were clear and the level of severity did not matter once the threshold was met. However, in the longitudinal analysis, progression is measured as the slope of MD over time. This means that a patient presenting with severe loss (say, -28 dB) is less likely to show further deterioration due to the limitations of the HFA itself, which would produce an artificially flattened slope. Because our data suggest that more-deprived communities are more likely to present late and near that floor, their progression rates are likely to be most suppressed, thereby biasing Panel B in Figure 1 towards the finding of no progression across deciles.

Ultimately, we have provided a useful assessment of issues around multiple deprivation and VF loss in glaucoma clinics in England, but the results are still not entirely current, being based on data extracted in 2015. Our most novel finding is observing no association between IMD and rapid rates of VF loss in patients in glaucoma clinics in HES. However, as always, the absence of evidence of an association is not evidence of the absence of an effect. Nevertheless, the data we use to illustrate this non-association is robust, being based on 15 094 patients with a median of seven HES visits, remarkably, about one-quarter of patients followed for a decade or more. Moreover, average rates of VF loss are expected to be greater in those eyes with more VF loss at diagnosis – this is a well-established association (Boodhna et al., 2015; Giammaria et al., 2022). So, it is surprising that those with more deprivation and more VF loss did not, on average, have worse rates of loss (progression) than those with less deprivation and less VF loss; we think this adds to the evidence of no association between rapid VF progression and multiple deprivation. Nonetheless, our results ought to be replicated in an observational cohort study facilitated by an EMR and this should be the subject of future work. Such a study could also quantify real vision loss in people who received a glaucoma diagnosis later than others, in part due to where they live and their IMD. Such data might support the idea of an intervention, perhaps screening for eye disease in selected groups (not the whole adult population), something that was considered a reasonable idea in a study done some time ago and has recently been revisited (Burr et al., 2007; Hamid et al., 2022). Such future work ought to consider the well-

reported complexity of estimating deprivation and SES (Stafford & Marmot, 2003). In fact, future studies ought to aim to untangle all the causes of people presenting at HES with advanced VF loss.

2.5 Conclusions

In summary, the likelihood of a patient presenting to glaucoma clinics in England with advanced VF loss is likely influenced by their level of multiple deprivation. Yet there is no evidence to suggest that their level of multiple deprivation is related to their glaucoma worsening whilst being managed by HES; this finding is both novel and reassuring. Our study and similar ones (Boodhna et al., 2015; Kelly et al., 2019) should act as motivation for others to use routinely collected data in eye clinics to assess aspects of eye health service delivery.

Chapter 3. Making better use of patients' time: Feasibility of performing self-administered vision assessments in waiting rooms

The other key aspect of this programme of work was to establish the feasibility of performing alternative testing to examine and monitor patients with age-related eye disease. This study aims to explore the feasibility of using this "wasted" waiting time by administering simple contrast sensitivity tests to patients with glaucoma while they wait in the waiting room for their appointment. A version of this study, prepared to journal specifications, was accepted for publication in the Journal Eye in August 2026. This work has been presented at invited talks for the Department of Optometry, SRM University, Chennai (November 2025), the Department of Ophthalmology, Advanced Research LLC, Florida (September 2025), and as a poster at the British Congress of Optometry and Vision Science, London (September 2024).

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Author contribution statement:

Rathore: Led the data collection and data analysis, contributed to the study design, prepared the original manuscript draft, edited the subsequent revisions, and was responsible for submission of the final version.

Founti: Study design, data collection, and manuscript review.

Rethi: Data collection.

Wulandari: Data collection.

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Scott: Ethical approval and study support.

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Crabb: Study design, funding acquisition, and project supervision

Jones: Designed the study, data analysis, manuscript editing, review, and project supervision.

Abstract

Patients often spend significant time in clinic waiting rooms. This study assessed the feasibility of using this "wasted" time to perform self-administered vision assessments, directly within the waiting area. Glaucoma patients attending routine appointments were asked to complete either a pen-and-paper (SpotChecks) or digital (PopCSF) contrast sensitivity (CS) test. Ambient illuminance, background noise, and crowd levels were recorded to assess potential environmental confounds. Test durations and patient feedback were recorded. Visual-Functioning Index-7 (VF-7), Pelli-Robson CS (reference) test results were collected for comparison. Of 173 patients approached, 155 (89.6%) agreed to participate, and 151(97.4%) participants completed testing before their appointment (77/78 pen-and-paper; 74/74 digital). Environmental factors had no significant impact (all $P>0.05$). Median completion times were 3.0 {2.6-4.5} minutes (pen-and-paper) and 2.5 {2.0-3.5} minutes (digital). Age did not impact the pen-and-paper testing times ($P=0.944$) but weakly correlated with the digital test ($r_{digital} = 0.27$, $P=0.020$). Functional CS scores correlated with the Pelli-Robson measurements ($r_{pen\text{-}and\text{-}paper} = 0.81$; $r_{digital} = 0.6$), age ($r_{pen\text{-}and\text{-}paper} = -0.58$; $r_{digital} = -0.37$), logMAR visual acuity ($r_{pen\text{-}and\text{-}paper} = -0.42$; $r_{digital} = -0.44$), and mean deviation scores ($r_{pen\text{-}and\text{-}paper} = -0.54$; $r_{digital} = -0.63$). Both tests were highly acceptable to patients (>80% on all questions). Visit durations were longer for participants (109 vs 88 minutes, $P=0.007$), but this was attributed to consenting and related research activities rather than the tests themselves. It is feasible for patients to self-administer portable CS tests in clinic waiting rooms. This approach may enable additional data collection, potentially improving patient management, clinic flow, and/or improving patient satisfaction.

3.1 Introduction

Ophthalmology patients often spend considerable time sitting in waiting rooms. For example, an audit in Ohio, USA, found that ophthalmology patients spend on average 80-106 minutes in waiting rooms, depending on whether trainees are involved or not (Goldstein et al., 2018). Also, Moorfields Eye Hospital (the UK's largest specialist eye centre) advises patients that: *"Depending on the number and type of tests you require, you might need to stay at the hospital or clinic for up to two or three hours"* (Moorfields Eye Hospital NHS Foundation Trust, n.d.). These waiting times are only likely to increase as populations age. In the UK, ophthalmology is already one of the busiest outpatient services, and the number of appointments is projected to rise from 7.5 million in 2022 to 9.0 million (a 20% increase) by 2030 (Association of Optometrists (AOP), 2023; NHS England, 2023, 2025).

Long waiting times are conventionally seen as a necessary burden, and are strongly associated with patient dissatisfaction (Arain et al., 2013; Bleustein et al., 2014; McMullen & Netland, 2013). However, we argue that they also present an opportunity, as this time could potentially be used to perform productive, clinically relevant activities. For example, prior studies have highlighted the possibility of using patient waiting time to collect quality-of-life questionnaire data, to educate patients about their general and eye health (Berkhout et al., 2018; Elley et al., 2014; Oermann, 2003; Taylor et al., 2024).

The present study aimed to assess the feasibility of conducting self-administered functional vision tests directly within clinic waiting rooms. Contrast sensitivity (CS) was selected for this initial pilot, as, unlike visual acuity, CS is not already routinely assessed and so might provide additional useful information ('European Glaucoma Society Terminology and Guidelines for Glaucoma, 5th Edition', 2021). CS tests are also less dependent on stimulus viewing distance, making them a pragmatic choice to use in spaces with a constrained floor area. A glaucoma clinic was chosen for this study because glaucoma services are among the busiest outpatient services [20% of all outpatient ophthalmology services (Harper et al., 2020)], and so any efficiency gains would have a sizeable impact. Note, however, that the focus of the current study was on the feasibility of self-administered vision testing in waiting rooms, not specifically on glaucoma management or the clinical utility of contrast sensitivity measurements.

3.2 Methods

3.2.1 Ethics:

This study was approved by the UK Health Research Authority (Reference number: #24/PR/0038 Research Ethics Committee 24/WS/0012) and adhered to the tenets of the Declaration of Helsinki.

3.2.2 Recruitment: Participants

3.2.3 The clinic and its workflow:

Data were collected between May and August 2024 at the Moorfields Eye Centre at Bedford Hospital (South), a busy tertiary eye department in suburban south-east England containing various sub-speciality clinics running in parallel. All testing was performed in the virtual glaucoma clinic. This technician-led four-hour clinic operates three times a week and typically sees ~87 patients/week (~29 per clinic). The waiting room has a seating capacity for ~70 people. (see **Supplementary**



for photographs of the waiting room).

Patients attending the clinic routinely undergo eye health history taking, distance visual acuity assessments (Thomson Test Chart, Thomson Software Solutions, UK), IOP measurements (Ocular Response Analyser, Reichert Technologies, New York, USA), visual field assessments (Humphrey Field Analyser, Zeiss, California, USA), and Optical Coherence Tomography (OCT, Topcon Medical Systems, Oakland, USA, and Carl Zeiss Meditec AG, Germany).

3.2.4 Study Inclusion Criteria:

Patients were screened for study eligibility a day before their appointment by the on-site research nurses (Authors RW and BR). Inclusion criteria were: a) suspected or confirmed glaucoma; b) attending a routine follow-up appointment; c) visual acuity of 6/18 in at least one eye; and d) the ability to provide informed consent. The better eye (in terms of visual acuity) was selected for the study, and the fellow eye was patched. If both eyes had equal visual acuity, the eye was chosen at random. No additional exclusion criteria were applied.

3.2.5 Study Protocol

3.2.5.1 Overview

Participants were randomly assigned a functional CS test to complete directly within the waiting room (i.e., patients remained seated in the chair they had originally selected upon entering the clinic). Half were given a pen-and-paper test: Spotchecks (Precision Vision, Woodstock, Illinois, USA). The other half were given a digital tablet-based test: PopCSF (Irida Health, London, UK). Details of both functional tests are given below. Participants were asked to wear their near vision spectacles during testing. During testing, we did not experience any further correction or reliability issues.

In addition, in order to check that the self-administered CS was completed successfully, all participants were also asked to perform a Pelli-Robson CS assessment at 1m distance for comparison (the Pelli-Robson chart being the closest approximation of a CS “reference” measure (Thakur et al., 2018)). Participants were questioned about their vision and its impact on their vision-related quality of life, using the Visual-Functioning Index-7 (VF-7) questionnaire (Uusitalo et al., 1999). This additional testing was completed in a small annexe which was spacious enough to include two chairs and a 90 cm (L) X 60 cm (B) table, and this annexe was located close to the waiting room. At the end of the session, participants were asked to rate the acceptability of the functional CS test using a custom survey comprised of nine questions (questionnaire provided in the Supplementary material, specifically section **9.1.1**).

3.2.6 PopCSF (The digital test)

PopCSF (**Figure 3.1A**) is a gamified tablet-based functional CS test, described previously elsewhere (Elfadaly et al., 2020). Participants were asked to "pop" these Gabor patches by pressing them. No strict viewing instructions were imposed (viewing distance was corrected for in near-real time using the tablet's integrated near-infrared distance sensor). The test was performed on an Apple iPad Pro 2 11" (Apple Inc., Cupertino, CA, USA). The primary outcome measure was the observer's contrast sensitivity function, from which we extracted the peak (G_{max}) expressed in units of log CS, for consistency with SpotChecks.

3.2.7 Spotchecks (The pen-and-paper test)

Spotchecks (**Figure 3.1B**) is a successor to a previously described CS test called "CamBlobs'" (Rijal et al., 2021). It consists of a single sheet of A4 paper containing dots of decreasing contrast. Patients are asked to mark the dots using a pen, and their sheet is scored based on the number of dots correctly identified. The primary outcome measure is LogCS score, for which a higher score is better, and a normally sighted person aged between 50 and 84 would be expected to score around 1.8 LogCS (Vu et al., 2024).

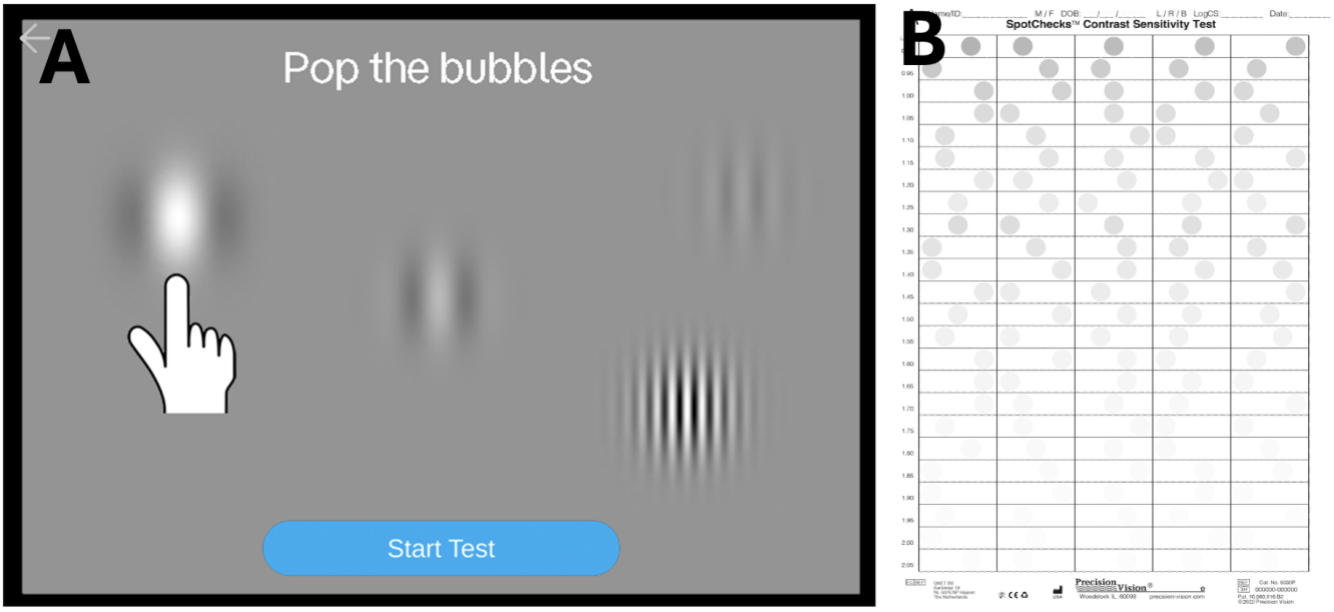


Figure 3.1. (A) Digital (PopCSF) and **(B)** Pen-and-paper (SpotChecks) CS measures. See the main text for descriptions of each.

3.2.8 Patient assessment-of-test acceptability

After testing, participants were asked to rate the acceptability of their randomly assigned test (PopCSF or SpotChecks) and of their overall waiting room testing experience, using a nine-item survey using a five-point Likert scale (5=strongly agree, **see Supplementary Material 9.1.1** for the complete survey).

3.2.9 Impact of the clinic's human and non-human environment:

Ambient illuminance in lux (Aoputtriver AP-881D; Zhuhai, Guangdong, China), auditory noise levels in dB_{SPL} (Type 2236 Sound Level Meter; Bruel and Kjaer, Denmark), and the number of other people in the waiting room were recorded to assess the possible impact of these environmental factors on the task. We also compared the total time taken for their visit ("visit duration") of participants and non-participants, who had similar arrival times and visit durations, using timestamps from the reception desk. Non-participants were defined as patients in the clinic who were not recruited into the study, either due to declining to participate or having not been approached due to limited research personnel.

3.2.10 Statistical Analysis

Analyses were performed using a combination of Microsoft Excel (Microsoft Corporation, Redmond, USA), GraphPad Prism Version 10.3.0 (GraphPad, Boston, USA), and R version 4.1.2 (R Foundation for Statistical Computing, Vienna, Austria). All data obtained were tested for normality using the Shapiro-Wilk test, and parametric or non-parametric assessments were applied accordingly. Completion rates and patients' clinical and demographic information (sex, ethnicity, age, diagnosis type, disease severity, and stability) were tabulated and compared between CS measures using parametric tests such as independent-samples t-tests or one-way ANOVAs, as appropriate. Differences in environmental factors (illuminance, noise, crowd) were compared using non-parametric tests such as the Mann-Whitney *U* test or the Kruskal-Wallis *H* test. The functional CS scores and clinical parameters were correlated using the parametric Pearson's correlation test. Visit durations were tested for statistical significance using the non-parametric Mann-Whitney *U* test. Acceptability proportions were compared using percentages and compared statistically using the Chi-square test. Statistical significance was set at $P<0.05$.

3.3 Results

3.3.1 Participant Profiles

Clinical and demographic data for all participants are given in **Table 3.1.** Most (69%) participants were 70 years or older, half (52%) were female, and most (72%) identified as White. At the time of their clinical appointment, most patients either had a diagnosis of primary open-angle glaucoma (28%) or were glaucoma suspects (28%), 35% did not show visual field damage, and 87% were considered stable by their consulting ophthalmologist.

3.3.2 Feasibility: Completion Rates

A total of n=173 patients were approached, of whom n=155 (89.6%) agreed to participate. Patients (10.4%) declined to participate due to several factors, including difficulty hearing, limited understanding of English, mobility concerns (i.e., consenting took place in a separate room, for ethical concerns), and undisclosed personal preferences.

Of the n=155 participants who agreed to participate, 151 (97.4%) successfully completed their assigned CS test. Specifically, 77/78 (98.7%) completed the pen-and-paper test, 74/74 (100%) completed the digital test, and 3 participants were called into their scheduled appointment before either CS test could be assigned. The one participant who failed to complete the pen-and-paper test did so due to limited comprehension of spoken English, which meant that they struggled to understand the test instructions.

3.3.3 Feasibility: Demographic factors

Table 3.1 presents the clinical and demographic information of the participants based on their current visit. No group differences in mean CS scores were observed between participants based on their sex (Mann-Whitney U test; $P_{pen\text{-}and\text{-}paper}$ =0.163, $P_{digital}$=0.072), ethnicity (Kruskal-Wallis H Test; $P_{pen\text{-}and\text{-}paper}$ =0.378, $P_{digital}$=0.381), or stability of their condition (Mann-Whitney U test; $P_{pen\text{-}and\text{-}paper}$=0.663, $P_{digital}$=0.793).

However, as one would expect, differences in mean CS scores were noted between participants based on their age (Kruskal-Wallis *H* Test; $P_{pen\text{-}and\text{-}paper}$ <0.001, $P_{digital}$=0.026), glaucoma severity (Kruskal-Wallis *H* Test; $P_{pen\text{-}and\text{-}paper}$ <0.001, $P_{digital}$=0.005), and diagnosis type (glaucoma, glaucoma suspect, etc.) (Kruskal-Wallis *H* Test; $P_{pen\text{-}and\text{-}paper}$ = 0.690, $P_{digital}$=0.006), though the latter only reached statistical significance for the digital test.

Table 3.1. Clinical and demographic information of the participants based on their current visit.

	Total (%) (N=151)	**Pen-and-Paper (N=77)**	**Digital (N=74)**
Sex			
Female	78 (52)	37 (27)	41 (25)
Male	73 (48)	40 (26)	33 (22)
Age (years)			
40-49	3 (2)	2 (1)	1 (1)
50-59	7 (5)	5 (3)	2 (1)
60-69	36 (24)	16 (11)	20 (13)
70-79	54 (36)	27 (18)	27 (18)
80-89	40 (26)	20 (13)	20 (13)
≥90	11 (7)	7 (5)	4 (3)
Glaucoma diagnosis of the tested eye			
Open-angle glaucoma	42 (28)	20 (13)	22 (15)
Angle-closure glaucoma	19 (13)	10 (7)	9 (6)
Glaucoma suspect	42 (28)	23 (15)	19 (13)
Awaiting diagnosis	22 (15)	12 (8)	10 (7)
Ocular hypertension	23 (15)	10 (7)	13 (8)

All other types of glaucoma	3 (2)	2 (1)	1 (1)
Ethnicity			
White / Caucasian	109 (72)	59 (39)	50 (33)
Indian	4 (3)	1 (1)	3 (2)
Black	3 (2)	2 (1)	1 (1)
Not specified	32 (21)	15 (10)	17 (11)
Mixed	1 (1)	0 (0)	1 (1)
East Asian	2 (1)	0 (0)	2 (1)
Glaucoma severity (HPA classification*)			
No visual field damage	53 (35)	26 (17)	27 (18)
Borderline	23 (15)	13 (9)	10 (7)
Mild	30 (20)	16 (11)	14 (9)
Moderate	25 (17)	14 (9)	11 (7)
Severe	15 (10)	5 (3)	10 (7)
Unreliable VF report	5 (3)	3 (2)	2 (1)
Glaucoma stability			
Stable	132 (87)	68 (45)	64 (42)
Unstable	18 (12)	8 (5)	10 (7)
Awaiting review	1 (1)	1 (1)	0 (0)

***HPA classification – Hodapp-Parrish-Anderson Criteria for glaucoma classification**

3.3.4 Feasibility: Resilience to environmental factors

We investigated the effects of illuminance, noise, and crowd levels in the waiting room to understand the potential impact of environmental factors on test performance. As shown in **Figure 3.2 [A], [B],** and **[C]**, none of these environmental factors had any significant impact on group mean log CS score, either for the pen-and-paper test or digital test (all P≥0.232; see **Supplementary Table 9.1** for statistics). There was also no difference in group mean CS scores based upon the time of day (morning versus afternoon, P=0.462).

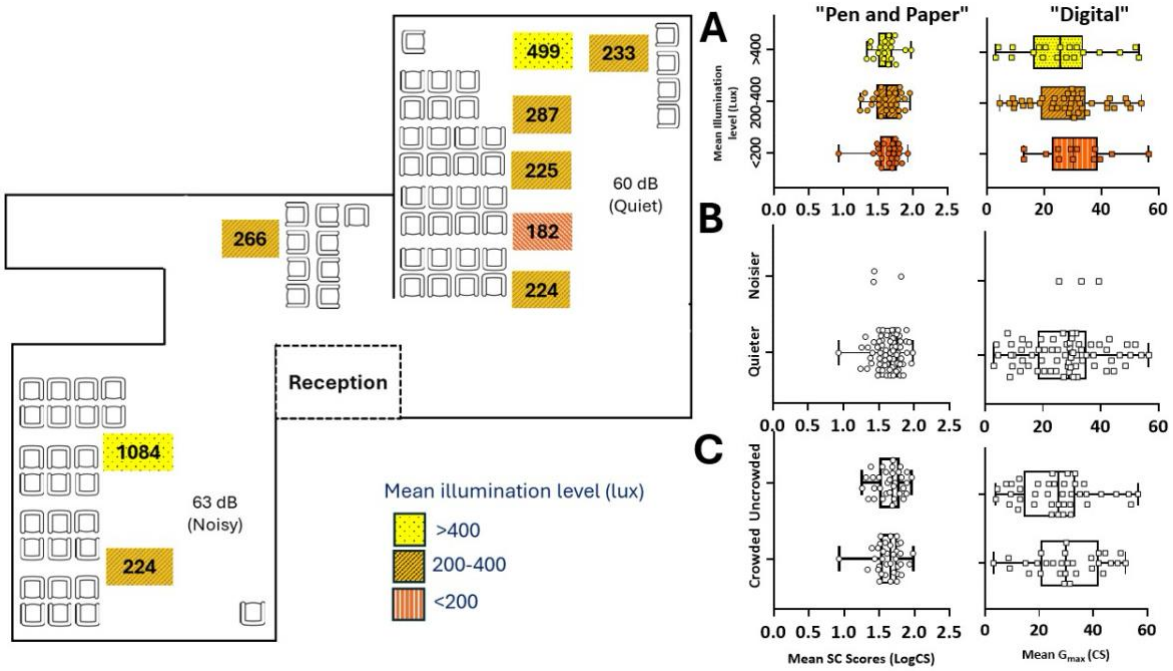


Figure 3.2. Resilience of the pen-and-paper (SpotChecks) and digital (PopCSF) functional CS test to differences in illuminance levels, auditory background noise and crowd size (number of other patients in the room). **(A) Illuminance:** The waiting room was divided into three zones: Zone 1 (< 200 lux), Zone 2 (200-400 lux), Zone 3 (>400 lux). **(B) Background Noise:** Most patients underwent testing on the right side of the waiting room, which had a mean noise level of 60 decibels. **(C) Crowdedness:** The number of people in the waiting room was recorded each time a patient performed the functional CS test. The waiting room was considered "crowded" when there were more people than the mean (nine people) during the test.

3.3.5 Feasibility: Correlation with the standard clinical tests

Figure 3.3 shows the correlations between each of the two CS tests and various other factors, such as the Pelli-Robson test, participant age, mean deviation scores (a visual field metric relevant in glaucoma), and distance logMAR visual acuity. The Pelli-Robson test, age, visual acuity in LogMAR, and mean deviation (in decibels) showed a statistically significant relationship with the two tests individually. Correlations were used instead of test-retest repeatability to compare the CS tests with Pelli-Robson, as we did not intend to clinically validate the two new methods. The correlations are perhaps a sanity check to see if the data can be meaningfully associated with the gold-standard Pelli-Robson test. The pen-and-paper test ($r_{pen\text{-}and\text{-}paper}$ *=0.81,* [CI_{95}: 0.71,0.88], *P*<0.001) correlated significantly more (z-statistic=2.36, *P*=0.018, Fisher's r-to-z test) with the Pelli-Robson than the digital test ($r_{digital}$*=0.62*, [CI_{95}: 0.45,0.74], *P*<0.001). Non-overlapping 95% confidence intervals and non-significant Fisher's r-to-z results across the other parameters (Age, VA, and MD) indicated no significant differences between the correlation coefficients of the two tests (all *P*>0.05).

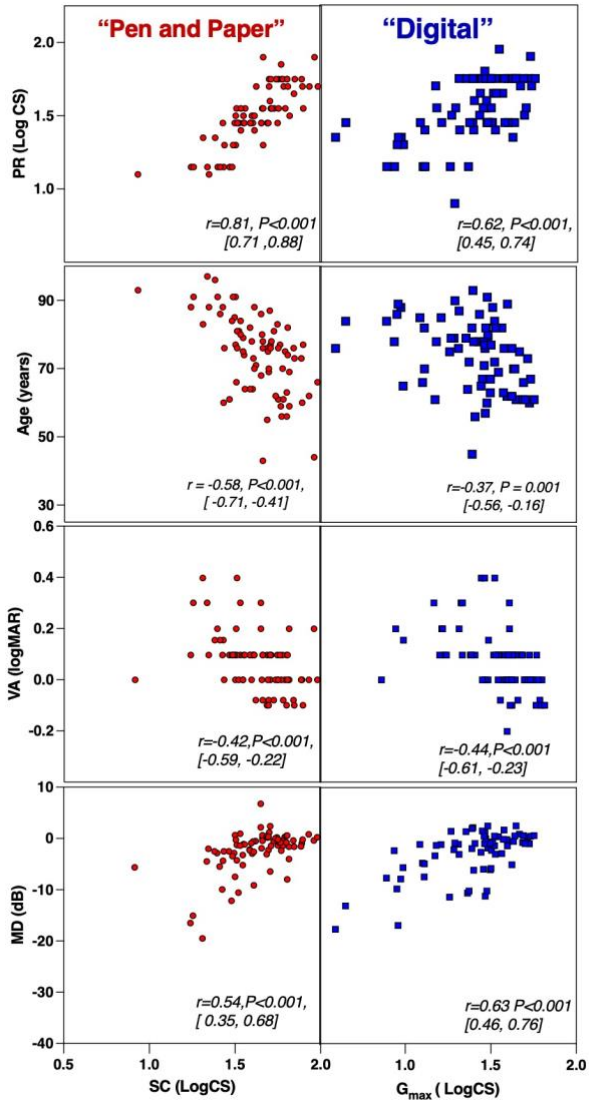


Figure 3.3. Correlations between the two waiting-room tests (pen-and-paper test and the digital test) with the current contrast sensitivity measure, the Pelli-Robson (PR) contrast sensitivity test, distance letter acuity (logMAR), age (years), and the visual field loss measure (Mean deviation [MD]). Numbers show the Pearson's rho coefficient (r), their 95% confidence intervals in square brackets and their respective P-values.

3.3.6 Feasibility: Patient acceptability

Patient feedback was largely positive. Most participants found both tests enjoyable (pen-and-paper/digital: 82%/81%) and understood the test well (99%/96%). When questioned about their experience in the waiting room, most felt comfortable (87%/92%) doing the tests in the waiting room and found it to be a beneficial use of their time (97%/95%).

For 4 of 5 acceptability questions, there was no significant difference between-subject ratings for the two tests (all *P*> 0.05, Chi-square). However, for the "ease to perform the test" statement, participants were more likely to agree that the pen-and-paper test was easy to perform (96%) than digital test users (84%, *P*= 0.011, *Chi-square test*, odds ratio: 4.79, [1.41,16.34]).

No adverse events were encountered for either test. Several patients anecdotally reported that they enjoyed speaking to someone and that the CS assessments were a welcome diversion. See **Supplementary Figure 9.2** for the graphical presentation of this data.

3.3.7 Costs: Time

Including time taken to explain how the test works, median {IQR} completion times were 3.0 {2.6-4.5} mins for the pen-and-paper (Spotchecks) test, and 2.5 {2.0-3.5} mins for the digital (PopCSF) test. Completion times for both were associated with visual-field mean deviation, logMAR visual acuity, and Pelli-Robson contrast sensitivity (all *P* >0.05). Age did not influence the pen-and-paper test duration (*P*=0.943). However, it showed a weak yet significant association with the digital test duration ($r_{digital}$ *= 0.27*, [0.05, 0.47], *P* =0.020). Based on linear regression (r^2*= 0.07, Slope = 0.84, Y-Intercept = 70.16*, *P* =0.020), test duration increased approximately 1 second/year, with an 80-year-old patient typically taking ~17 seconds (13.8%) longer compared to a 60-year-old patient.

To understand the potential impact of waiting-room testing on clinic flow, we analysed the total time of the patient's visit. **Figure 3.4** shows the median visit duration for both participants (109 minutes {IQR = 83.5-153}) and for patients who attended the clinic without participating in the study, i.e., non-participants (93 minutes, {IQR =67-154}). This difference was statistically significant (*P* =0.007), indicating that participants spent a longer duration in the clinic than non-participants. Retrospectively, after excluding the time taken for these research-related activities (consenting, the VF-7 questionnaire, the Pelli-Robson test, and the post-study patient assessment of test acceptability survey), there was no difference (*P*=0.562, Mann-Whitney *U* test) between the median visit duration of non-participants (93 minutes, {IQR =67-154}) and participants (Median=90 minutes, {IQR=67-132}).

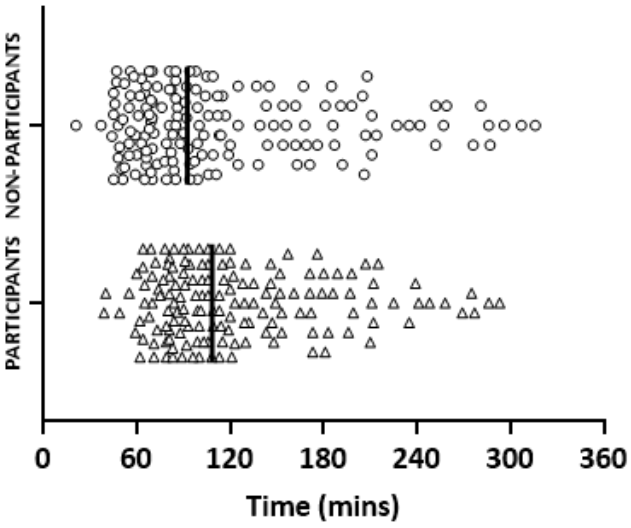


Figure 3.4. Total time spent in the clinic (visit duration) by study participants (triangles,109 minutes) and non-participants (circles, 88 minutes). Vertical black lines show the median time for each group. As described in the main text, the total time spent by the two groups differed significantly (P=0.007, Mann-Whitney U test).

3.4 Discussion

3.4.1 Summary of the study

This pilot study investigated the feasibility of utilising otherwise "wasted" time in ophthalmology waiting rooms to have patients self-administer additional vision testing. The results showed that both pen-and-paper and digital contrast sensitivity (CS) tests were quick (2.5 - 3 mins), could be feasibly completed by most patients (97.4% completion rate), were acceptable to patients (>80% positive feedback on all questions), and were relatively resilient to anticipated variations in illuminance, noise levels, and clinic crowdedness (all $P>0.05$). Encouragingly, the tests correlated with various demographic and clinical parameters, such as age, Pelli-Robson contrast sensitivity, visual acuity, and visual field mean deviation, suggesting the data may be clinically meaningful.

Conversely, 2.6% of participants were unable to complete the test (primarily due to a lack of time prior to the appointment), and 11.4% of patients in the waiting area declined to participate, in part for reasons relating to language barriers that might also have impeded their ability to do the tests. These are important feasibility barriers that would need to be carefully considered. The financial costs associated with these tests were also not trivial and would need to be carefully considered (see **Supplementary Table 9.2** on Financial Costs).

3.4.2 Comparisons with previous findings

Several healthcare-related studies have shown that time spent waiting for routine appointments can be utilised to benefit both patients and clinicians (Berkhout et al., 2018; Elley et al., 2014; Jones et al., 2021; Taylor et al., 2024). Within Ophthalmology, waiting time has been used in a study to educate patients about eye conditions (Oermann, 2003), specifically about glaucoma; however, the US-based study did not find any positive impact of that exercise on patient satisfaction regarding their visit (Oermann, 2003). Their study was conducted in the waiting rooms of general eye clinics and did not specifically target glaucoma patients. This suggests that patient satisfaction from an 'intervention' in the waiting area may depend on various factors, including the clinical setting, patient demographics, and the nature of the intervention.

Beyond ophthalmology, Spoladore et al. (2024) conducted a systematic review of “smart” waiting rooms, which included studies that focused on enhancing the waiting room experience and on pre-visit data acquisition, such as collecting vital-sign measurements (e.g., blood pressure, heart rate) in waiting areas (Spoladore et al., 2024). This review concluded that it was feasible to use waiting rooms as a data collection point, consistent with our present results. In particular, they found no significant safety or workflow barriers. However, they did acknowledge the organisational and integration hurdles, which is partially consistent with our study, as we had no safety, integration or organisational concerns, but our patients did take longer, ultimately impacting workflow. Similarly, studies performed in paediatric, obstetric and general hospital populations have shown that testing in waiting rooms is feasible, fast and acceptable by patients, provided patients receive adequate guidance (Ivaska et al., 2015; Tompson et al., 2019; Wagner et al., 2014).

We compared our CS test results with routine clinical data, such as visual acuity, MD, etc., to look for their clinical relevance in our sample of glaucoma patients. Both CS tests showed a better correlation with visual acuity than those reported by Hawkins et al. ($r_{127} = 0.57$, $P < 0.001$), who measured CS using the Pelli-Robson test in glaucoma patients (Hawkins et al., 2003). Both CS tests also showed a moderate correlation with MD, in agreement with existing literature on how CS is well associated with field defects in glaucoma patients (Burton et al., 2012; Hawkins et al., 2003; Jang & Lee, 2023; Richman et al., 2010).

3.4.3 Impact of the tests on clinical efficiency and waiting times

Hospital visit durations are often a measure of efficiency of the hospital and significantly influence patient satisfaction (Bleustein et al., 2014) and patient anxiety (Thu, 2015). However, our participants did spend longer on median in the clinic than non-participants, which raises concerns about efficiency. Patient-perceived waiting times are strongly correlated with the actual calculated waiting times but have a greater impact on patient satisfaction (Holbrook et al., 2016; Thompson et al., 1996). Luo (2017) and Chu et al. (2019) also highlight how interactive or health-related tasks can help improve the waiting experience (Chu et al., 2019; Luo, 2017). In reality, while it may not be possible to eliminate waiting time in clinics, converting passive waiting into brief, meaningful activities like quick vision tests may enhance patients’ care.

3.4.4 Financial costs

Hypothetically, we estimated that if one were to implement the digital tests and pen-and-paper tests in UK clinics routinely in the same way that they were administered in the present research study, this would cost the health service approximately £29,512 (digital) and £58,682 (pen-and-paper) per clinic. These costs (see **Supplementary Table 9.2** for a breakdown of our assumptions) were mostly due to staffing. Thus, in the present study, although the functional CS tests themselves were self-administered, a healthcare professional distributed the test, explained the procedure, and was available in case the patient had questions or experienced any difficulties. If, however, the tests could be administered entirely autonomously without the need of a designated health-care professional, the costs drop by 53% for the pen-and-paper test (£2.07 / patient) and by 93% for the digital test (£0.13 / patient). Against this, however, patients specifically expressed that part of what they enjoyed about the testing was having someone to speak to while they waited.

3.4.5 Limitations and Future Research

The study design was intended to be pragmatic and reflective of real-world conditions. Anecdotally, however, the clinic waiting room selected was relatively quiet and orderly. A multicenter trial would be required to generalise to other ophthalmology referral clinics, and it would not be reasonable to generalise to other clinical settings, such as general emergency clinics which often experience excessive noise, a lack of comfort and safety, and inadequate staff assistance when required (Innes et al., 2015; Kamali et al., 2013; Lovato et al., 2013; Welch, 2010).

Future research could focus on patient groups beyond glaucoma, identify the specific tests that provide the most valuable information for clinicians, systematically evaluate the impact of such testing on patient satisfaction, and/or conduct a comprehensive cost-benefit analysis. Our cohort of patients was also relatively enthusiastic (155 out of 174 of the approached patients agreed to participate) to engage with these tests, which may not always be the norm in other busy clinics across the country. Demographic variables such as sex, gender, etc., were chosen as they were easily available from the patients' medical records. However, in the future, it would be interesting to assess the impact of factors such

as the presence of a disability, socio-economic status, and literacy rates to gain a deeper understanding of socio-economic factors on the implementation of alternative methods of testing.

Although the costs associated with the implementation of such tests in the clinic were hypothetically explored, further research is required to understand the complete implications of implementing such a test in a routine clinic. Understanding the impact of such tests beyond pilot testing and on clinical workflow, staff management and appointment planning would be useful. Future work assessing the impact of high digital literacy rates on testing performance using digital tests, irrespective of their visual function, could also help judge the quality of the tests.

3.5 Conclusion

Testing in a waiting room using simple tests, like these functional CS tests, is feasible and can provide potentially valuable clinical data while patients wait for their appointments. These were acceptable to patients in a glaucoma clinic and could potentially support decision-making. Pursuing these tests incurs significant costs for the clinic; therefore, careful consideration, especially in terms of staff availability and resource assessment, is crucial before implementation. If integrated well in the clinical workflow, these tests may provide a way to provide additional data and potentially increase patients' satisfaction.

Chapter 4. Eyecatcher 3.0 – validating the use of "smartglasses" as a low-cost, portable method of assessing visual fields

Similar to Chapter 3, this chapter argues for the feasibility of performing alternative testing to examine and monitor patients with age-related eye disease, specifically glaucoma, here. This study aimed to evaluate the feasibility of self-conducting VF assessments in glaucoma patients from their respective homes, unsupervised, and in normally sighted adults under simulated home-like conditions. A version of this study, prepared to journal specifications, was published in the journal Translational Vision Science and Technology (TVST) in August 2025.

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Author Contributions

Rathore: Data collection, data analysis, manuscript writing and editing, and manuscript submission.

Reddingius: Data collection, data analysis, and manuscript editing

Campbell: Study design and data collection.

Crabb: Study design and acquired funding for the project.

Jones: Study design, formal data analysis (lead), manuscript writing and editing, and project supervision.

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Abstract

For this study, we used Eyecatcher 3.0, a novel, lightweight and low-cost test which uses smartglasses hardware that functionally attempts to mimic the HFA in some respects but has a smaller field of view and luminance range. Five patients with glaucoma used Eyecatcher to test themselves at home for 3 months. The test produced a reduced 24-2 grid that was compared to HFA data collected in the clinic, and to normative Eyecatcher data collected from 76 normally sighted young adults. A subset of normally sighted participants (n = 16) also underwent two additional sessions of follow-up testing to assess repeatability. Usability was assessed via questionnaires. Our results showed that all patients completed all Eyecatcher tests successfully, with a reasonable agreement with HFA in terms of mean deviation. However, the HFA exhibited better repeatability, although not statistically significant. The novel test took 6.5 minutes to test both eyes and was rated easy-to-use, although some specific concerns were expressed by some participants. Through this study, we concluded that this novel testing solution may provide a feasible way to pursue home-monitoring of visual fields because of its similarity to the HFA in some respects, portability, and ease-of-use. We did not explore its diagnostic and clinical utility in detail, which may require further research.

4.1 Introduction

Glaucoma is a leading cause of irreversible blindness worldwide, with 112 million cases expected by 2040 (Tham et al., 2014). It requires regular, lifelong monitoring (Crabb et al., 2014b). Every patient should receive a visual field (VF) assessment every 12 months (Stein et al., 2021), with some patients likely benefiting from additional, more frequent testing (e.g. 4 to 8 monthly (Anderson et al., 2017; Boodhna & Crabb, 2016; Gardiner & Crabb, 2002; Saunders et al., 2013; Wu et al., 2017). These requirements are often unmet, however. Many patients currently wait more than a year between appointments (Broadway & Tibbenham, 2019; Fung et al., 2013; Stagg et al., 2022), leading to instances of avoidable, irreversible sight loss (Foot & MacEwen, 2017; Healthcare Safety Investigation Branch, 2020). The lack of frequent monitoring is particularly concerning for the 3% (Saunders et al., 2013) to 15% (Heijl et al., 2013) of individuals with fast-progressing VF loss (i.e. −1.5 decibels [dB]/year or more).

The problem is a global one (Ahmed et al., 2020; Foreman et al., 2020; Founti et al., 2018; George et al., 2010; Stagg et al., 2022), and is only likely to increase as societies age. For example, in the United Kingdom (UK), the number of patients with glaucoma is forecast to double in the next 20 years (Harper et al., 2020), despite already accounting for over 1 million UK hospital outpatient appointments per year (Fu et al., 2023) (20% of the total ophthalmic workload).

Telemedicine, and, in particular, vision home-monitoring, has been suggested as a potential solution to the twin challenges of oversubscribed clinics and insufficient monitoring of high-need cases (Faes et al., 2020). Its proponents suggest variously that it might allow hospital appointments to be shortened (by collecting VF data in advance), to be reduced in frequency for low-risk patients, to be conducted remotely, or for additional “high-frequency” VF testing to be performed in newly referred or high-risk individuals. In addition, whereas telemedicine has historically been of niche interest in ophthalmology (Adams et al., 2018; Chew et al., 2014; Rathi et al., 2017), interest has surged, post-coronavirus disease (COVID), both within

glaucoma (Che Hamzah et al., 2020; Faes et al., 2020), and across other chronic eye conditions (Galiero et al., 2020; Ward et al., 2021).

Recently, we conducted a 6-month pilot of vision home-monitoring, using a tablet-based threshold perimeter (Eyecatcher 2.0)(Jones et al., 2021). Consistent with others (Prea et al., 2021), we observed a good association between VFs measured at home and in the clinic (MD correlation: $r = 0.94$, $P < 0.001$), and good adherence (98%). However, conversations with patients also raised practical concerns (Jones et al., 2021), including (i) the cost of the equipment; (ii) the size of the equipment (which patients found heavy and inconvenient to store/transport); (iii) a lack of control over viewing distance and ambient lighting; (iv) difficulties remembering to patch the fellow eye; and (v) difficulties connecting to the internet to upload/transmit data.

To address these practical challenges, the Eyecatcher visual field test was comprehensively redesigned to run on "smart glasses" (see Fig. 1). Unlike a conventional virtual reality headset, smart glasses consist of relatively ordinary-looking glasses with two integrated display screens (one per eye). They are often relatively light (70–200 g) and inexpensive (US $200 to $500) – owing to the fact that they rely on a connected smartphone/computer to provide all of their power and data-processing. There is no need for patching because stimuli can be presented independently to either eye. In addition, because the screens are effectively "fixed" to the patient's head, viewing distance and ambient lighting can be controlled precisely.

In this initial study, we assessed the feasibility of using novel smart glasses technology as a portable static threshold perimeter (Eyecatcher 3.0) by asking 5 patients with glaucoma to test themselves at home for 3 months and, for comparison, assessing 76 normally sighted young adults in the clinic.

4.2 Methods

4.2.1 Participants

Participants were 5 patients with glaucoma and 76 normally sighted young adults. As detailed in **Table 4.1**, the 5 glaucoma patients were aged 67 to 75 years (mean = 73 years), and all had an established diagnosis of stable glaucoma (MD loss/year < 2 dB, as confirmed

by at least 4 years of Humphrey Field Analyser [HFA] data). Due to the smaller sample size and availability of data, a less-stringent definition of stable glaucoma was chosen for our methodology when compared to Chapter 2. In hindsight, a uniform decision would have further supported the methodology of the thesis. The ability to perform standard automated perimetry (SAP) reliably was not an inclusion criterion. However, as shown in **Table 4.1**, all patients did, in practice, show low false positive/negative response rates. Reliability metrics were employed to ensure accuracy in the normally sighted participants, as the cohort was unfamiliar with the test.

The 76 normally sighted participants were aged between 18 and 30 years (mean = 21 years) and were recruited from a university research database. Normal vision was defined as: (i) distance monocular visual acuity ≤ 0.2 logMAR (as measured at 3 m using an Early Treatment Diabetic Retinopathy Study [ETDRS] letter chart; Precision Vision, Woodstock, IL, USA); (ii) distance monocular contrast sensitivity ≥ 1.50 logCS (as measured at 1 m using the Pelli-Robson chart; Precision Vision, Woodstock, IL, USA); (iii) VF within normal limits (as measured using the HFA, running 24-2 SITA Fast; Carl Zeiss Meditec Ltd., Dublin, CA, USA); and (iv) no self-reported eye conditions. Two additional people were screened but were excluded from the study (*n* = 78 screened). The refractive error of patients and participants was documented through their previous prescriptions or by measuring the dioptric power of their current spectacles using a focimeter on the day of the experiment.

The study was approved by the Ethics Committee of City, University of London (#ETH2021-2265/2105) and adhered to the tenets of the Declaration of Helsinki. Patients with glaucoma were entitled to travel expenses. Normally sighted participants received a £10/hour compensation for their time.

Table 4.1. Glaucoma patient clinical characteristics. As described in the Results, participant 014 did not complete the final HFA evaluation because of an injury that prevented them from attending their final appointment. (POAG = Primary Open Angle Glaucoma, PACG = Primary Angle Closure Glaucoma).

Glaucoma Patients' Characteristics

			Optical Prescription, Mean Spherical Error		Mean HFA MD, dB					
					Visit 1 (pre)		Visit 2 (Post)			
Study ID	Age, Y	Diagnosis	OS	OD	OS	OD	OS	OD	FP%	FN%
003	69	PACG	−0.50	−0.63	−26.3	−5.9	−27.1	−5.2	1.6	3.6
004	75	POAG	−2.00	−0.50	−3.0	−0.1	−4.4	−2.4	7.9	8.5
010	75	POAG	−6.50	−5.00	−13.1	−11.4	−11.4	−10.4	1	1.8
014	70	POAG	0.25	−0.25	−8.5	−20.3			0.8	3.8
017	72	POAG	−0.75	−1.00	−10.7	−24.0	−9.6	−22.9	1.1	1.9

PACG, primary angle closure glaucoma; POAG, primary open angle glaucoma.

As described in the Results section, participant 014 did not complete the final HFA evaluation because of an injury that prevented them from attending their final appointment.

HFA MD, dB indicates the mean MD value from two HFA tests (see Figure 2 for protocol). FP% and FN% indicate the false positive and false negative values, averaged across all HFA assessments for both eyes ($n = 8$ for all but participant 014).

4.2.2 Overview of the Novel Eyecatcher Device

As shown in **Figure 4.1A**, Eyecatcher 3.0 is a head-mounted perimeter incorporating inexpensive "XReal Light" smart glasses (XReal Inc., Beijing, China). It is being developed by Irida Health Ltd. (a spin-out from City, University of London) but is not yet commercially available.

As per conventional SAP, the user is asked to fixate on a central light and press a button when a target (Goldmann III spot; ⌀ = 0.43 degrees) of varying luminance and spatial location is seen. Target intensity is varied trial-by-trial using a custom maximum likelihood algorithm. The exact details of this algorithm are proprietary, but it essentially consists of a modified QUEST+ (QUaternion ESTimator) procedure (Watson, 2017), which is, in turn, a more sophisticated/generalised superset of the familiar ZEST (Zippy Estimation by Sequential Testing) perimetric algorithm (Anderson & Johnson, 2006). As shown in **Figure 4.1B**, the output is similar to that of the HFA and includes patient details, reliability indices, greyscales, total/pattern deviation plots, and various summary metrics, including mean deviation (MD). False positive and false negative response rates were assessed using explicit minimum-/maximum-luminance stimuli (i.e. as per historic SAP, before these trials were removed in commercial perimeters to save time (Tan et al., 2025)).

In this study, the background luminance was fixed at 10 cd/m^2 and targets were 200 msec Goldmann III white circles, arranged on a reduced 24-2 test grid (see Fig. 1C). Bitstealing (Tyler, 1997) was used to achieve greater-than-10-bit luminance precision, and the luminance of each pixel of every display was individually calibrated using a custom-made robotic optical system designed for imaging inside head-mounted displays. Note that whereas smart glasses typically allow the external environment to remain visible (i.e. with the screen outputs superimposed onto the outside world as a "head-up display"), for our purposes, we fitted a light-weight plastic occluder to the front of the glasses. This blocked all incoming light from the front and partially prevented light ingress from the sides, also allowing the adapting luminance of 10 cd/m^2 to be maintained. Magnetic insert lenses (**Figure 4.1D**) were used as required to correct for refractive error (at 2 m – the projected distance of the images on the screen). The magnetic frames housing the lenses were manufactured by XReal (XReal Inc., Beijing, China), whereas the lenses themselves were manufactured by Essilor (Essilor International, Paris, France). These lenses were used to correct for Spherical Equivalent (SE) refractive error, in 0.5 dioptre steps from -6 to +6 dioptres. Outside of this range, the users would be required to wear contact lenses, similar to the HFA, although in practice, this did not occur during the study. No further correction or reliability issues were noted with the method of correction. During the test, verbal encouragement and instruction were provided by a speech synthesiser via speakers embedded in the glasses. This encouragement consisted primarily of generic phrases ("keep it up," and "doing well") selected at random intervals (constrained to occur no more than once per minute), as well as important temporal information (e.g. "test starting in 3..2..1..," and "about 1 more minute to go"). Additional feedback based on the pattern of user responses (e.g. if no button was pressed for over a minute, or other anomalous behaviours were detected) was also available, but was seldom, if ever, triggered.

With Eyecatcher, either one eye can be tested monocularly (as per the HFA), both eyes tested monocularly (interleaved), or both eyes tested binocularly. In the present study, controls were tested monocularly (single eye only), whereas both eye monocular testing was used in patients, with the test eye alternating trial-by-trial **(Figure 4.1E).** Note that on any single trial, the user is unaware of which eye the target was presented to, obviating any psychological effects from knowing that the better/worse eye is currently being assessed. No

patching was used, as stimuli were presented independently to each eye, with negligible light leakage between the two.

Target Δ Luminance (increment from background) varied from 0.1 to 140 cd/m^2 (i.e. 10.1 to 150 cd/m^2 in absolute luminance). This corresponds to 13.6 to 45 dB on the HFA decibel scale, and, for ease of comparison, all data in the present manuscript are reported in the HFA dB scale. Note that this means that due to the limited dynamic range of the smart glasses, very intense stimuli could not be presented (NB: for comparison, the maximum intensity of the HFA is 3183 cd/m^2).

The gamma function was approximately 2.2. However, note that, in accordance with best practices (and to account for local irregularities in the input-output function), we did not use a gamma function to calibrate the luminance output of the glasses. Instead, a brute force approach was used in which the luminance output for every possible input level was measured empirically for every pixel of each display of every headset. This calibration was performed using a custom-built robotic test rig, which was itself calibrated using an integrating sphere with an in-built photometer (Labsphere Inc.; North Sutton, NH, USA). During the course of the study, patients who took the device home were not expected to do any additional calibration procedures during the study period.

In addition, note that given the limited field of view (FoV) of the glasses (W × H = 45 degrees × 25.5 degrees), the most peripheral of the 30 locations on the 24-2 grid were not presented, and testing was restricted to the reduced 24-2 grid shown in **Figure 4.1C**. This is a significant limitation of the hardware, although one that may reduce over time as newer screen technologies are developed (discussed further in section 3.4. Discussion).

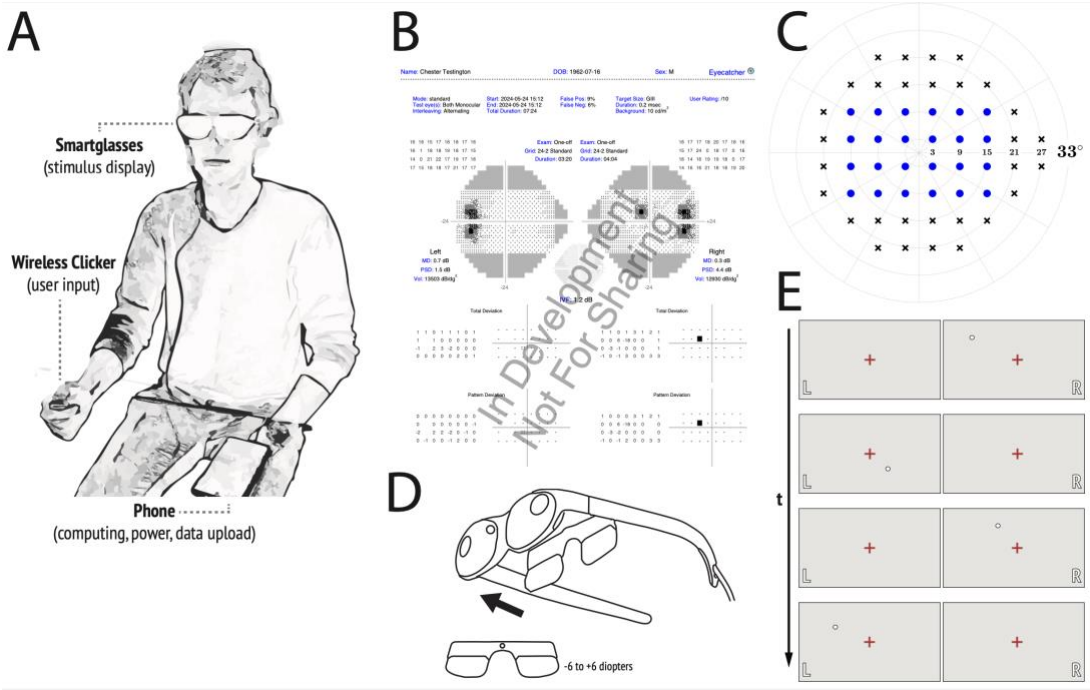


Figure 4.1. Eyecatcher 3.0.**(A) Hardware:** Eyecatcher ran on an Android smartphone connected to a wireless clicker and a pair of XReal Light smartglasses. **(B) Output**: example .pdf printout from the Eyecatcher device, showing the data from both eyes together. (**C) Test grid**: The subset of the 24-2 grid assessed. **(D) Optics**: magnetic lens inserts were used to correct for spherical error, as required. **(E) Test eye interleaving**: the target was presented alternately to each eye.

Finally, note that the screens within the smart glasses are flat, unlike the conventional SAP bowl (a “tangent perimeter”). The target stimuli were therefore warped in software to be invariant in size and shape across the VF. However, this correction was applied only for mathematical completeness. Given the limited FoV, the required changes to the stimuli were minimal, and it is unlikely that the results would be measurably affected if this correction had not been applied.

Unlike newer models released subsequently, the XReal smart glasses used in the present study assumed a fixed interpupillary distance (IPD) of 63 mm (with an anecdotally reported tolerance of approximately ± 8 mm). Because IPD could not be adjusted, it was not measured for participants, and to the extent that participants differed in their true IPD, this may have contributed to random or systematic measurement error. A crude workaround was implemented in which patients could manually adjust the horizontal placement of the fixation cross. However, in practice, this feature was not used, as no participants reported,

when questioned, any difficulty fusing the fixation cross. Newer smart glasses allow IPD to be adjusted to each user, although this customisation would add some additional time to the overall test duration.

4.2.3 Study Protocol

4.2.3.1 Overview

As shown in **Figure 4.2,** the 5 patients with glaucoma were each given an Eyecatcher device (see **Supplementary Figure 9.3** for the hardware and case provided) to take home for 3 months and were asked to test both eyes, monocularly, once every 2 weeks (6 tests total per eye; and 12 tests total per patient). Patients were given a short, informal demonstration of the device in the clinic, but all testing was performed at home, unsupervised. No reminders were issued, although in practice, all patients successfully completed the regimen. Meanwhile, the 76 normally sighted participants were tested only once, in the clinic (better eye only, as determined by visual acuity). A subset of 16 healthy controls was also invited for a follow-up in which 2 further Eyecatcher tests were performed, 1 month apart, in order to assess test-retest variability.

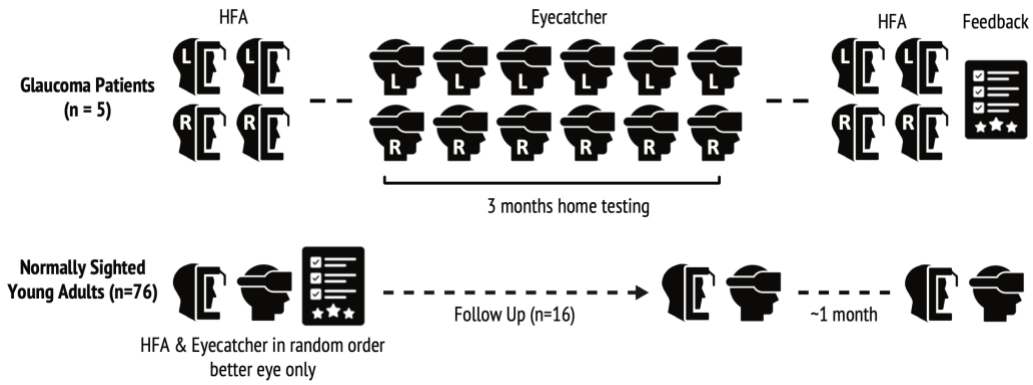


Figure 4.2. Testing protocol. Patients performed 3 months of home testing, with in-clinic HFA assessments before and after. Both eyes were tested monocularly. Normally sighted healthy controls were tested in the clinic only, with only one eye assessed once, although a subset of 16 healthy controls also repeated the test twice at a later date, to assess test-retest repeatability. These retests were performed in separate sessions, the first occurring around 2 months after the main study, and the second 1 month later.

4.2.3.2 Humphrey Field Analyser Reference Measures

Reference measurements were made with the HFA (Carl Zeiss Meditec, Dublin, CA, USA), using a 24-2 grid, the SITA Fast (Artes et al., 2002) algorithm, and the same background level and stimulus size/duration as Eyecatcher (10 cd/m^2 background, 200 msec Goldmann III targets). SITA Fast was used rather than SITA Standard, as SITA Fast exhibits only marginally lower reliability (Tan et al., 2025) and has become the de facto standard in many clinics.

As shown in **Figure 4.2**, patients performed two HFAs in each eye, directly before and after the home monitoring period (4 HFAs per eye, total). In the healthy controls, HFA measurements were made on the same day as Eyecatcher, with the order of Eyecatcher and HFA randomly counterbalanced between participants.

4.2.3.3 Usability Feedback

At the end of the study, the five patients with glaucoma were asked to provide feedback regarding the usability of Eyecatcher via the System Usability Scale (SUS)(Brooke, 1996). The SUS is a well-established, general-purpose, Likert-based questionnaire for assessing the perceived usability of digital technologies, comprised of 10 statements including “I felt very confident using the system” and “I think I would need the support of a technical person” (full

list is provided in the **Supplementary Table** 9.3. Breakdown of raw patient responses using the System Usability Scale (SUS).

The 76 healthy controls were also asked about usability, but due to time constraints, they were not given the SUS and were instead given 5 Likert statements ("I found the test... enjoyable, easy to perform, tiring, hard to concentrate on," and "I understood the test well").

4.3 Results

4.3.1 Completion Rates

The Eyecatcher completion rate was 100% for all participants (including the 60 Eyecatcher tests performed at home by people with glaucoma, unsupervised), with no adverse events encountered. Notably, the HFA completion rate was 99% (across all patients and controls) as one patient was unable to attend their final appointment due to injuries sustained in a minor road accident. (The Eyecatcher test equipment was instead mailed back, and the patient debriefed over the phone.)

4.3.2 Accuracy (Correlation with Reference Measures)

As shown in **Figure 4.3**, Eyecatcher and HFA MD values were significantly correlated (Pearson's Correlation = $r_{116} = 0.85$, $P < 0.001$), with 80% of MD values differing by 3.6 dB or less. The correlation was $r_8 = 0.78$, $P = 0.008$ if just considering the 10 glaucomatous eyes. Across all eyes, the intraclass correlation coefficient (ICC) 95% confidence interval (95% CI) was r = 0.78, 95% CI = 0.70–0.84.

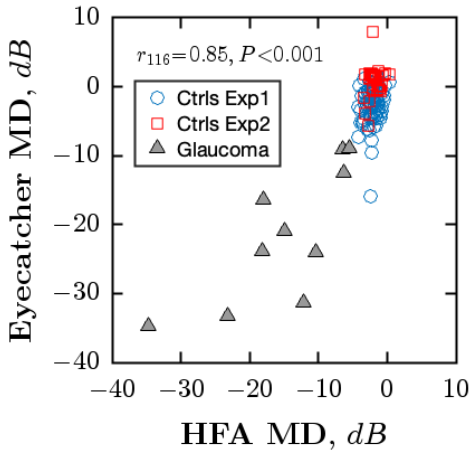


Figure 4.3.Scatterplot showing Pearson correlation between Eyecatcher and HFA, in terms of mean deviation (MD). Markers represent mean MD values for individual eyes (grey triangles = 5 patients with glaucoma tested at home; blue circles = 76 controls; and red squares = 16 follow-ups). Note that the raw Eyecatcher values were rescaled to be in the HFA dB scale, as detailed in the Methods section.

At the pointwise level, 80% of individual points differed by 6.3 dB or less (median absolute difference = 2.8 dB), and concordance in the pattern of loss is evident by inspection of the raw greyscales (see **Figure 4.4**). Although imperfections can also be observed (e.g. the exaggerated inferior field loss in patient 004's right eye, or the inferotemporal defect in patient 017's right eye). Some eyes also appeared to exhibit a somewhat more constricted field versus the HFA (e.g. patient 003 OS and patient 017). In part, that may be an artefact of the smoothing that is applied when producing the greyscales, although we cannot rule out other causes, including perceptual effects (e.g. rim artefacts from the lens inserts), cognitive/attentional effects (for points falling close to the visible boundary of the display), or calibration errors in the far periphery. In addition, evident in **Figure 4.4** is the reduced spatial extent of the Eyecatcher visual field (due to limitations of the present hardware).

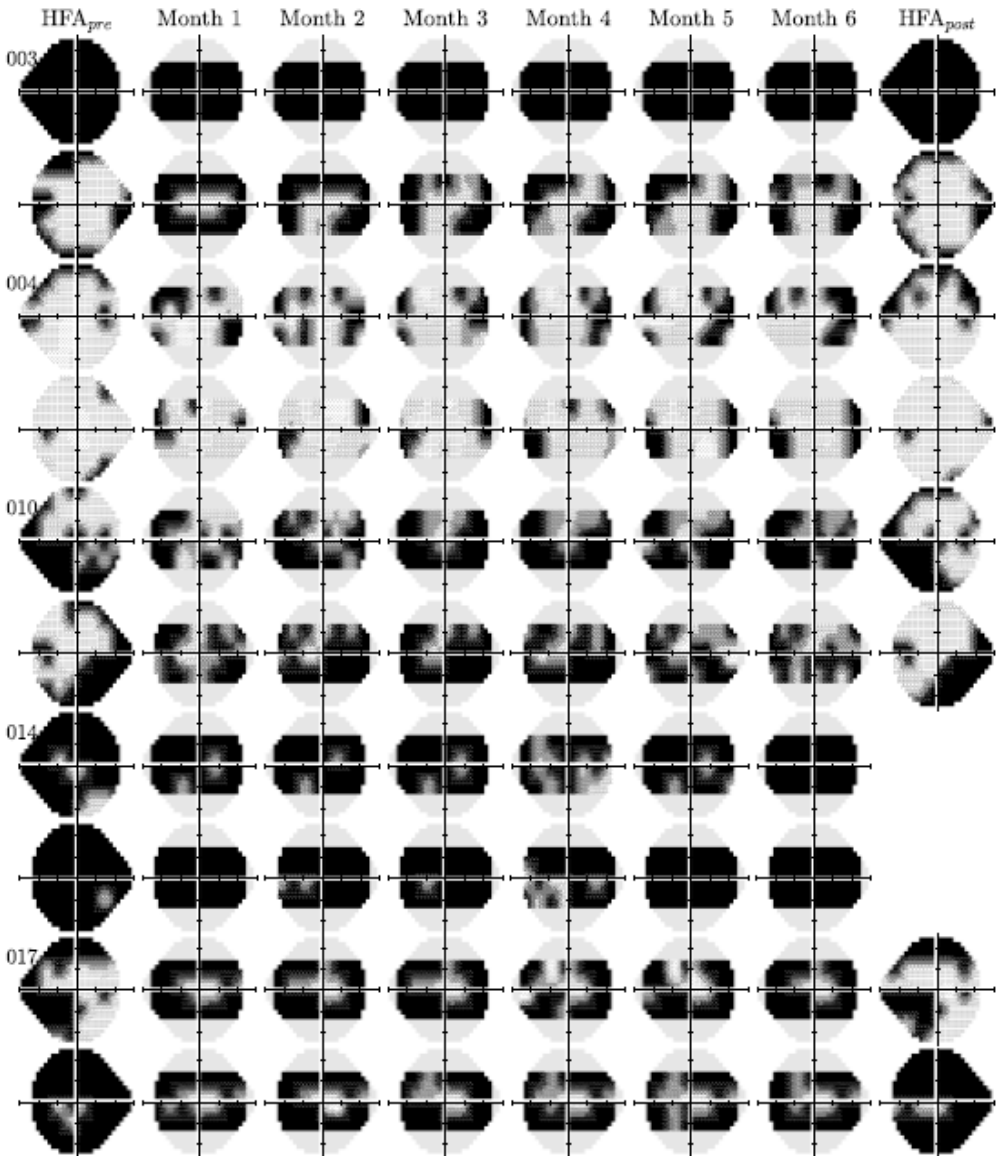

HFA$_{pre}$
Month 1
Month 2
Month 3
Month 4
Month 5
Month 6
HFA$_{post}$
003
004
010
014
017

Figure 4.4.All of the visual field greyscales generated by patients with glaucoma (n = 10 eyes). Each individual was asked to perform the Eyecatcher tests once every 2 weeks, at home, unsupervised (6 tests total per eye). The first and last columns show the HFA data, before and after the Eyecatcher test period (mean of 2 tests performed on the same day). Participant #014 was unable to attend his final HFA assessment due to an injury (see main text). Note that for ease of comparison, the HFA greyscales have been "thresholded," such that all pointwise values lower than 13.6 dB (i.e. outside of the Eyecatcher's dynamic range) have been set to 0. The raw, unadulterated data can be seen in the Supplementary material **(Supplementary Figure 9.4)**

As would be expected, MD significantly differed between tests from patients with glaucoma and healthy controls ($t198 = 22.85$, $P < 0.001$), and there was near-perfect separation between eyes with mild/no visual field loss and those with pronounced visual filed loss – with an Area Under the Receiver Operating Curve (AUROC) of 0.99, 95% CI = 0.95 to 1.00, AUROC = 0.99, 95% CI = 0.96 to 1.00, and AUROC = 1.00, 95% CI = 1.00 to 1.00, when separating eyes with mild/no VF loss (MDHFA > –5 dB) from those with moderate (MDHFA = –5.01 to –11.99 dB), advanced (MDHFA = –12.00 to –19.99 dB), or severe (MDHFA ≤ –20 dB) VF loss, respectively. This should not, however, be taken to indicate that Eyecatcher is perfectly capable of detecting glaucoma. Careful inspection of Figure **4.4**, for example, shows a relative absence of patients with mild/early visual field loss in our sample, and even in our cohort of patients with mid-to-late-stage glaucoma, 3% of the healthy controls exhibited a poorer MD than the best-performing patient (MD = –7.2 dB).

4.3.3 Reliability (Test-Retest Repeatability)

Figure 4.5 shows test-retest repeatability (of MD) for both Eyecatcher and the HFA, as measured in patients with glaucoma and the 16 follow-up healthy controls. The 95% CI was smaller for the HFA (2.9, 95% CI = 2.1–4.1 dB) than Eyecatcher (3.9, 95% CI = 2.8 – 6.1 dB), indicating that the HFA produced somewhat more reliable, consistent data. However, Eyecatcher's repeatability value fell within the HFA's 95% CI, meaning that this difference was not statistically significant ($P > 0.05$).

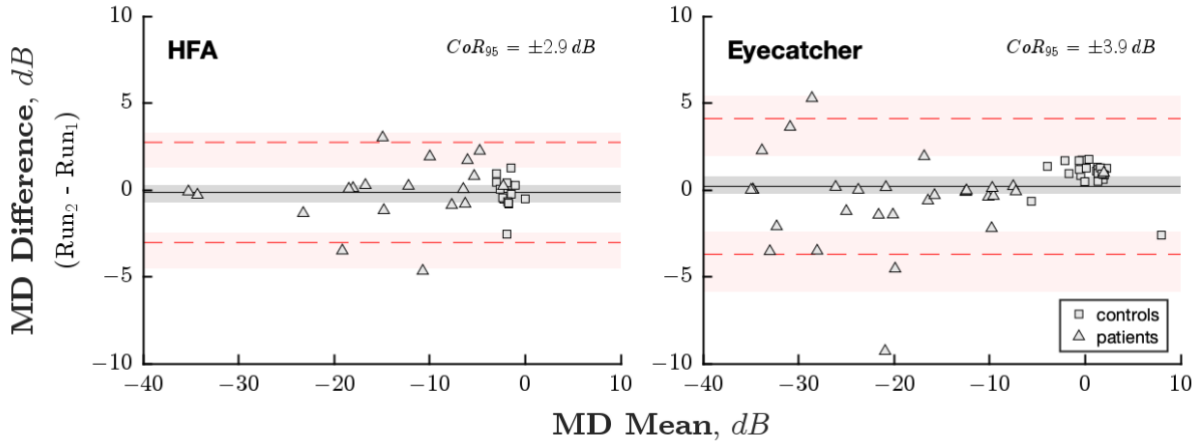


Figure 4.5. Bland-Altman plots depicting the test-retest repeatability of the HFA (left) and the Eyecatcher (right).Markers represent individual eyes from controls (squares; n_{HFA} = 16, n_{Eyc} = 32) and patients (triangles; n_{HFA} = 18, n_{Eyc} = 30). The solid horizontal lines show the bias (mean difference [MD]) in MD values. The dashed horizontal lines show the 95% limits of agreement (1.96 standard deviations [SDs] from the mean). The shaded regions denote 95% confidence intervals, derived using bootstrapping (N = 20,000; bias-corrected and accelerated method). Note that for the Eyecatcher, when analysing the patients, differences were computed between each successive pair of home tests.

4.3.4 Test Durations

For patients with glaucoma, the median (quartiles) total time taken to test both eyes was 8.9 (8.4-9.6) minutes for the HFA, and 6.5 (6.2–6.9) minutes for Eyecatcher (**Figure 4.6**). This difference was significant (Mann-Whitney *U* test; $Z = 6.33$; $P < 0.001$), even without taking into account the additional time required by the HFA to physically swap over the test eye (an additional 1–2 minutes on average), or the fact that Eyecatcher included false-negative ("easy") catch trials. However, this is to be expected, given that the HFA test grid included almost twice as many test locations (32 vs. 54). In contrast, in healthy controls, the median (quartiles) test duration was faster ($Z = -11.76$, $P < 0.001$) for the HFA (3.1 (2.8–3.3) minutes) than Eyecatcher (3.7 (3.6–3.8) minutes), even despite the additional test locations, indicating that SITA Fast is remarkably well optimised for normally sighted eyes. Note, however, that this difference of approximately 40 seconds is substantially smaller, for example, than the time that was required to seat the control participants and explain the HFA test procedure in the present study (median [IQR] = 141,[155] seconds), suggesting that the difference in test

duration may be relatively small in practical terms. Overall, these data indicate that the two tests are broadly similar in speed.

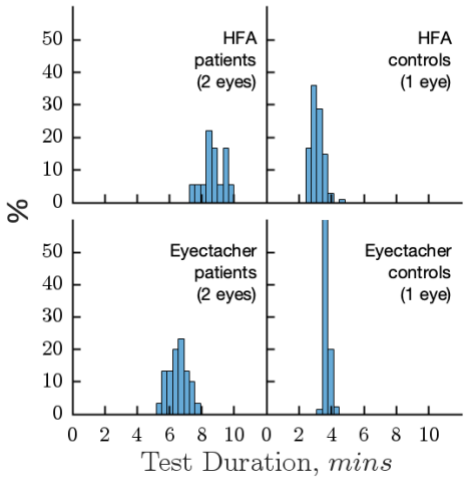


Figure 4.6.Histograms showing the distribution of test duration for the Eyecatcher and the HFA. Note that patients tested both eyes (monocularly), and the combined time for both eyes is given. Controls only tested one eye. In total, patients completed 18 pairs of HFA assessments and 60 pairs of the Eyecatcher assessments, whereas healthy controls completed 76 single-eye HFA assessments and 152 single-eye Eyecatcher assessments.

4.3.5 Usability

The median SUS score for patients with glaucoma was 93 of 100, with individual patients giving SUS scores of 93, 100, 93, 45, and 68. For context, a score above 80 is generally considered an “A” (very easy to use), whereas a score below 50 is an “F” (very hard to use). Thus, the data indicate that most, but not all, patients found Eyecatcher very easy to use. A complete breakdown of answers is given in the **Supplementary Table 9.3**. All patients reported that they would not need technical assistance to operate the system and that most people would learn to use it quickly, but some patients found visual field testing cumbersome and would not like to perform it frequently.

Most of the young-adult normally sighted group reported that they understood the test well (82.9%) and that it was easy to perform (59.2%) and enjoyable (59.2%). Although 31 (40.1%) and 28 (36.8%) people stated that the test was hard to concentrate on and tiring, respectively (see **Supplementary Figure 9.5**). Note that due to an oversight, equivalent ratings were not elicited for the HFA, so no direct comparison between the devices can be made.

4.4 Discussion

This study demonstrates the feasibility of using a portable, smart glasses-based perimeter (Eyecatcher 3.0) to assess glaucomatous visual fields at home, unsupervised ("telemedicine").

4.4.1 On the Use of Smart Glasses

Head-mounted displays (HMDs) confer several benefits over conventional bowl perimeters (e.g. control over ambient lighting and viewing distance, no need for patching, reduced size and weight, easier transport, and better accessibility). In addition, several previous groups have investigated the use of HMDs for assessing VFs (Goukon et al., 2019; Griffin et al., 2024; Johnson et al., 2023; Pradhan et al., 2021; Razeghinejad et al., 2021; Wakayama et al., 2019; Wong et al., 2023). However, the present study is one of the first in which patients have used such a device at home, unsupervised (Berneshawi et al., 2024; Hu et al., 2023) and the first to use low-cost smart glasses as opposed to conventional virtual reality displays.

Because the smart glasses draw their power and computing over USB from an attached device (smartphone/computer), they are substantially cheaper and lighter than conventional virtual reality headsets. For instance, the smart glasses used in the present study retailed for US $399 at the time of writing (similar to the cost of 1-to-2 years' worth of topical glaucoma medication in many countries (Buys et al., 2021; Feldman et al., 2020; Fu et al., 2023), and weighed approximately 125g – over 3 times lighter than, for example, the Meta Quest 3 (Meta, Menlo Park, CA, USA; 513g) and other similar HMDs used previously by other groups (Chen et al., 2022; Griffin et al., 2024; Terracciano et al., 2023). The Eyecatcher software also benefits from other features that set it apart from other devices, including individual-pixel luminance calibration, 10-bit luminance control, refractive correction via lens inserts, 5G cloud synchronisation, DICOM connectivity with electronic medical records, and compatibility with the Open Perimetry Interface (Turpin et al., 2012).

4.4.2 Agreement With Previous Literature

In terms of test performance, the level of association for global measures of sensitivity observed between the HFA and Eyecatcher (r = 0.83) was similar to that reported for other portable perimeters, such as the Melbourne Rapid Fields (r = 0.85)(Prea et al., 2021) and

Olleyes VisuALL (*r* = 0.5–0.8 depending on the participants) (Razeghinejad et al., 2021). Agreement was lower, however, than reported previously, using an earlier, tablet-based iteration of Eyecatcher (r = 0.94)(Jones et al., 2021). This change was not entirely unexpected. In part, it may reflect a change to new, faster algorithms (test durations were approximately 50% faster in the present study). It may also reflect the transition from tried-and-tested hardware to an entirely new form of displays (waveguided smart glasses' panels) that present substantive new challenges in terms of stimulus calibration and head positioning.

In terms of glaucoma vision home-monitoring in general, the present study indicated that at least some patients are able and willing to perform VF testing at home (and notably, one was able to do so even when too injured to attend in-person for an HFA assessment). The adherence rate of 100% reported in the present study is marginally higher than the 97% to 98% reported by ourselves and others previously (Jones et al., 2021; Prea et al., 2021). However, all of these numbers likely overestimate how telemedicine would really fare in routine clinical practice (i.e. owing to the highly selective nature of research volunteers). Pending a formal randomised clinical trial (RCT) of ophthalmic telemedicine, we believe that somewhat more realistic insight can be found in Bianchi et al., where 233 random patients with cataract were mailed a pen-and-paper test to complete at home, to which 108 patients (46%) responded (Bianchi et al., 2024). A small Eyecatcher learning effect was observed in the healthy controls, and this too is broadly consistent with previous data (Kang et al., 2023; Prea et al., 2022).

4.4.3 Limitations and Future Work

Regarding Eyecatcher itself, the device is limited by the small size of the screen (precluding assessment of the full 24-2 grid) and the limited luminance range (precluding quantification of very deep scotomas). These limitations will likely be mitigated by continuing, incremental improvements to commercial hardware (e.g. since this study was performed, newer smart glasses have become available with triple the maximum luminance output – allowing testing down to approximately 8 dB_{HFA}). The present study also demonstrates that the software could be improved, given that the SITA Fast test algorithm was faster in normally sighted

controls and produced more repeatable results. The study also highlighted some hardware issues, such as fixation monitoring, that could be improved.

Another important practical consideration is that, in the present study, each pixel of each display was individually calibrated. Whether this is strictly required, or whether a single "exemplar" calibration would be sufficient for every headset of the same make and model, remains an open question (further data collection and analysis are ongoing). However, preliminary observations seem to indicate substantial device heterogeneity, with luminance output differences of up to 25% observed between different pixels/displays (as well as occasional "dead pixels" or other abnormalities). This raises significant quality control considerations and would mean in practice that users wishing to precisely control the luminance of the target and/or background could not, for example, simply download the Eyecatcher software onto their own uncalibrated device and would instead need to be supplied with calibrated hardware or follow some defined calibration protocol. Notably, the comparisons between the Eyecatcher device and the HFA may need to be interpreted cautiously. Particularly because our pilot cohort had varying degrees of glaucoma, with most of them having moderate to severe levels. There is a risk of the device reaching a ceiling effect due to the thresholding at 13.6 dB. Concurrently, the comparison against healthy controls having low MD scores correlated much better, highlighting that the device may need to be evaluated further in cases of moderate to advanced glaucoma. The SUS scale was chosen to quantify the device's usability, while we do acknowledge that a qualitative-style feedback collection would have provided more valuable information. Unfortunately, no further investigation was performed to understand the reasons for the variability in the SUS scores amongst the patients. We have tried to overcome this limitation by performing a qualitative study (Chapter 6) to understand patients' views, hopes, and concerns, specifically, the Eyecatcher.

Regarding the present study, the key limitation is the size and self-selecting nature of the patient sample. A larger sample is also required to quantitatively evaluate the pointwise concordance between Eyecatcher and the HFA (data collection ongoing). Furthermore, the present study is only intended as a feasibility pilot, and a much larger study examining a representative cross-section of patients is required to formally assess diagnostic accuracy or clinical utility (see above). Having a larger sample size will also allow us to sample patients

with a range of severities. This would provide us with a better understanding of the success of home-monitoring implementation across the disease spectrum. Thus, whereas the present study indicates that portable smart glasses can be used to remotely monitor VFs in some patients, it should not be taken as evidence that such technology would scale effectively to routine clinical practice. The present study was also not designed to assess the clinico-economic utility of portable VF technologies, and it remains to be seen exactly what the best clinical use cases for them are (e.g. home-monitoring, screening, or alternative care pathway for individuals unable to attend in-person clinics). Furthermore, the present study does not include patients with early-stage glaucoma, nor does it include any age-matched healthy controls. It does not, therefore, provide any information regarding, for example, Eyecatcher's ability or inability to detect early glaucoma.

4.5 Conclusion

This study indicates that a novel, smart glasses-based perimeter (Eyecatcher 3.0) is capable of monitoring the vision of some patients with glaucoma at home, widening the scope for telemedicine in eye care. Although there are several practical advantages of using these glasses over conventional perimeters, technical aspects like screen size and luminance range would benefit from further refinement. Further research is also required to formally establish diagnostic accuracy for detecting progression and to determine the most appropriate use for portable/home perimetry technology.

Chapter 5. Assessing the resilience of portable vision tests to an uncontrolled home environment

In Chapters 3 and 4, I discussed empirically collected evidence that suggests that novel testing may be feasible with some considerations. For the safe and effective implementation of these novel tests at scale, the resilience of these tests to different testing conditions required further assessment. This study aims to investigate the resilience of two portable contrast sensitivity tests under the exposure of potentially confounding factors that may have been encountered in a home setting. A version of this study, prepared to journal specifications, was published in the journal PeerJ in December 2025.

AUTHORS:

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Author Contributions:

Reddingius: Data collection, data analysis, manuscript writing, editing, and manuscript submission.

Rathore: Data collection, study design, data analysis, and manuscript review.

Crabb: Study design, funding acquisition, and project supervision.

Jones: Ethical approval acquisition, data analysis, and manuscript writing.

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Abstract

In ophthalmology (and medicine more widely), there is increasing interest in telemedicine: having patients perform tests at home for greater efficiency and to meet growing demand. However, despite this increased interest in vision home monitoring, many vision tests are evaluated in standardised clinical settings, not home environments. Here, we investigated the resilience of two portable contrast sensitivity tests to the sorts of potentially confounding factors that may be encountered in a home setting.

Normally sighted adults (n=107) performed two contrast sensitivity tests (one pen-and-paper and one tablet-based). Testing took place in a furnished apartment, where we could control/measure various extraneous factors (including illumination, time of day, seating type, screen cleanliness). Key outcome measures were raw contrast sensitivity scores, test-retest repeatability, and test duration, and how these metrics varied with extraneous factors.

No effect of time of day, participant motivation, or seating type was observed (all $P_{Bonferroni}$>0.140). Scores on the pen-and-paper test were not affected by illumination ($P_{Bonferroni}$=0.348), except when tests were conducted in extreme darkness (≤1 lux; $P_{Bonferroni}$=0.036). A follow-up study indicated that screen smudging (caused by fingerprints) had no significant effect on the outcome of the tablet-based test (P=0.573).

Taken together, the results indicate that, contrary to our expectations, both digital and pen-and-paper contrast sensitivity tests appear relatively resilient to many of the sorts of extraneous factors encountered in a home setting. This speaks to the potential viability of vision home monitoring, though study limitations and necessary future work are discussed.

5.1 Introduction

Many eye conditions are age-related, and so, as societies age (Tham et al., 2014; Wong et al., 2014), ophthalmology clinics worldwide are facing increasing strain (Foot & MacEwen, 2017; Foreman et al., 2020; Buys & Bellan, 2023). One way to help cope with greater patient numbers may be telemedicine: Measures of visual function that can be self-administered at home or in the community, for the purposes of monitoring, screening, or patient prioritisation.

Several portable vision tests have been developed in the past decade, including measures of visual acuity (Bastawrous et al., 2015; Chen et al., 2023; Han & Jones, 2019), visual field loss (Jones et al., 2019; McLaughlin et al., 2024; Ong et al., 2014; Vingrys et al., 2016), and contrast sensitivity (Dorr et al., 2013; Elfadaly et al., 2020; Habtamu et al., 2019; Karampatakis et al., 2024; Kollbaum et al., 2014; Rodríguez-Vallejo et al., 2015; Vivas-Mateos et al., 2020). Often, however, such tests are evaluated in standardised clinical settings. The goal of the present study was to investigate the resilience of such tests to the potential confounding factors associated with an uncontrolled home environment, such as variations in lighting or seating type. Note that we use the new term “resilience” to refer to a test’s general robustness (in every measurable sense) to use in an uncontrolled home environment. A maximally resilient test would be one whose performance (i.e., repeatability, duration, and ease of use) remained unchanged either when used at home unsupervised or in the clinic under supervision. In contrast, many conventional clinical measures, like letter charts and static perimeters (even those that may be relatively fast, accurate, and repeatable when used in a clinic), would likely be relatively non-resilient (i.e., would be slower, less accurate, and/or less repeatable at home), as they were never designed for use by patients unsupervised.

To assess resilience, we asked a large cohort of normally sighted young adults to perform two self-administered contrast sensitivity (CS) tests in a specially constructed living room environment: A furnished apartment built within our university campus (**Figure 5.1**). A “control” cohort of normally sighted young adults was selected for this initial work in order to ensure an extremely homogeneous sample (e.g., in terms of visual ability), allowing us to more easily detect any confounding effects from extraneous factors (between-subjects). In

future, however, we plan to extend the present approach to patient groups (see *Discussion*). The use of the constructed apartment allowed us to conveniently let certain extraneous factors vary freely (e.g., ambient illumination and time of day) while controlling others (e.g., seating type) and allowed us to assess test performance within a relatively naturalistic setting.



Figure 5.1. (A) Photo of the testing location and **(B)** Floor plan. Participants were randomly assigned to be seated on the sofa (blue square) or at the kitchen table (red circle). In a small number of cases, a floodlight was positioned at the locations of the green arrows to further increase illumination and simulate strong glare. Large south-facing windows extended across one wall, allowing almost constant sunlight within the hours of testing (08:30 -19:00).

In addition, in the present study, we also investigated several other factors not directly related to the environment, but that might similarly limit the feasibility of home vision testing. First, we investigated task engagement. Some participants may be intrinsically more motivated or capable of performing vision tests, and such differences in motivation may be particularly pronounced when tests are self-administered in a home environment (i.e., without a technician present to encourage or reassure the participant throughout the test). To investigate the effects of task engagement, we extracted response reliability metrics from visual field assessments performed as part of screening (visual field assessments being a notoriously challenging clinical procedure that produces a measurable quantity of "false positive" and "false negative" responses; (Glen et al., 2014)) and examined whether participants who exhibited better reliability metrics subsequently produced higher or more consistent CS scores in the home environment. These measures were used as surrogate measures to provide an indication of the person's motivation to perform the test. In addition, we also asked participants to answer several questions about the tests afterwards to examine whether people who rated the test more highly (e.g. enjoyed it more) also produced better or more consistent CS scores. Second, we evaluated whether the level of instruction was important, as it may be that the performance of a home test depends on how carefully the procedure is explained to the patient. To this end, half of the participants had the test explained by a qualified optometrist, and half by a junior, non-clinical researcher. We hypothesised that participants who received the optometrist instructions might perform the tests more quickly or reliably. Third and finally, for the tablet-based test, we further assessed screen cleanliness, as with home testing, smudges may accumulate naturally over time through sustained use, and we cannot assume that patients will always remember to clean the screen. To this end, a subset of follow-up patients was asked to repeat the tablet-based test with and without the presence of finger smudges.

The goal of the study is to assess whether these two CS home-monitoring tests are resilient to the extraneous factors that varied within our testing studio apartment. To do so, we assessed the impact of the illumination, seating type, time of day, participant motivation and level of instruction on the raw score, the repeatability and the duration of the two CS tests.

5.2 Methods

5.2.1 Participants

Participants were 107 normally sighted adults aged 18 to 30 years (median {interquartile range}: 20 {4} years). An overview of the demographics of the participants can be found in **Table 5.1.** While there was a clear imbalance in sex, this did not affect performance (see **Table 5.2**). As described in the introduction, we chose young, normally sighted adults in order to minimise individual variability due to age or pathology (i.e., to get a "pure" measure of the effects from extraneous factors alone).

Normal vision was defined as no self-reported history of visual impairments or ocular disease, a habitually corrected distance letter acuity ≤ 0.2 logMAR in the better eye (ETDRS chart at 3m; Precision Vision, Woodstock, Illinois, USA), a contrast sensitivity ≥ 1.5 logCS in the better eye (Pelli-Robson chart at 1 m; Precision Vision, Woodstock, Illinois, USA), and a visual field of "within normal limits" or "borderline" in the better eye on a 24-2 visual field test on a Humphrey Visual Field (HVF) analyser using the SITA-FAST algorithm (Zeiss, Dublin, CA, USA). Two additional prospective participants failed screening (i.e., *n*=109 screened). Of these, one was "outside normal limits" in their visual field, while the other did not bring their prescription spectacles and so failed the acuity criterion.

Participants were recruited via adverts around the campus of City St George's, University of London, and received £20 compensation for their time. Ethical approval was granted by the Optometry Proportionate Review Committee at City St George's (#ETH2021-2265, #ETH2122-1956 and #ETH2324-0149). The study was carried out in accordance with the Declaration of Helsinki and participants provided informed written consent.

Table 5.1. Demographic overview of the participants.

	Female	Male	Total
Number (*n* [%])	86 (80%)	21 (20%)	107
Age (median [IQR]; *years*)	20 (19 to 23)	22 (19 to 27)	20 (19 to 23)
Refractive error – spherical equivalent (median [IQR]; *dioptre*)	0 (-2.50 to 0.00)	0 (-3.25 to 0.00)	0 (-2.50 to 0.00)
Myopic (*n* [%])	41 (48%)	8 (38%)	49 (46%)
Hyperopic (*n* [%])	4 (5%)	2 (10%)	6 (6%)
Emmetropic (*n* [%])	41 (48%)	11 (52%)	52 (49%)
Visual Acuity (median [IQR]; L*ogMAR*)	0 (-0.04 to 0.06)	0 (-0.10 to 0.00)	0 (-0.07 to 0.06)

Table 5.2.Effect of binary variables (participant sex, seating type and presence of a clinician) on the test performance.

	SpotChecks			PopCSF		
	Raw score, (SD), logCS	Repeatability (SD) (|test2 – test1|), *logCS*	Duration (SD), secs	Raw score (SD), AUCSF	Repeatability (SD) (|test2 – test1|), *AUCSF*	Duration (SD), secs
Sex						
Male	1.85 (0.07)	0.05 (0.04)	193 (49)	1.48 (0.18)	0.10 (0.09)	132 (20)
Female	1.84 (0.14)	0.05 (0.05)	177 (46)	1.53 (0.15)	0.10 (0.08)	131 (21)
	P=0.619	*P*=0.534	*P*=0.187	*P*=0.236	*P*=0.926	*P*=0.923
Seating Type						
Sofa	1.85 (0.11)	0.06 (0.05)	185 (53)	1.52 (0.15)	0.11 (0.08)	135 (23)
Table	1.83 (0.15)	0.05 (0.05)	176 (40)	1.52 (0.16)	0.10 (0.08)	128 (18)
	P=0.543	*P*=0.264	*P*=0.315	*P*=0.901	*P*=0.451	*P*=0.094

Administered by						
Clinician	1.85 (0.07)	0.06 (0.04)	170 (52)	1.51 (0.16)	0.12 (0.09)	134 (25)
Non-clinician	1.83 (0.17)	0.05 (0.05)	191 (39)	1.53 (0.15)	0.09 (0.08)	128 (15)
	P=0.327	*P*=0.107	*P*=0.023	*P*=0.458	*P*=0.084	*P*=0.158
All Participants	1.84 (0.13)	0.05 (0.05)	180 (47)	1.52 (0.15)	0.10 (0.08)	131 (21)

5.2.2 Protocol overview

Participants performed two CS tests in a room furnished as an ordinary apartment (see **Figure 5.1**). We chose to measure CS as it is known to be symptomatic of a range of eye diseases (Pelli & Bex, 2013) such as glaucoma (Richman et al., 2010), macular degeneration (Kleiner et al., 1988), diabetic retinopathy (Stavrou & Wood, 2003), and cataract (Shandiz et al., 2011), and since, unlike visual acuity, it is relatively tolerant to variations in viewing distance (i.e., likely making it a more pragmatic choice for home monitoring).

The two specific CS tests selected were the tablet-based PopCSF (Irida Health Ltd, London, UK) and pen-and-paper SpotChecks test (Precision Vision, Woodstock, Illinois, USA). Details of each are given below. Two different presentation modalities were chosen to evaluate their relative strengths and weaknesses (e.g. we predicted that the pen-and-paper test would work better under strong illumination, and the digital test under low illumination). A third CS assessment, the Pelli-Robson, was also performed as part of initial screening and was used as an approximate reference measure (though all three CS measures use different stimuli and would not be expected to perfectly correlate). The Pelli-Robson chart was chosen for pragmatic reasons as it is quick to perform and provides an outcome measure similar (in principle) to SpotChecks. In retrospect, it would also have been desirable to use the CSV-

1000 (Vector Vision, Greenville, Ohio, USA) as an additional reference measure since, like PopCSF, it assessed the whole CSF.

Of the two tests used in the main study (PopCSF, SpotChecks), the starting test was randomly counterbalanced, and each test was performed twice (AABB / BBAA) in order to assess test-retest repeatability. All tests were performed using habitual refractive correction, and in the better eye only (fellow eye patched), though typically the difference between the visual acuity of the better and worse eye was minimal; Mean Δ logMAR = 0.06 (standard deviation [SD]: 0.09). The better eye was determined by visual acuity (*n*=83), by the dominant eye in case of a tie (*n*=22) or defaulted to the right eye if dominance was unclear (*n*=2).

Participants were consented and instructed by one of two randomly selected experimenters, one of whom was a first-year PhD student at the time of this study and the other a qualified clinical optometrist.

5.2.3 Creating a realistic home-testing environment

Participants were tested in a furnished studio apartment, constructed within the second floor of City, St George's, University of London. This space simulates a home environment and is also currently used, e.g., by nursing students to practice 'at-home' interactions. As shown in **Figure 5.1**, the apartment contained a bed, a sofa, a kitchen area with a kitchen table, and a bathroom. Participants were randomly directed to one of two seating types: the sofa (a more laid-back or "relaxed" position) or at the kitchen table (a more upright or "active" position). However, participants were not instructed to sit in a specific manner (in keeping with a general intention to allow participants to behave in a naturalistic, ordinary way).

For most participants (*n*=93), the blinds in the apartment were kept open, and illumination was allowed to vary freely with time and the weather. Illumination was recorded using a lux meter (Aoputtriver AP-881D, Zhuhai, Guangdong, China) and is reported in the results as an independent variable. To further extend the range of illuminations, either the blinds were closed to achieve extremely low illumination (*n*=3), or a flood light (Lepower ZSTGD-100W, Shenzhen, China) was used to provide very high illumination (*n*=12).

Participants were given brief standardised verbal instructions on how to perform the test. During the test, however, participants were free to do the test how they preferred without interference. While the experimenter was present in the room for the study, they stood out of the participants' line of sight (usually on the sofa if the participant was seated in the kitchen and vice versa) and did not intervene or try to correct the participant, as per a "normal" home environment.

5.2.4 The SpotChecks (pen and paper) contrast sensitivity test

Details of SpotChecks have been described previously (Anderson et al., 2017; Bianchi et al., 2024; Crossland et al., 2021). In brief, the test consists of a single sheet of A4 paper, containing grey circles of varying contrast that the user must circle with a pen (see **Figure 5.2A**). Contrast progressively decreases down the page (0.05 logCS per line), and participants were asked to mark each circle that they could see until they could not see another grey circle anymore. The output measure is an overall estimate of CS (-log10(Weber contrast [%]) of the smallest detectable contrast; in logCS).

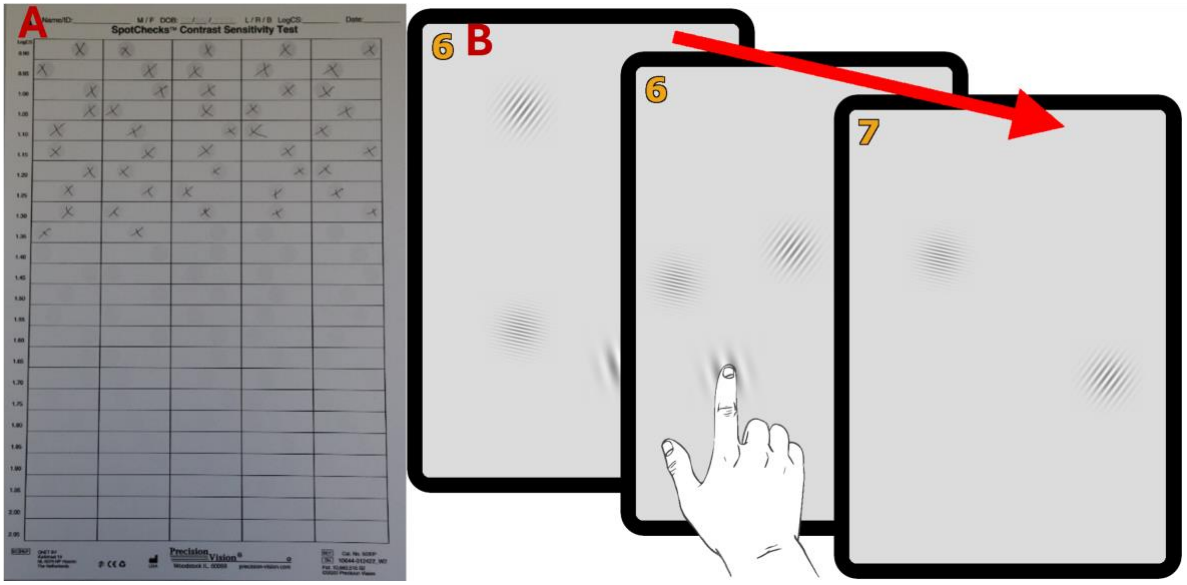


Figure 5.2. The contrast sensitivity tests. **(A)** A partially completed pen-and-paper SpotChecks sheet (visible stimuli marked in pencil with a cross). **(B)** Drawing of PopCSF mid-test. The leftmost tablet shows the initial version, with three different Gabors visible. The middle tablet shows the person tapping the screen at the location of one of the Gabors. The rightmost tablet shows the test after one of the Gabors was successfully "popped"; two Gabors now remain (but more will be periodically generated throughout the test). The number in the top left of the tablet shows how many Gabors were correctly "popped" by the participants, though this score was for motivational purposes only. The Gabors have been made easier to identify in this visual representation and are therefore not fully isoluminant as in the real test.

Participants were free to take as much time as they wanted to complete the test. The participants were presented with a sheet of paper laid down on the table when seated at the table or handed to them when seated on the sofa. But they could hold or move the paper as desired. When seated on the sofa, some participants performed the test on their lap, while some used the coffee table. Others opted to place a book from the coffee table behind the test for stability. Some participants held the test closer or further away during the test, sometimes even holding it up to the light to get a better look.

5.2.5 The PopCSF (tablet-based) contrast sensitivity test

As shown in **Figure 5.2B,** PopCSF (Crossland et al., 2024; Elfadaly et al., 2020) is a tablet-based contrast sensitivity test where the user is required to “pop" bubbles (horizontal Gabors of variable contrast and spatial frequency) by touching them as they drift across an isoluminant grey background. The test is designed to be game-like (e.g., includes audiovisual feedback), and the exact location of each Gabor on the retina is not controlled, though they generally fall within the macula.

The test ran on an iPad Pro 11-inch (2nd Gen) tablet (Apple, Cupertino, California, USA), with a 2388x1668-pixel touchscreen display (264 pixels per inch). Real-time head tracking (via the integrated near-infrared TrueDepth camera) was used to modify the spatial frequency of the Gabor patches to adjust for the viewing distance. The TrueDepth camera had a precision of approximately 1 mm (Andrews et al., 2023) and a measurement error of approximately 5% of the target distance (Breitbarth et al., 2019). The screen was calibrated (linearised) using central measurements of screen luminance, made using a Konica Minolta LS100 luminance meter (Konica Minolta, Tokyo, Japan).

PopCSF measures the CS at various spatial frequencies and fits a 3-parameter contrast sensitivity function (Elfadaly et al., 2020). Here, the Contrast Sensitivity Functions (CSF) are summarised/reduced to a single scalar value by computing the area under the CSF (AUCSF)(Dorr et al., 2017).

5.2.6 Analysis

Some data was lost. For seven participants (7%), data for PopCSF were not saved due to a technical error, while for two participants (2%), ambient illumination information was not recorded due to human error (see **Supplementary Material 9.3.1.1**). Since the proportion of missing data was small, and since instances were independently randomly distributed, we do not believe these missing data materially affected the study conclusions.

Analyses were performed using R v4.4.1 (R Foundation for Statistical Computing, Vienna, Austria). Correlations were calculated using Pearson correlation, while differences between conditions were evaluated using unpaired *t*-tests unless otherwise specified. Since six analyses were performed for each subsection of the results, a simple Bonferroni correction

was applied. As a result, only *P* values < 0.0083 were considered statistically significant. However, for completeness, we also highlight where the uncorrected result is significant. This is only relevant for two findings (the duration of SpotChecks depending on the clinician's experience and the repeatability of SpotChecks depending on the time of day); the potential consequences of this are discussed.

5.3 Results

5.3.1 Preliminary overview of results

Table 5.2 shows the overall effect of various binary variables (participant sex, seating type, and instructor's clinical experience) on (1) contrast sensitivity scores; (2) test-retest repeatability, and (3) duration. In brief, this table shows that these three binary variables do not have an impact on the score, repeatability or duration. However, specific results are described in the sections below (seating type in Section 5.3.3, instructor's clinical experience in Section 5.3.5).

Table 5.3 shows the overall effect of various continuous variables (illumination, time of day, participant feedback and clinical reliability [from perimetry]) on the same 3 dependent variables (raw scores, repeatability, duration). Again, these show in general no significant effects but are explored in more depth in the sections below (illumination in section 5.3.2, time of day in section 5.3.4, participant feedback in section 5.3.5.1 and clinical reliability in section 5.3.5.2).

Table 5.3. Effect of various continuous variables (illumination, time of day, participant) on test performance.

Numerical values indicate Pearson correlation coefficients and significance values *(P)*

	SpotChecks			PopCSF		
	Raw score, *logCS*	Repeatability (|test2 – test1|), *logCS*	Duration, secs	Raw score, AUCSF	Repeatability (|test2 – test1|), AUCSF	Duration, secs
Illumination	0.19	0.08	0.10	0.11	-0.11	0.16
	-0.01 to 0.37	-0.11 to 0.27	-0.09 to 0.29	-0.09 to 0.29	-0.30 to 0.09	-0.04 to 0.35
	P=0.058	*P*=0.401	*P*=0.294	*P*=0.296	*P*=0.274	*P*=0.114
Time of day	0.02	-0.21	0.10	0.12	-0.07	0.02
	-0.17 to 0.21	-0.38 to -0.02	-0.09 to 0.28	-0.08 to 0.31	-0.27 to 0.12	-0.18 to 0.21
	P=0.836	*P*=0.032	*P*=0.319	*P*=0.251	*P*=0.464	*P*=0.881
Feedback	0.10	-0.04	-0.16	0.05	0.07	-0.06
metric	-0.09 to 0.29	-0.23 to 0.15	-0.34 to 0.03	-0.15 to 0.24	-0.13 to 0.26	-0.25 to 0.14
	P=0.301	*P*=0.655	*P*=0.096	*P*=0.642	*P*=0.520	*P*=0.582
HVF	-0.01	-0.12	-0.06	-0.18	0.04	-0.00

reliability	-0.20 to 0.18	-0.30 to 0.08	-0.25 to 0.13	-0.37 to 0.01	-0.16 to 0.24	-0.20 to 0.19
metric	*P*=0.896	*P*=0.235	*P*=0.512	*P*=0.066	*P*=0.689	*P*=0.977

5.3.2 Resilience to ambient illumination

Illumination varied from 0.09 (scotopic) to 2649 lux (high photopic) between participants. For context, 50 - 750 lux is the range typically recommended for indoor office environments (HSE, 2025).

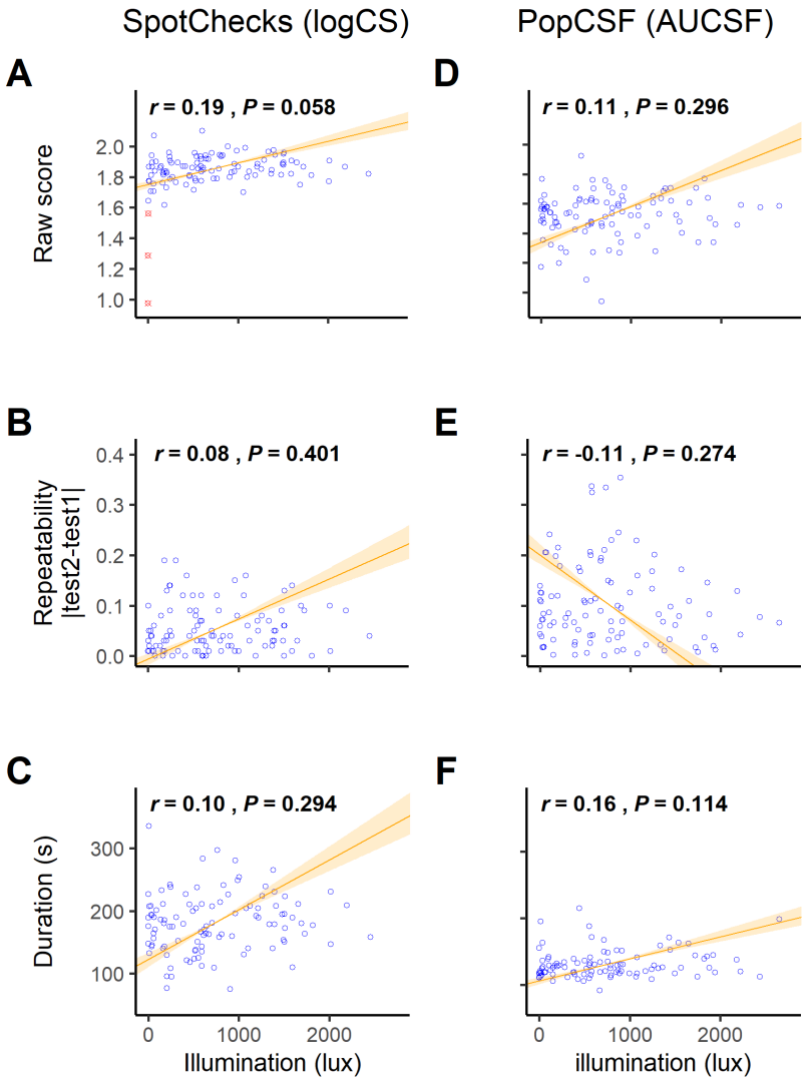


Figure 5.3. Figures of the resilience to Illumination. Scatterplot of the raw SpotChecks score **(A**), note that three participants (tested at less than 1 lux; shown as a red crossed circle) were removed as outliers, and the raw PopCSF score **(D)** with the illumination in the room at the time of testing on the x-axis. Scatterplot of the absolute difference between the two SpotChecks scores **(B)** and the absolute difference between the two PopCSF scores **(E)**, with illumination in the room at the time of testing on the x-axis. Scatterplot of the duration of SpotChecks **(C)** and the duration of PopCSF **(F)** with the illumination in the room at the time of testing on the x-axis. Numerical values indicate Pearson correlation coefficients and significance values. The line signifies the standard major axis regression, with shaded regions indicating the slope's 95% confidence interval.

For SpotChecks (**Figure 5.3 A-C),** there was no correlation between illumination and test-retest repeatability [r_{103}=0.08, P=0.401], or between illumination and test duration

[r_{103}=0.10, P=0.294]. There was a weak positive correlation between illumination and raw CS score [r_{103}=0.19, P=0.058]. However, if the tests conducted at ≤ 1lux (scotopic) were removed, this correlation ceases to be significant [r_{100}=0.19, P=0.058]. Given that for those tested at ≤1 lux, it was so dark that participants could barely see the sheet of paper, we believe that no reasonable person would ever attempt the test in such conditions. This indicates that ambient lighting is not a practical concern for SpotChecks. We also conducted a formal piecewise linear analysis, which indicated that anything above 11 lux did not substantively affect CS score on SpotChecks (see **Supplementary Figure 9.8** and **Figure 5.3**).

For PopCSF (**Figure 5.3 D-F**), there was no correlation between illumination and score [r_{98}=0.11, P=0.296], repeatability [r_{98}=-0.11, P=0.274], or test duration [r_{97}=0.16, P=0.114].

Overall, these analyses indicate that variations in indoor illumination levels have no substantial effect on test performance for either test, except in extremely dark cases for the pen-and-paper test.

5.3.3 Resilience to seating type

Next, we investigated whether performing the test sitting in a more relaxed posture (sitting on a sofa) or a more active posture (sitting at a table) could alter test performance.

For SpotChecks (**Figure 5.4A-C**), there was no effect of seating position (sofa vs. table) on score [t_{101}=0.61; P=0.543], repeatability [t_{105}=1.12; P=0.264], or duration [t_{94}=1.01; P=0.315].

Likewise, for PopCSF (**Figure 5.4D-F**), there was no effect of seating position on score [t_{98}=0.12, P=0.901], repeatability [t_{98}=0.76, P=0.451], or duration [t_{87}=1.70, P=0.094].

Overall, these analyses indicate that seating type has no substantial effect on test performance, either for the pen-and-paper SpotChecks or the tablet-based PopCSF.

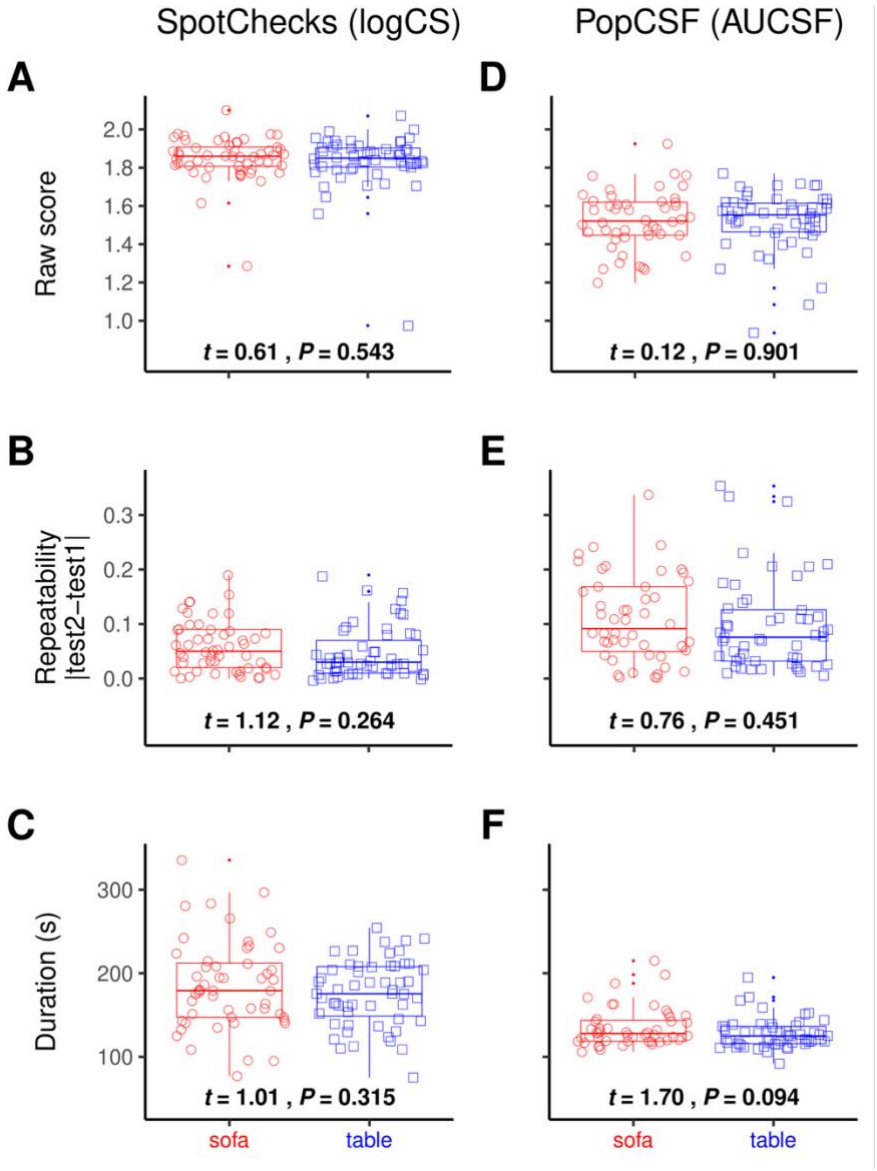


Figure 5.4. Figures of the resilience to seating type. Boxplots of the raw score **(A & D)**, the repeatability **(B & E)** and the duration **(C& F)** separated by the participants who performed the test at the table, and those who performed them on the sofa. For SpotChecks, the raw score and repeatability are in LogCS, and for PopCSF, those are in AUCSF, both duration graphs are in seconds. The numbers represent the t-test statistics and significance values.

5.3.4 Resilience to the time of day

For Spotchecks **(Figure 5.5A-B),** there was no correlation between the time of day and score [r_{105}=0.02, P=0.836] or between time of day and test duration [r_{105}=0.10, P=0.319]. As shown

in **Figure 5.5C**, there was a weak negative correlation between time of day and the precision (repeatability) of SpotChecks [r_{105}=-0.21, P=0.032], but this ceased to be significant following Bonferroni correction ($P < 0.008$).

For PopCSF (**Figure 5.5D-F**), there was no correlation between the time of day and score [r_{98}=0.12, P=0.251], repeatability [r_{98}=-0.07, P=0.464], or test duration [r_{97}=0.02, P=0.881]. Overall, these analyses indicate that the time of day has no significant impact on test performance.

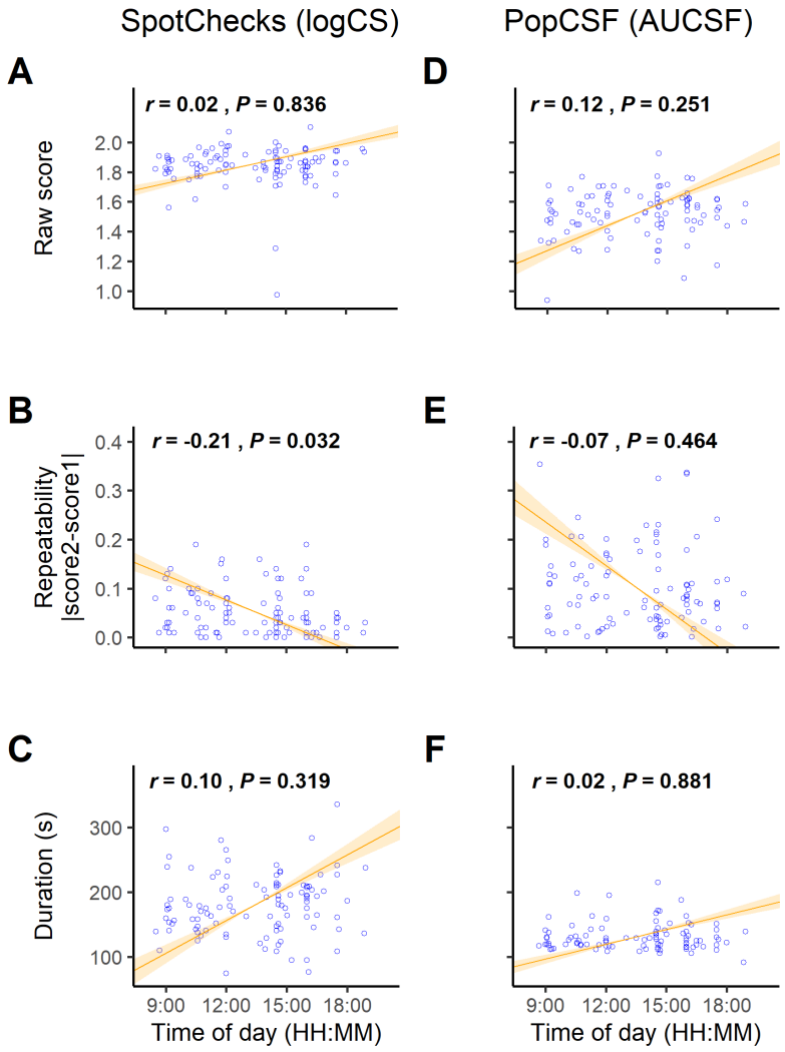


Figure 5.5. Figures of the resilience to time of day. Scatterplot showing dependent variables for **(A - C)** SpotChecks and **(D - F)** PopCSF as a function of the time of day. Numerical values indicate Pearson correlation coefficients and significance values. The line signifies the standard major axis regression, with shaded regions indicating the slope's 95% confidence interval.

5.3.5 Resilience to participant motivation

Some participants may be inherently more invested in performing well on a test, and these differences in task motivation may manifest as differences in performance. This is always a concern for any test, but we predicted the effects might be particularly acute/pronounced in a telemedicine environment, with no experimenter to actively monitor/encourage the participant. We used two proxies for motivation: (i) whether the participant rated the test

positively (Patient feedback); (ii) whether the participant was consistent during the HVF test (HVF reliability score).

5.3.5.1 Participant feedback

Participants were asked five feedback questions after the experiment: Whether they (i) understood the test, and found it (ii) easy, (iii) enjoyable, (iv) hard to concentrate on, and (v) tiring. Participants would rate these questions using a five-point Likert scale from (1) strongly disagree to (5) strongly agree. Their answers to these five questions were combined into one 'feedback metric', which ranged from 5 to 25, with 5 meaning that the participant was extremely negative on each subject and 25 meaning that they were extremely positive about the test.

For SpotChecks (**Supplementary Figure 9.9**), there was no significant relationship between the feedback metric and contrast score [r_{102}=0.10, P=0.301], but only when excluding the 3 participants tested at ≤1 lux. If included, there was a significant relationship [r_{105}=0.26, P=0.006], as these 3 individuals scored extremely badly on the test and rated the test very negatively. Even with these participants included, there was no correlation between the feedback score and the repeatability [r_{105}=-0.04, P=0.655] or test duration [r_{105}=-0.16, P=0.096] (**Supplementary Figure 9.9 B-C).**

For PopCSF (**Supplementary Figure 9.9 D-F),** there was no correlation between the feedback metric and CS score [r_{98}=0.05, P=0.642], repeatability [r_{98}=0.07, P=0.520], or test duration [r_{97}=-0.06, P=0.582].

5.3.5.2 HVF reliability score

The HVF provides three variables to indicate the reliability of a visual field report: the percentage of false positives, false negatives and fixation losses. These indicate how consistent a participant is during a visual field test and have been shown to affect HVF test performance (Lee et al., 1994). These three percentages were summed into a composite score that shows how consistent a participant was, labelled here as the "HVF reliability metric".

For SpotChecks (**Supplementary Figure 9.10 A-C),** there was no correlation between the HVF reliability metric and the score [r_{105}=-0.01, P=0.896], repeatability [r_{105}=-0.12, P=0.235], or test duration [r_{105}=-0.06, P=0.512].

For PopCSF (**Supplementary Figure 9.10 D-F),** there was no correlation between the HVF reliability metric and the score [r_{98}=-0.18, P=0.066], repeatability [r_{98}=0.04, P=0.689], or test duration [r_{97}=-0.00, P=0.977].

Overall, these analyses indicate that participant motivation has no substantial effect on test performance.

5.3.6 Resilience to the level of instruction

Participants largely "tested themselves". However, as per real clinical practice, somebody had to explain what to do beforehand. For n=53 participants, this explanation was given by author PFR (who at the time of the study was a first-year PhD student with no clinical background or experience), while for the other n=54 participants, this explanation was given by author MR: a qualified clinical optometrist with formal training in explaining vision testing procedures.

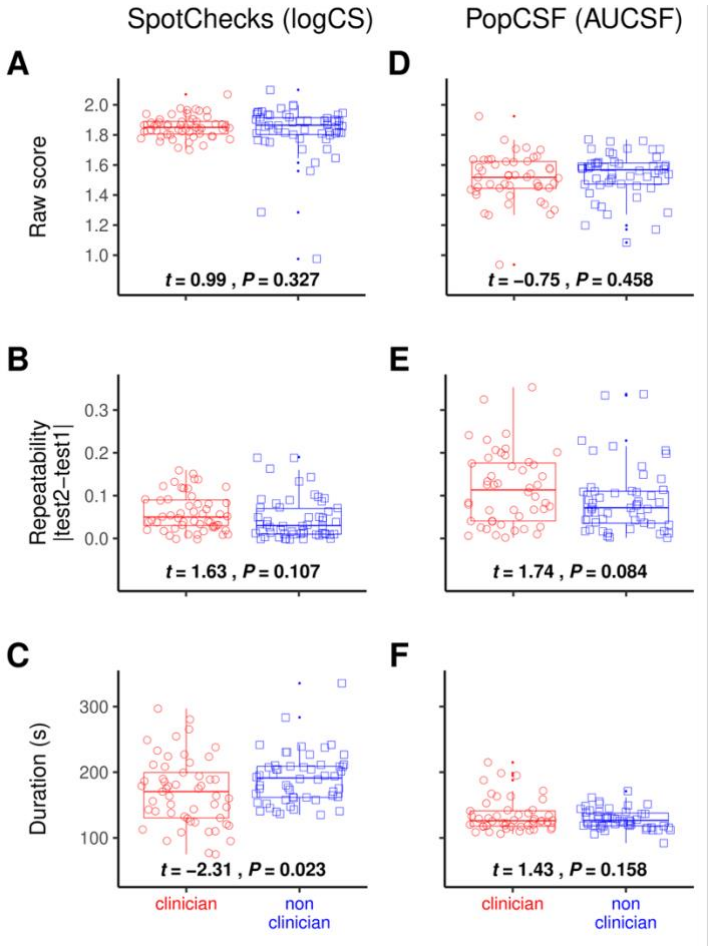


Figure 5.6. Figures of the resilience to the presence of a clinician. Boxplots of the raw score **(A & D)**, the repeatability **(B & E)** and the duration **(C & F)** separated by the participants that were tested by the clinician and those that were tested by the non-clinician. For SpotChecks, the raw score and repeatability are in LogCS, and for PopCSF, those are in AUCSF; both duration graphs are in seconds. The numbers represent the t-test statistics and significance values.

For SpotChecks (**Figure 5.6 A-B)**, there was no effect of the experimenter's clinical experience on the score [t_{72}=0.99, P=0.327] or repeatability [t_{104}=1.63, P=0.107]. There was, however, a significant difference between the participants tested by either experimenter on the duration [t_{96}=-2.31, P=0.023], with the people completing the test on average 20 seconds (11%) faster when instructed by the clinician (**Figure 5.6 C).** This was not significant after considering a Bonferroni corrected significance value, however (P<0.008).

For PopCSF (**Figure 5.6 D-F),** there was no effect of the experimenter on the score [t_{96}=-0.75, *P*=0.458], repeatability [t_{95} =1.74, *P*=0.084] or test duration [t_{76}=1.43, *P*=0.158].

Overall, these analyses indicate that the performance of tests in a home-type environment can be measurably affected by the person delivering the test instructions (even when the instructions themselves are standardised), but that the nature/magnitude of this effect is relatively slight (in this instance, a small difference in test duration).

5.3.7 Resilience to screen smudges

For a pen-and-paper test, such as SpotChecks, a new, fresh sheet is used for every assessment. In contrast, a tablet-based test such as PopCSF is reusable. Over time, screen smudges are liable to occur, possibly obscuring low-contrast stimuli. In our main experiment, any effects of smudging were minimised as we thoroughly cleaned the screen between participants. In the real world, however, a single patient using the device at home may not be so diligent. To investigate the potential effect of screen smudging, we therefore performed a follow-up experiment in which *n*=5 randomly selected participants were called back to perform an additional, intensive testing session comprised of 24 successive PopCSF tests. Participants performed groups of six tests, starting randomly with a clean (see **Figure 5.7 A**) or dirty screen (see **Figure 5.7 B**) and alternating between the two conditions until they had completed 24 tests in total (12 clean, 12 dirty).

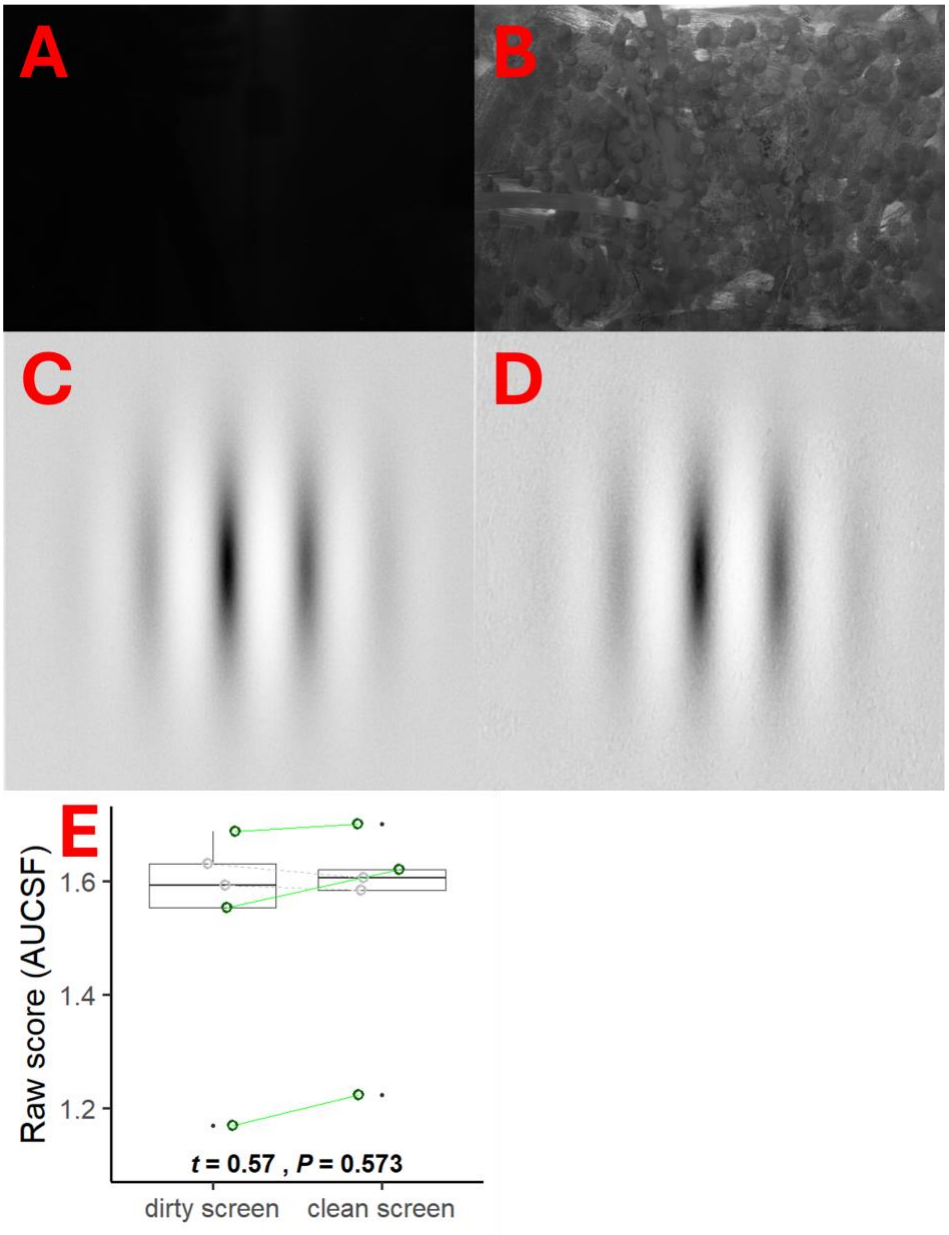


Figure 5.7. Images and figures of the resilience to screen smudges. **(A)** Image of the iPad with the screen turned off and a clean screen, and **(B)** that same image with a smudged screen. **(C)** A zoomed image of the PopCSF screen showing a Gabor patch with a clean screen and **(D)** with a dirty screen. **(E)** A boxplot of the mean score (AUCSF) of each participant (coloured) and whether a clean screen caused them to perform better (green continuous line) or worse (grey striped line). A boxplot of the overall effect is also shown within the figure. Numerical values indicate the results of a t-test on the data.

The screen was smudged by the participants themselves by greasing their hands with crisps and wiping them all over the screen, making sure that the entire screen was covered in grease. The difference between the clean and dirty screen was very clearly visible with the screen turned off (clean: **Figure 5.7A**, dirty: **Figure 5.7B**). The same pictures were made of the same clean and dirty screen displaying a Gabor as PopCSF would present it (clean: **Figure 5.7C**, dirty: **Figure 5.7D**). Visual inspection shows that there was a huge difference when the screen was turned off (**Figure 5.7A&B**), but hardly any difference when the screen was displaying the Gabor (**Figure 5.7C&D**)**.** This was likely due to the light reflecting off the grease on the screen when the screen was turned off, but that effect was overpowered by the light emanating from the screen when it was turned on.

To try to quantify the effect of the smudging, we used a simple pixel intensity analysis, where each pixel of the image was ranked from 0 (completely black) to 255 (completely white). For the images with the screen turned off (**Figure 5.7A&B),** the mean intensity was 7 (SD: 1) for the clean screen and 80 (SD: 15) for the dirty screen. For the image of the Gabor **(Figure 5.7C&D),** the mean intensity was 213 (SD: 19) for the clean screen and 212 (SD: 18) for the dirty screen. This shows that even though the smudginess is very clearly a factor when the screen is turned off, it hardly makes any difference when the screen is turned on.

As shown in **Figure 5.7E,** two of the five participants actually performed slightly better on average (higher CS) with the smudged screen, and there was no significant difference in performance between the clean and dirty screen [t_{115}=0.57, P=0.573]. This indicates that smudging the screen does not substantially affect the performance on the tablet-based test.

5.4 Discussion

With the growing interest in vision home monitoring (Che Hamzah et al., 2020; Han & Jones, 2019) the present study aimed to evaluate the extent to which various extraneous factors (seating type, illumination, time of day, motivation, instructors clinical experience, and screen smudging on two portable CS) might confound two portable CS tests (one pen-and-paper based, one digital tabled-based).

Contrary to our expectations, none of these factors appeared to be substantive confounds, suggesting that these (and potentially other similar portable CS tests – see below) are relatively resilient to the extraneous factors examined in this study. Specifically, there were no significant effects of the seating type, motivation or presence of a clinician on the CS score, repeatability and duration of either test. And while there was a significant effect of the illumination on the pen-and-paper-based test, SpotChecks, this was manifest only in extremely dark conditions (<11 lux) in which no reasonable person would ever attempt to perform the test.

For SpotChecks, there were two borderline effects that ceased to be statistically significant following Bonferroni correction. There was a 20-second (12%) increase in time spent on the test when tested by a non-clinician instead of a clinician, and a weak correlation (r=-0.21) between the repeatability and the time of day. These may warrant further investigation in future, but even if they prove significant, the effect sizes are small (i.e., they would unlikely affect the clinical utility or acceptability of the intervention).

One particularly novel and important finding of the present study was that there was no effect of the seating location on the resilience of either CS test. When seated at the table, participants would keep the test on the table, but when seated on the sofa, they had no easy spot to put the test. This meant people were encouraged to improvise, e.g. holding the PopCSF tablet on their lap or grabbing a book to put under the SpotChecks sheet in order to write on it. This is encouraging, as it suggests that vision home monitoring could potentially be performed without the need for strict instructions or unrealistic assumptions regarding patient compliance.

5.4.1 Previous Literature

Many previous studies using portable vision tests such as PopCSF or SpotChecks have used standardised testing environments (Anderson et al., 2023; Crossland et al., 2024; Elfadaly et al., 2020; Nixon & Flinn, 2021; Rijal et al., 2021). Two studies, however, had patients perform SpotChecks at home (Bianchi et al., 2024; Vu et al., 2024), and both reported similar results at home and in the clinic. This is consistent with our present findings, where we did not find any extraneous factors that substantially affect the resilience of the home CS tests.

A study by Abraham et al. (Abraham et al., 2023) investigated the effect of several colour filters and changes in illumination on participants with moderate to severe vision impairment. They found no changes in CS when tested at 100, 300, 700 or 1000 lux. This is consistent with our findings, as we did not find an effect of illumination (ranging from 0.1 to 2453 lux) on the SpotChecks score.

Similarly, looking beyond the particular CS measures employed in the present study, Cox et al. (Cox et al., 1999) investigated the effect of illumination on the performance of the Pelli-Robson CS chart. At 4 meters, they found that increasing illumination from 9 lux to 900 lux caused an increase in CS of roughly 1 logCS. However, at 1 metre distance, Cox and colleagues found no significant effect of illumination on CS. This again is broadly consistent with our present findings, since in the present study both SpotChecks and PopCSF were held at arm's length (i.e., < 1 m).

Montolio et al. (Montolio et al., 2012) systematically investigated the factors that influence visual field performance in clinics and found that test outcomes varied by the time of day that the participant was tested. This is inconsistent with our findings, as we found no effect of the time of day on the contrast sensitivity score as measured by either of our two home tests. However, a visual field test is a much more intense procedure than the CS tests featured in our study, which may explain why we found no effect of the time of day on the raw score of either test.

Finally, Vingrys et al. (Vingrys et al., 2016) and Harris et al. (Harris et al., 2022) investigated whether the outcome and reliability of the tablet-based visual field test (Melbourne Rapid Fields) were affected by illumination. Both studies found no effect of illumination on the outcome or reliability of the test, which is consistent with our present findings.

Finally, we can compare our repeatability findings to recent studies that tested PopCSF and SpotChecks, either in the clinic or at home. A recent study by Crossland et al. (Crossland et al., 2024), which studied both SpotChecks and PopCSF in the clinic, reported a CoR_{95} of 0.13 logCS and 0.29 AUCSF, respectively, similar to our recorded CoR_{95} of 0.14 logCS and 0.26 AUCSF, respectively (see **Supplementary Section 9.3.3**). Another study by Vu et al. (Vu et al., 2024) calculated the inter-day repeatability of SpotChecks at 0.18 logCS in the clinic and 0.18 logCS at home, similar to our intra-session repeatability of 0.14 logCS. Our repeatability was likely lower as we tested in one session (intra-session) while in the study by Vu et al., the repeatability was assessed over multiple sessions (inter-day). This seems to indicate that there is no change in repeatability when testing at home, in the clinic, or in our uncontrolled simulated home environment.

5.4.2 Limitations and Future Work

A key limitation of the present study is that we only recruited normally sighted young adults. This was intentional, as it allowed us to investigate the effect of the extraneous factors without large individual differences. However, long-term, it would be necessary to extend the present approach to a wider age range and to those with visual disorders. For instance, it is known that due to age-related changes throughout the eye, older adults often have more trouble seeing in low light conditions (Owsley, 2011) and in the presence of glare (Kimlin et al., 2017), meaning that, for example, home tests may be less resilient to changes in illumination in older adults. Our next step will be to confirm the initial findings on the resilience of these tests in participants with a wider age range and in those with visual disorders. Additionally, since this was an exploratory study, we could not conduct a formal power analysis before starting the study. However, by recruiting over 100 participants, we believe that we achieved a proper spread of participants over our variables to answer our research questions.

Second, future studies could also investigate additional extraneous factors not considered in the present study, such as the auditory distractions from music, TV, or people talking. It might also be instructive to study in the future the effects of inappropriate refractive correction. Thus, when unsupervised, it is likely that some patients might forget to wear their spectacles or wear inappropriate ones (e.g., distance rather than reading glasses), and

this could also be an additional source of home-measurement error. While this would be most important for home visual acuity testing, it might also cause issues for CS testing. For example, in visual field testing (which is effectively a form of peripheral CS test), a 1 dioptre refractive error has been shown to decrease the sensitivity by 1.26 dB in the central 6 degrees of the visual field (Weinreb & Perlman, 1986). Finally, for screen-based tests, there might also be concerns about screen calibration if patients are expected to download the test onto their own devices. Though it should be noted that the PopCSF test used in the present study is not widely available to the general public for that very reason, and potential solutions for "self-calibrating" (Han & Jones, 2019) or "psychophysically-calibrated" tests (To et al., 2013) have been suggested.

A third limitation of the present study is that we only investigated two contrast sensitivity (CS) tests. However, we have no reason to expect other similarly CS tests (e.g., PeekCS (Habtamu et al., 2019) or qCSF (Dorr et al., 2013)) to perform markedly differently, and we predict similar levels of resilience. What is less clear, however, is how well the present findings would generalise to other measures of visual function (e.g., visual acuity, colour vision, visual fields), which may be more or less susceptible to extraneous factors. Thus, while visual acuity has, for example, been shown to be measurable by patients at home (Crossland et al., 2022), it places more demands on users (e.g., to maintain a precise and constant viewing distance) and so may potentially be less resilient to unsupervised use in a home setting.

Fourth, for practical reasons, we used a standardised testing location rather than participants' actual homes. The room was set up as closely as possible to an actual home and contained all the furniture and amenities of a real studio apartment. This provided an ideal location to perform this study, as we could let many extraneous variables vary freely (e.g. illumination) while still having a semi-standardised environment (e.g. windows in the same place). However, there is clearly a difference between being in a home with an experimenter present and being in your own home. For example, participants seated on the sofa were mostly sitting neatly and would not lie down on it as one might do at home. Additionally, participants were instructed on how to do the test right before performing it. Normally, there would be a much longer period between the explanation and when the participant would perform the test at home. Therefore, it would be desirable to build upon

these initial findings in the future by letting people test themselves fully unmonitored at home, though in such circumstances, it would be more challenging to measure and/or account for extraneous factors such as illumination and seating position.

Fifth, this study is only meant to assess the resilience of home monitoring vision tests, not the much wider question of whether patient home monitoring is desirable or effective. The latter further encompasses issues such as value for money, clinical utility and patient acceptability that fall outside the scope of the present study. In the next chapter (Chapter 6), I discuss how, while patients think home monitoring could be beneficial, it could also create non-trivial challenges surrounding issues such as patient anxiety, digital exclusion, and fatigue. Sixth and finally, this study was performed in a simulated home-like environment and does not address factors and concerns that may arise as a result of long-term use, such as in age-related eye conditions. The next chapter (Chapter 6) provides the reader with deeper insights into such patients that would need to be factored for the success of its implementation.

5.5 Conclusion

Extraneous factors (seating type, time of day, presence of a clinician, and motivation) did not significantly affect the contrast sensitivity score, repeatability and duration of either a pen-and-paper or digital CS test.

The findings indicate that the portable CS tests may be relatively resilient to variations in environmental conditions and might therefore be appropriate for patient home monitoring. Next, these results will need to be extended to older individuals and those with vision deficits, as well as testing the individuals in their actual homes.

Chapter 6. The views and opinions of glaucoma and age-related macular degeneration patients on vision home-monitoring: A UK-based focus group study

My final contribution to this programme of work addresses patient acceptability, an important aspect of the feasibility of alternative testing. The study aims to explore the views, expectations, and concerns of patients living with glaucoma and age-related macular degeneration regarding vision home-monitoring. A version of this study, prepared to journal specifications, was published in BMJ Open in July 2024.

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Campbell: Study design, data analysis, and final review of the manuscript.
Edgar: Study design, data analysis, and final review of the manuscript.
Crabb: Funding acquisition, final review of the manuscript and supervision of the project.
Callaghan: Formal analysis, funding acquisition, final review of the manuscript and supervision.
Jones: Data analysis, drafted the manuscript, acquired funding, and supervised the project.

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Abstract

In this qualitative study, participants were given three disease-relevant home-monitoring tests to try. The tests consisted of three visual field tests for the glaucoma groups (Melbourne Rapid Fields, Eyecatcher, Visual Fields Fast) and three acuity and/or contrast-sensitivity tests for AMD groups (AllEye, PopCSF, Spotchecks). After trialling, the participants underwent semi-structured interviews, following which the data were thematically analysed. Six themes emerged from focus groups, the two most frequently referenced being: "concerns about home-monitoring" and "patient and practitioner access to results". Overall, participants believed home-monitoring could provide patients with a greater sense of control, but also expressed concerns, including: the possibility of home-monitoring replacing face-to-face appointments; the burden placed on clinicians by the need to process additional data; struggles keeping up with requisite technologies; and potential anxiety from seeing worrying results. Most devices were scored highly for usability, though several practical improvements were suggested. Our study concluded that patients with mild-to-moderate glaucoma and AMD expect vision home-monitoring to be beneficial but have significant concerns about its potential implementation.

6.1 Introduction

By 2040, the number of people worldwide living with glaucoma or age-related macular degeneration (AMD) is expected to rise from 268 to 400 million (Tham et al., 2014; W. L. Wong et al., 2014). Both conditions require regular monitoring (e.g., yearly (Royal College of Ophthalmologists, 2021), or twice yearly (Crabb et al., 2014a; Wu et al., 2017), or sometimes even more frequently (European Glaucoma Society, 2021)). This monitoring will place increasing strain on hospital eye services, many of which were struggling to meet minimum standards even pre-COVID (Clothworkers Foundation, 2016; Fung et al., 2013; Healthcare Safety Investigation Branch, 2023).

Home-monitoring could help alleviate the strain. Its proponents claim variously that it could provide more efficient, intelligent patient management, produce more reliable, timely patient data, and/or free up appointment availability for high-priority cases (Brady et al., 2015; Suo et al., 2022).

However, evidence for the practical viability of ophthalmic telemedicine remains lacking. Most studies validating home-monitoring devices collect data under artificial, "laboratory" conditions (Busquets & Sabbagh, 2021; Chen et al., 2022; Jones et al., 2019). And those few studies that have asked patients to make longitudinal measurements at home (Guigou et al., 2021; Hu et al., 2023; Jones et al., 2021; Ritchie et al., 2021) have generally focused predominantly on the accuracy and reliability of the core technologies, without considering wider structural questions, including affordability, feasibility, or patient acceptability.

Careful reading of the literature does, however, hint at potential concerns regarding the real-world viability of home-monitoring. For example, while Hu et al. (2022) showed that many glaucoma patients consider home perimetry and tonometry both acceptable and useful, 25% of patients needed to contact the researchers for assistance during the study, and 1 in 20 participants were excluded altogether due to 'an inability to demonstrate competence' (Hu et al., 2023). Similarly, Guigou et al. (2021) investigated AMD home acuity assessments and found that by the end of the nine-month study period, only 24% of participants remained active users (Guigou et al., 2021).

The present study used focus groups to qualitatively explore patients' views regarding the acceptability of home-monitoring and its perceived challenges and opportunities. Participants were shown a range of potential, disease-appropriate home-monitoring devices to avoid focusing on any one specific technology. We included both glaucoma and AMD patients to try to generalise beyond a single patient population. Focus groups were chosen over questionnaires to address this question, as we wanted qualitative information about home-monitoring and did not wish to project any preconceived ideas about patients' perspectives on home monitoring.

6.2 Methods

6.2.1 Participants

Fifteen people with established diagnoses of glaucoma (*N*=8) or AMD (*N*=7) participated in focus groups at City, University of London between May and June 2022. (Two focus groups for glaucoma patients. Two for AMD. Three or four people per group.) The groups were intentionally kept small to encourage everyone to participate. Recruitment was through a database of previous research volunteers, and via newsletters of two UK eye charities (Glaucoma UK; The Macular Society). Anecdotally, these volunteers were well-informed about their condition and, as recruited through charities, were quite happy to participate in research. A summary of their conditions is provided in **Supplementary Table 9.7**. Table showing participant demographic and diagnosis information.**Table 9.7**. Inclusion criteria were: (i) a self-reported diagnosis of glaucoma or AMD, and (ii) the ability to travel to City, University of London. All participants provided written informed consent. The study had ethical approval from the Optometry Proportionate Review Committee at City, University of London (#ETH2122-0368) and was conducted in accordance with the Declaration of Helsinki.

6.2.2 Home-monitoring tests

Participants were given 3 example home-monitoring technologies to try (though no actual clinical data were collected). Glaucoma patients were given three visual field tests (**Figure 6.1A-C**), while AMD patients were given one hyperacuity test and two contrast sensitivity tests (**Figure 6.1-F**). Details of all six tests are given in **Supplementary Material 9.4.1**. Except for the Eyecatcher smartglasses, which used special lenses fitted through detachable lens inserts (Similar to Chapter 3), all tests were performed using their habitual near correction.

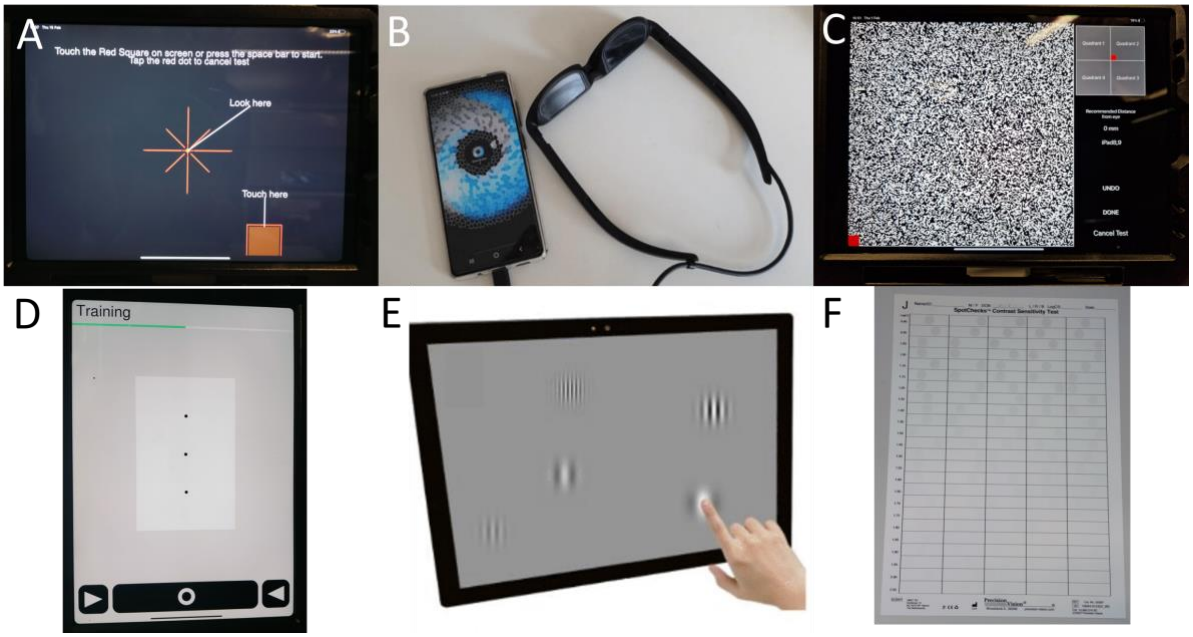


Figure 6.1. Images showing the tests given to participants in the glaucoma groups (Panels A-C) and the AMD groups (Panels D-F). These were: **(A)** Melbourne Rapid Fields (Image from: (Prea et al., 2022)); **(B)** Eyecatcher; **(C)** Visual Fields Fast; **(D)** AllEye; **(E)** PopCSF; and **(F)** Spotchecks.

6.2.3 Procedure

The present focus group study used a positivist, qualitative study approach, featuring semi-structured topic guides, and was facilitated by authors SD and MR. The study is positivist by nature, as it is not based on a researcher's hypothesis; all our findings were empirically collected, and patients' views were considered the objective truth. This methodology allowed participants to communicate with each other and explore their views in a relatively informal setting. Focus groups also encourage participants to engage in open conversation and generate their own questions and analysis from shared experiences (Lewis, 2018). A copy of the topic guide for the focus groups can be found as supplementary material (**Supplementary Table 9.5**).

First, authors SD, PJ, and TG had initial discussions to identify the relevant predefined topics relevant to the specific tests used. The predefined topics focused on: participants' thoughts on the specific tests experienced; thoughts on the concept of telemedicine/home-monitoring in general; how frequently they would be willing to do these tests at home;

whether anything would stop them from using the tests, and what would motivate them to keep using the tests.

To contextualise focus group responses, additional steps were taken to roughly characterise: (i) participants' technical proficiency, and (ii) the usability of the home-monitoring technologies. To assess technical proficiency, participants were asked a series of simple questions ('What technology do you currently own?', 'Do you need any help using the technology?' and 'From whom do you get help?'). To assess the usability of each device, participants were asked to complete the System Usability Scale (SUS): a general-purpose, Likert-based standardised scale for assessing perceived usability of digital technologies (Gale et al., 2013), containing statements such as "I felt very confident using the system". All participants completed the SUS once for each device. Finally, to further understand how home-monitoring systems might be improved, participants were presented with six possible features (**Supplementary Table 9.6**) and asked to rank them by importance.

6.2.4 Analysis

Focus group proceedings were transcribed by a professional transcription service (Sterling Transcription Service Ltd, London, UK). Thematic analysis was performed using NVivo 12 (QSR International Ltd, Cambridge, Massachusetts, USA), as follows. The thematic analysis consisted of seven steps: transcription, familiarisation, coding, developing an analytical framework, applying the analytical framework, charting data into the framework matrix, and interpreting the data. Post-transcription, author SD familiarised herself with the data and identified common themes or "nodes". Issues and discussion points from the transcripts were coded into different sections ("nodes"). The nodes were independently reviewed by another researcher (PJ), and disagreements were taken to a third researcher (TC) for the final decision. The research group was a mix of clinicians, product developers, and psychologists who helped reduce biases and encourage researcher reflexivity. The final agreed-upon nodes were grouped into key themes, which were reviewed by two researchers (PJ and TC) to create the final framework for analysis.

6.2.5 Patient and public involvement

After drafting the manuscript, all participants were given a copy of the report and asked to provide feedback on whether the themes and points accurately reflected their views and

priorities. Five participants replied, all of whom responded positively, indicating that their views were well represented.

6.3 Results

Eight people with glaucoma and seven with AMD participated (see **Supplementary Material Table 9.7** for demographics and disease type). All participants had been diagnosed at least three years prior to the focus groups (mean 7.4 years) and lived within one hour travelling time by public transport/taxi from City, University of London.

Six overall themes emerged (**Figure 6.2** and **Figure 6.3**). The most frequently discussed theme among glaucoma patients was 'concerns regarding the costs/challenges of home-monitoring' (**Figure 6.2**)**.** The most frequently discussed theme in AMD groups was 'the positives of home-monitoring' (**Figure 6.3**)**.** The following sections present key findings for each theme: Theme 1 was referenced most frequently by all focus groups combined, while Theme 6 was referenced least often.

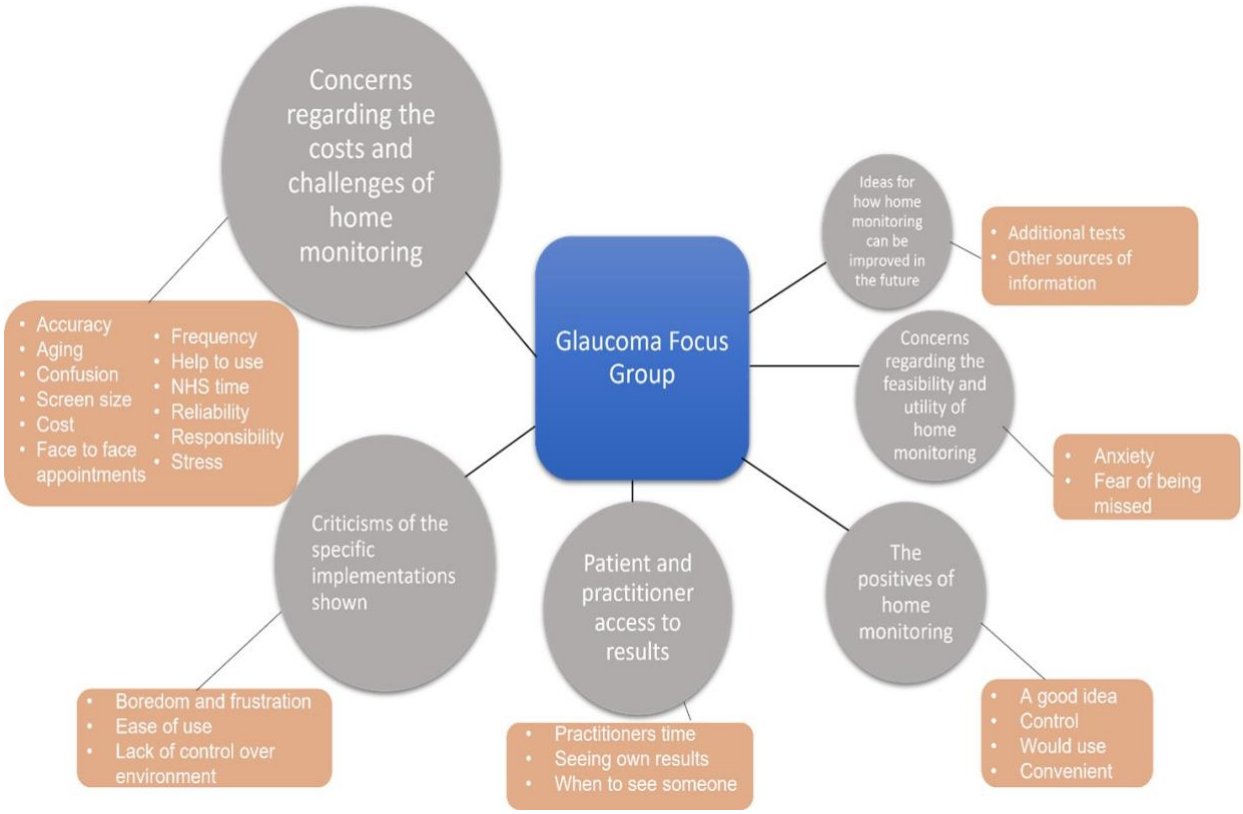


Figure 6.2. Spider diagram displaying the themes from the glaucoma focus groups. The grey circles represent the themes, and the orange boxes are the sub-themes or 'nodes'. See also **Supplementary Figure 9.11** for a more conventional, bar-chart visualisation of these same data.

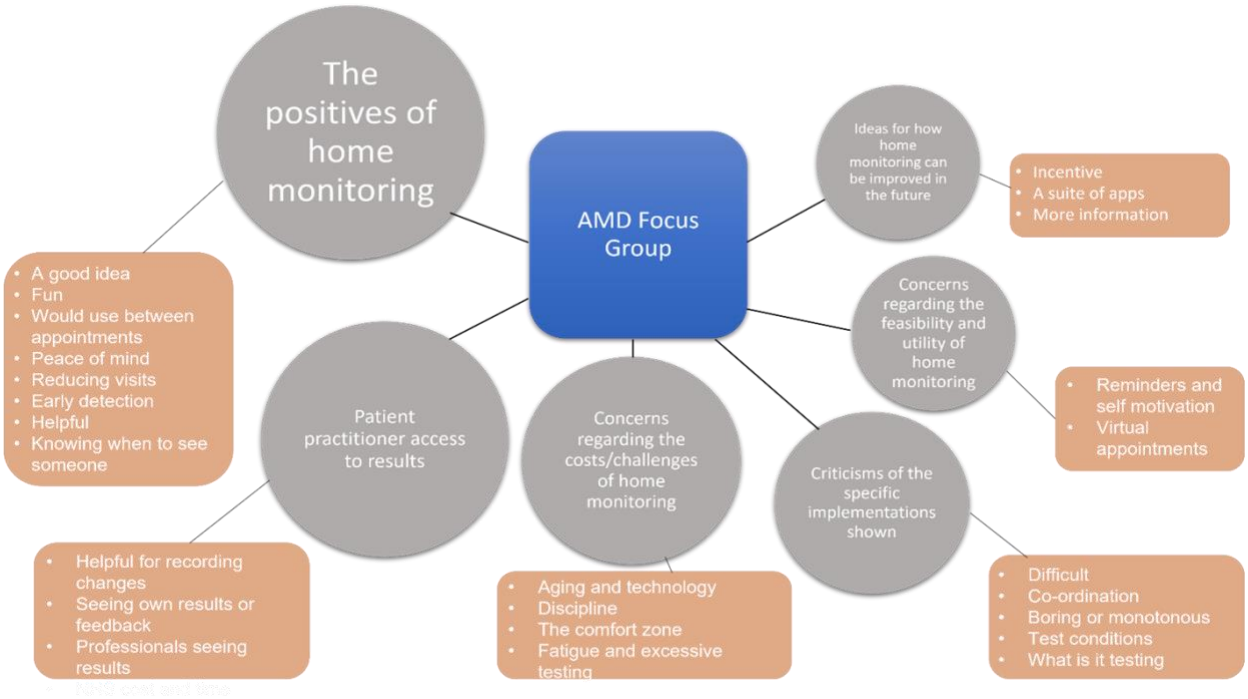


Figure 6.3. Spider diagram displaying the themes from the AMD focus groups shown in the same format as **Figure 6.2**.

6.3.1 Theme 1: Concerns regarding the costs/challenges of Home-monitoring

The theme with the greatest number of comments overall was concerns regarding the practical feasibility of home-monitoring. These comments mostly focused on a number of challenges, delineated below, that participants felt needed to be addressed before home-monitoring could be implemented effectively.

First, both patient groups expressed concerns that as individuals age, they either may lack access to the requisite technology or may struggle to keep up with the requisite technologies, potentially resulting in changes in patients' vision being missed:

"Of course, it's relying on, to some extent, the ageing process and then us still being able to manage to do our own testing at home, and then we've not sort of – for some reason we're now past it, so to speak."- Glaucoma P3

“I think young people, you know, do it, they just cope with everything. Where, for me, I mean I don’t even – I mean, I use my computer simply because I have to, not because I want to…” -AMD P1

“The other thing is there are quite a fair number of people who probably would find even that little gadget a bit difficult to use, and if the system started depending on people using those devices, some people might really get missed, because they really weren’t quite up to the tech.” -Glaucoma P2

“I think we must realise in this country that not everybody has a computer, a laptop, or a smartphone, and they certainly don’t know how to use it. But I would say that a lot of very elderly people cannot and don’t want to learn how to use a computer…”- AMD P5

To explore further our participants’ access to --- and proficiency with --- technology, we asked them to record what devices they own. 93% owned a laptop or desktop, 80% a smartphone, and 47% of participants owned a tablet. Subsequently, when asked about whether or not they needed assistance with using their technology, 33% said they needed some help, with most helpers being ‘friends and family’.

Second, participants questioned how home-monitoring might impact health care costs. All thought home-monitoring would be helpful in reducing the number of hospital visits. But several noted that results would still require scrutiny. Therefore --- given the greater potential volume of data --- they wondered whether the workload for clinicians might remain unchanged, or even increase:

“The only concern is, of course, is it being monitored when it gets to the other end, or is it just being sort of filed away for another six months.”- Glaucoma P1

“But if you’re sending them results every month, they’re going to get overwhelmed. We won’t be saving any money.” – AMD P1

Finally, participants were asked how frequently they would be willing to perform these home-monitoring tests, with the concern being testing fatigue. All said they would do the tests as frequently as their clinicians asked them to. However, the glaucoma group did express concerns about fatigue from excessive testing:

"I felt tired at my eyes. So doing this every two weeks, for me, might be too often"- Glaucoma P4

On the other hand, AMD participants all said that with reminders, they would be more likely to do the tests when required, and therefore frequency of testing was less of a concern:

"I think it's good because, from my experience, I don't have any regular check-ups in the diary, so it's good to force yourself to be aware to check and – because you might not notice."- AMD P1

"But if it was a matter of going in to see a clinician, they wouldn't be able to do it more than once every three months or something, would you? So, you've got to – if you do it every two weeks at home that would surely be an advantage, yeah, for those who bother to do it."- AMD P7

In summary, unsurprisingly, all participants mentioned at least one challenge regarding the feasibility of home-monitoring, the most common being technical impediments, and the potential staffing costs for healthcare providers. The question about the frequency of testing had mixed responses, with participants agreeing about the fatigue that comes with testing but also understanding the value and importance of regular monitoring.

6.3.2 Theme 2: Patient and practitioner access to results

In both groups, questions were raised about what would happen to the results once the tests had been completed at home. Two main issues emerged: the level of patient access to their own data, and the integration of telemedicine technologies with clinicians and clinical care.

All participants wanted to be able to see their own results and have an explanation of what their results mean:

"Yes [we would like to see our own results], and what it means"- AMD P4

Indeed, some individuals went further and intimated they would be comfortable with using these data themselves to monitor their condition and/or make management decisions:

"You see at the moment, one of my eyes I have a visit for every 12 weeks, the other eye is six weeks, and in between, I go to another consultant for my eyes. But if I had this and I noticed

that the eye which is quite good, and I only go [every] 12 weeks, has suddenly got worse, then I could e-mail the consultant and say, can I come in, or I could go straight to A&E…"- AMD P2

"I think if you're better informed then you can make the proper decisions, can't you."- Glaucoma P1

"I think it would be very good, and I like this idea of being able to monitor it. That's what I think the best beauty is. Not necessarily rushing to see the doctor but be able to monitor it."- AMD P1

However, it was suggested that clear guidance was required regarding how the data were presented, with several individuals favouring a clear 'thermometer' or 'traffic light' format:

"In other words, if you do fall below the number, then you must – well, you should come in and be seen."- AMD P7

Furthermore, several participants stressed that they would not want to be solely responsible for evaluating their results, and that it was imperative that their clinician had timely access to the data:

"You'd send in the results – you'd see the results yourself, and he gets them as well, and you both independently make up your mind whether you need to go and see him, I'd have thought."- AMD P7

"I would do it, if like [P6] says, it links up with a clinician who can interpret the results, then I would do it, not just randomly on my own."- Glaucoma P5

During discussions, two participants in the glaucoma groups raised the point that waiting for a clinician to evaluate telemedical data could *diminish* the perceived level of control patients have over their own health:

"[In those circumstances, home-monitoring] wouldn't be empowering because you'd still be sat there waiting for somebody else to do something."- Glaucoma P5

Overall, all participants favoured seeing their results, provided there was clear guidance on how to interpret the data, and provided this was not abrogating clinician responsibility, discussed further below (see *Theme 5*).

6.3.3 Theme 3: The positives of home-monitoring

All participants believed that, practical challenges notwithstanding, home-monitoring could improve healthcare by augmenting existing, in-person appointments:

"In the gaps between appointments…not instead of…It's not taking over the appointment"- AMD P1

As presented later (see *Theme 5*), participants were keen to stress that home-monitoring ought not replace in-person clinic appointments altogether. But some participants thought home-monitoring might nevertheless be helpful in reducing the overall number of hospital visits:

"Within reason. If you can cut down the visits to once a year rather than once every three months that's reasonable, isn't it?" - AMD P2

"Well, you could probably space [out] appointments a bit more, which would mean that the system would work better for everybody." - Glaucoma P2

"That's also less time-consuming for the NHS, then that would be good."- Glaucoma P3

And that such benefits might be particularly opportune for individuals in remote geographic locations, for whom attending hospital appointments is costly:

"If you were out in, say, a rural area, where I was brought up, it would be a whole day to go to hospital. I mean now it takes me a good hour or more. So, you need transport, whereas if you were monitoring at home, it would give you peace of mind, wouldn't it?"- AMD P4

Participants also discussed other potential benefits of home-monitoring, such as the tests providing patients with more information to discuss with their clinicians during clinic visits:

"The fact that you've got something you can do at home and you can do it before you see a consultant, I think that's a big benefit because I've had conversations with a consultant

where he's said, well we didn't do your visual fields so I've got nothing to compare it [with]."- Glaucoma P6

"You're reminded usually when your yearly appointment is, so if they say well, is there anything else you want to look at during this appointment, then you say, I would like to look at the results of my [home-monitoring tests]"- AMD P5

Additionally, both groups made the point that home-monitoring would be beneficial in facilitating early detection of changes in visual function. For example, one participant mentioned the benefit of home-monitoring tests allowing young people to check their eyes frequently:

"I think it would be a good thing if people were taught to check their eyes from quite a young age, because since I've had problems with my eyes, I've got my nieces and nephews to check their eyes…and the quicker it's picked up, the quicker they can save your eyesight."- AMD P2

Participants in the glaucoma group discussed the importance of home-monitoring in helping patients feel they are in control of their condition:

"I think being able to have something that enables you to do your own testing and monitoring is really empowering, and I would love to have something like that."- Glaucoma P5

"I mean the other thing is it gives you a feeling of being in control as well, doesn't it? So, if you acquire one of those things and you feel there is something wrong and contact them."- Glaucoma P1

"The eyes are the most important part of your body – somebody's body, [laughs] so you don't [want] to lose your sight. So, you want to be able to manage it properly, and yeah."- Glaucoma P4

Finally, participants in both groups believed home-monitoring was a good idea and they would use it if they were advised to do so by their practitioner.

"Yes, if I was advised by my ophthalmologist to do it, then yes I would"- Glaucoma P2

“I would love to have something to measure visual fields and eye pressure that I could monitor at home.”- Glaucoma P5

Overall, although there were a number of positive comments about home-monitoring from both groups, especially when discussing the control and self-monitoring aspects of testing their own vision at home, there were a higher number of negative comments.

6.3.4 Theme 4: Criticisms of the specific implementations shown

The following comments were made regarding the three specific tests that each participant experienced (see **Figure 6.1**). In the glaucoma group, participants questioned the potential (in)accuracy of the tests and expressed a general lack of confidence in the notion of home-assessments:

“At the moment, I don’t feel confident that I would be getting really accurate results. I don’t think I would really want to use any of these tests unless on a very occasional basis, but I don’t see me pursuing these tests at home [at] the moment.”- Glaucoma P1

“I felt the testing needed some sort of refinement. I just felt that it wasn’t quite complete in some way.”- Glaucoma P2

“[I] Would be really sceptical about trying anything that isn’t as accurate as things you have already. So, anything not as good, I don’t really see the point of using them.”- Glaucoma P8

However, as many of the study participants have had their diagnosis for a number of years, they said this response may reflect their familiarity with tests done in the clinic, so deviating from these would cause confusion:

“I wasn’t used to it. I’m so conditioned by the Humphrey visual field [test], it’s like anything that detours from that. I don’t like change, and I’m just used to doing that.”- Glaucoma P4

Similarly, despite limited references to this theme in the AMD group, one criticism was that other issues, such as poor co-ordination, may cause them to have a lower score:

“You had to be more dextrous because you were having to get your finger up and down the page…and it depends how quick you are, I think…you could miss quite a few, I think.”- AMD P2

Another issue from the AMD group was that the tests varied markedly in difficulty depending on the stage of macular degeneration and, thus, may not be appropriate for patients across the disease spectrum. For example, one participant with unilateral wet AMD said:

"I found the middle one with the bubbles [PopCSF] really very difficult because they were so light, and I find with my macular degeneration I need sharp objects to see them."- AMD P4

However, two AMD tests were measuring contrast sensitivity which would explain why some participants had difficulties with the test.

In the glaucoma group, some concerns were raised about a lack of control of the testing environment due, in particular, to the nature of visual field testing being dependent on low light conditions. Participants expressed that it would be better to complete the tests in complete darkness, similar to the clinical environment.

"Criticisms of [Eyecatcher] would be that I want an immersive thing that it can just block out everything else that's going on around me. So almost like I'm on a VR headset so I've got nothing else that I can see out past there."- Glaucoma P1

"[For all of the tests] Being able to block out the rest of the light would be much better."- Glaucoma P2

Finally, all participants expressed frustration and confusion with the Visual Fields Fast test, an unconventional noise-campimeter (see **Figure 6.1C**):

"I mean I was wondering whether I understood it properly while I was using it – actually, what am I looking for here? Where's the dot – you know what a dot is?"- Glaucoma P5

"Yeah, so perhaps it was a bit too difficult to see the anomalies. It was a bit too difficult to figure out what you were looking for exactly"- Glaucoma P5

To explore further the usability of each test, participants were asked to rate each using the SUS (see *Methods*). Overall, ratings were generally high on the 5 positive statements (see **Figure 6.3**). The MRF and Eyecatcher, on average, scored highly (4.1/5) in the glaucoma group, while in the AMD group all 3 measures were rated highly on average on the positive

statements, with Alleye scoring highest (4.8/5) followed by Spotchecks (4.6/5) and PopCSF (4/5).

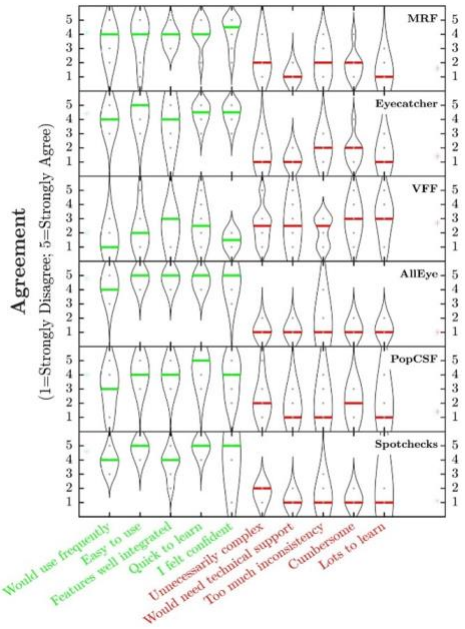


Figure 6.4. Violin plots showing how each test was rated on the SUS. The green font represents positive statements, and the red font represents negative statements. The higher a test is rated on the green text statements and lower on the red statements, the more the test is preferred.

Overall, participants all felt that more work was required to refine current tests. The glaucoma group expressed more concerns with the frequency of testing and testing environment, whereas the AMD group were more concerned about differing abilities and other issues that may affect performance.

6.3.5 Theme 5: Concerns regarding the feasibility and utility of home-monitoring

Concerns about missing appointments or home-monitoring replacing face-to-face visits were mainly expressed in the AMD group:

“I look forward to seeing the consultant and I wouldn’t want to do that online because this is a serious condition.” - AMD P3

Anxiety was expressed in the glaucoma group only and included that, without feedback or supervision, they may perform the test incorrectly:

“The anxiety of doing it just at home and there’s nobody; it’s like there’s no-one coming to see what I’m doing” – Glaucoma P1

There were also concerns that the results --- even if correct --- may be disheartening:

“I didn’t think I got very good results, which might concern me.”- Glaucoma P5

“I feel probably if your eye condition was getting worse and worse you might not want to know that.”- Glaucoma P8

Finally, glaucoma group members were concerned that home-monitoring might shift the burden of responsibility from clinicians to patients:

“I wouldn’t want to be reliant for it to be me only, that I’m responsible for the results and interpreting them and stuff like that.”- Glaucoma P7

Participants also discussed fears about home-monitoring which, if poorly implemented, could lead to worsening of existing services, ultimately leading to poorer patient care:

“But the only trouble is it can become a sort of way in which the system – I mean the system misses you, because you’re so busy testing yourself at home and thinking things are all right, and the health system may be seeing that’s all right, he’s checking himself at home. But really, if you had actually been visiting the clinic, you might have had something further – further test or investigations done and maybe something could be caught.”- Glaucoma P1

“I don’t know, it seems to be a two-tier society, and I think some people will get left behind by this if telemedicine is treated as the norm. There’s still a need for people to go there and be looked [at].”- Glaucoma P8

“But I mean I think the anxiety around it is that the system is trying to fob me off with this piece of equipment, in the hope that I won’t bother them so much.”- Glaucoma P4

In summary, the main concern for AMD patients is that the face-to-face elements of appointments should not be replaced. Participants believed that seeing a clinician face-to-face or even having a phone discussion is very important, providing benefits beyond results screening, and should not be completely replaced.

6.3.6 Theme 6: Ideas for how home-monitoring measures could be improved in the future

Participants in all focus groups expressed ideas about what they would like to see from home-monitoring devices in the future. In the glaucoma group, participants felt it was important to have a system alerting them to contact someone:

“Well, I think in-built warning system would be beneficial, apart from your own viewing the documents or results”- Glaucoma P2

“If they had a phone line where you could ring and you spoke to somebody, a sort of triage system where they could go, yeah, okay, these are your results. Don’t worry that’s not a concern, keep monitoring or they could say, no come in tomorrow or now.”- Glaucoma P6

Similarly, participants in the AMD group all liked the traffic light system in one test which helped to interpret results and gave an alert when they should see a practitioner:

“The one where you had to line up the dots, it gives you a score at the end, and the score will either appear in green if you’re doing better than your previous one, it will appear in yellow if you’ve kept it the same, or it will appear in red if you’ve done worse than your previous one.”- AMD P2

Participants in the glaucoma focus group asked whether home-monitoring of visual function could be complemented by measurement of intraocular pressure:

“Would we ever be able to do eye pressure testing at home? Is that something that’s on the cards?”- Glaucoma P4

All participants in the AMD group expressed the importance of having reminders to complete the tests, drawing from their experiences of not using the Amsler grids as regularly as they should:

“I think a reminder’s good because, yeah, you’ve got to be self-motivated for anything like that, like exercise or anything that you know you’ve got to do because it’s good for you…”- AMD P2

Some participants in the AMD group brought up the idea of having a 'suite' of tests, with all the home-monitoring tests recommended by the clinic in one place:

"It was only the second one I favoured less, but I still think as a suite, it would be good to have all of them…"- AMD P1

Another suggested improvement from the AMD group was to incorporate an incentive for patients to do their testing, such as a spinning wheel that can reward patients for completing their tests:

"I've not got one of those automatic meters yet, and every month they say they want the record sent in, and if you do that, they give you a free spin on their little magic wheel, and if you win, you're supposed to get £2 or £5 or something, how about that as an idea? You know, give people some incentive, even though it's a little bit just to do this thing."- AMD P7

Both groups agreed on the importance of having more information available to them, especially about their own results, other home-monitoring tests and advice:

"But I need information, and I need regular testing to know that it's not getting worse."- AMD P7

"There's so much information out there, it is confusing. But there are respectable sources, I mean, you need to find out about them."- Glaucoma P1

Based on participant comments about what they would like to see in the future, both groups prioritised very different features, but agreed that more information and feedback were of fundamental importance. Participants completed a questionnaire that asked them to rank the importance of features they wished to see in future home-monitoring technologies. The most important feature across both groups was 'being notified of when to see someone'.

6.4 Discussion

Even within a small cohort of glaucoma and AMD patients, views regarding vision home-monitoring were mixed. The main positives were that home-monitoring would give patients a greater sense of control over their own condition and could provide clinical benefits by enabling early detection of disease progression. However, the single most commonly discussed themes were concerns about costs and challenges of home-monitoring, and concerns regarding access to data (incl. the cost of requiring clinicians to process large volumes of additional information).

Specific concerns were also raised regarding the tests themselves. Patients generally rated usability of the technologies as high, as indicated by favourable scores on the System Usability Scale (SUS). However, they also identified possible design and implementation flaws that could limit adherence or accuracy. They also provided suggestions regarding what they would like to see from home-monitoring devices in the future.

6.4.1 Reducing the burden on patients and practitioners

Using home-monitoring to *augment* existing monitoring was universally well received (participants recognised potential logistical and financial benefits). However, participants had mixed views regarding home-monitoring *replacing* in-person assessments, with concerns raised about possible reduced quality of care (e.g., concerns that after being issued a home-monitoring device, patients might be forgotten). They also questioned whether home-monitoring would even reduce the burden on clinicians, noting that the additional data collection might decrease technicians' current workload, but actually *increase* clinicians' workload. Though they also noted that the extra information provided might help clinicians make faster or more accurate decisions (Faulkner et al., 2012; Maissenhaelter et al., 2018) – something that has also been noted by wider research regarding home-monitoring of other systemic health conditions (Schramm et al., 2019).

6.4.2 Patient-practitioner access to results

All participants expressed that, in addition to sending the practitioner their results, they would also want access to their own results. This is consistent with research into other conditions (e.g., vascular hypertension), where patients often note that seeing their own

results gives them a sense of control (Shah et al., 2015) and affords better management of their own health (Cappuccio et al., 2004; Mak et al., 2015). Though in this respect it is important to note that ophthalmic data is often relatively complex, and it may be significant that all the participants in the present study had lived with their diagnosis for many years and so may feel relatively confident interpreting eye test data. Research confirms that patients may struggle with comprehension of complicated medical results (Pyper et al., 2004; Wilkie, 2019), and inaccurate interpretation of results can increase the number of hospital visits and levels of anxiety (Korot et al., 2022). Our participants also shared these concerns, particularly that a 'worse' result than normal would worry them, even though they had been undergoing the tests for a number of years. Interpretation of results could be a much greater concern for 'newer' patients.

6.4.3 Access to technology

One practical obstacle discussed in all focus groups was digital exclusion: the idea that a shift towards home-monitoring might result in some patients 'missing out' because they were unable to keep up with the requisite technology. Consistent with this, prior research has found that many patients are put off by digital technologies (Middle & Welch, 2022), and digital exclusion has a significant impact on patient care in mental health services, particularly in community services (Berry et al., 2019; Razavi et al., 2018).

In this respect, it is interesting to note that even amongst our sample of reasonably 'tech savvy' participants, even though a majority owned a computer or smartphone, almost a third expressed a regular need for assistance to use their devices (typically from friends or family members). A post-pandemic paper assessing the digital literacy of patients at an urban cancer centre in Pennsylvania, USA, highlighted that older, less-educated patients belonging to ethnic minorities are more likely to have low levels of eHealth literacy. Our participants also expressed similar concerns, indicating how health-care providers need to be conscious of these differences in digital literacy before implementing technology on a larger scale (Leader et al., 2021).

6.4.4 Comparing the views of glaucoma versus AMD patients

Participants with glaucoma discussed the positives of home-monitoring less often than those in the AMD groups. The reasons for that are not entirely clear, though one obvious

factor is that visual field testing for glaucoma is a significantly longer and more onerous procedure. Additionally, AMD participants are already familiar with the concept of home-testing via the Amsler grid (Prea et al., 2022), and noted that digital technologies could help by providing automated reminders. Conversely, needing reminders was never discussed in the glaucoma group, where the main discussion point was fatigue caused by excessive home testing. Though ultimately most participants agreed they would carry out home-monitoring as often as their physician deemed was required.

6.4.5 Limitations and future work

The primary limitations of this study relate to the generalisability and representativeness of the sample population. First, participants all lived in highly urban areas. Second, they were highly motivated and self-selecting (being research volunteers). These research volunteers were noticeably more enthused about new research and technology in comparison with the general hospital-going population. Third, they were contacted via email, necessitating that they possess baseline familiarity with digital technology (though many nevertheless needed regular assistance, as previously noted). Fourth, while their visual impairment was not formally assessed, all participants self-reported their condition as mild-to-moderate, and could travel independently, and all had lived with their conditions for some time. All these factors limit the overall generalisability of the findings and hint towards further research in regular hospital-going patients to truly understand the impact of using such devices.

Some of these factors (e.g., digital familiarity, high motivation) may have promoted positive opinions about the feasibility of remote monitoring, while others (urban-centric, well-established diagnosis) may have led to particular benefits and opportunities being underreported. Ultimately, a much larger study is required to understand the acceptability of vision home-monitoring within the patient population more generally, or within specific subgroups (e.g., the very elderly). In that sense, the present work should be understood only as an initial exploration of a much wider topic. Though we hypothesise that it is precisely the present patient types (relatively young, self-motivated, and with mild-to-moderate disease) for whom home-monitoring is likely to prove most feasible and of greatest utility, short-term. In the future, it would also be helpful to understand the impact of demographic and socio-economic factors such as education, levels of deprivation, language, ethnicity, and

other barriers and facilitators that impact the implementation of these devices in mainstream care.

Regarding the study design, focus group discussions were facilitated using prompts to encourage discussion about the idea of home-monitoring (e.g., *What do you think about the idea of telemedicine?*). Although an established qualitative technique, this is also an inevitable source of potential bias. For example, some prompts used wording that could have led participants to focus on negatives (e.g. *This app is recommended to be used once every two weeks, would you be likely to do this?*) while others could have a focus on positives (e.g*., did you think the system was user friendly?*). While strenuous efforts were made to maintain impartiality, a key corollary is that readers should not, for example, place too much emphasis on the exact ratio of positive/negative comments.

Although we try to provide evidence for short-term feasibility and patient acceptability, we did not consider factors impacting sustained engagement and compliance with these tests over long-term monitoring periods. Understanding long-term usage patterns would only be possible through longer clinical trials that extend over a couple of years, which was beyond the scope of this study and the PhD.

A final limitation was the setting and limited time that participants had with the range of devices (around 30 minutes, under supervision, within a university setting). Despite minimal intervention by the researchers, this does not reflect 'real-life' home-monitoring. To achieve this, it would be necessary to allow participants to take the devices home for an extended period (e.g., as per (Shickle et al., 2015)). Similarly, a future, larger study could examine how patients' perceptions of home-monitoring vary with disease severity and/or years since diagnosis, or other important practical issues, including the health economics associated with home-monitoring (i.e., costs of the test, reimbursement of charges, etc.).

6.5 Conclusions

In conclusion, participants with glaucoma and AMD have a number of concerns regarding home monitoring. Despite references to an increased sense of control and the potential for early detection of changes, many participants still felt there was more work to be done. The tests in this study were criticised for some aspects of their design and reliability, but

participants were clear about what future tests should include. Further work on larger samples can provide more insights based on diagnosis and location.

Chapter 7. General Thesis Discussion

7.1 Overall summary of findings

In this thesis, I explored the feasibility of employing novel vision tests to examine age-related eye tests in England. In short, I found that: people residing in neighbourhoods with higher deprivation levels are more likely to present with advanced visual field loss to the clinic; however, rapid worsening (progression) of visual field loss is not noted once the patient is under the care of the HES (Chapter 2). Beyond clinical necessity, my work demonstrates that it is feasible to both assess patients using novel vision tests in a clinic waiting room (Chapter 3) and to monitor glaucoma patients' visual field using unsupervised head-mounted visual field glasses (Chapter 4). This work also confirmed that home vision assessment technologies (both printed and digital) are largely resilient to several uncontrolled environmental factors (Chapter 5). Critically, while these technical strengths exist, my work also revealed mixed opinions among glaucoma and AMD patients regarding the adoption of such new remote home-monitoring devices (Chapter 6).

7.1.1 Comparison of current results to the wider literature

7.1.1.1 Socio-economic deprivation and other age-related eye diseases (Chapter 2)

My work on deprivation in this thesis focused only on glaucoma; however, there is substantive evidence that socio-economic distress is directly related to other age-related eye diseases other than glaucoma, such as cataract, AMD, and diabetic retinopathy.

Regarding cataract, patients from lower socio-economic conditions tend to present to the clinic for cataract care later than average (Johnston et al., 2020), consistent with my findings in Chapter 2 (Section 2.2.3). Johnston et al. analysed a dataset of NHS cataract patients across 68 NHS centres, using the IMD scale to compare the population, similar to the work described in Chapter 2. A comparison of the median pre-operative visual acuity between the most and the least deprived decile revealed significant differences; however, Johnston et al. did not report the odds of presenting earlier or later for surgery (logistic regression). Notably, no evidence was found between socio-economic status and care-seeking access to

cataract surgery, highlighting that there was no evidence of inequality once the patient was in their database, irrespective of their socio-economic disadvantage (Johnston et al., 2020). In contrast, Keenan et al. (2007) found that cataract surgery rates, as reported by local authorities, exhibited a moderate positive correlation (r^2=0.24, r=0.49) with higher IMD scores (more deprived regions), indicating a slight increase in surgery rates within more deprived regions (Keenan et al., 2007). These findings align with my own analysis of longitudinal data in Chapter 2 (Section 2.3.2), as both studies underscore the extent to which progression rates can be enhanced by systemic equity.

By contrast, the evidence correlating deprivation with poorer visual outcomes in AMD has been more controversial. A 2021 study, using a large sample of 130K+ participants from the UK Biobank database, reported that having no qualifications reduced the odds of developing macular disease; yet lower annual household income (<£18,000) was associated with a higher risk (24%) than people with a larger annual income (>£100,000) (Yip et al., 2021). This finding appears to be contradictory, as better education and income are often correlated; however, the analysis relied solely on questionnaires, so people with no qualifications were likely underrepresented. The study also used the Townsend Deprivation Index rather than IMD. Contrastingly, the EPIC-Norfolk eye study that used IMD (2010 version) as a measure reported that socio-economic disadvantage did correlate with a higher prevalence of AMD. The study showed that people living in the most affluent areas had roughly half the odds of developing AMD, after controlling for factors of age, sex, education, social class, and smoking. However, their study also noted that the cohort analysed was generally more affluent, similar to my study's cohort from Chapter 2, which may limit the generalisability of the results (Yip et al., 2021).

A similar socioeconomic gradient has also been observed in patients with diabetic retinopathy. A recent paper by Giannakis et al. states that assessing the individual components of the Index of Multiple Deprivation rather than the aggregate score could help better inform specific drivers of inequality and inform targeted socioeconomic interventions (Giannakis et al., 2024). Their analysis identified that scores on living environment, education and income had the biggest impact on the development of incident referable DR. Whether this pattern extends to glaucoma and other eye conditions needs further investigation.

Deprivation has shown an impact beyond age-related eye disease. In UK-based adults with refractive error, socio-economic deprivation has been linked to a shorter axial length (-0.24 mm difference between the highest and lowest IMD quintile) and increased astigmatism (-0.12D difference between the highest and lowest IMD quintile), though no association has been noted with spherical refractive power (Goverdhan et al., 2011). This pattern has also been observed in children with the risk of amblyopia and its associated conditions, as children from more deprived localities in Scotland were more likely to fail their preschool vision screening than those from affluent neighbourhoods (Conway et al., 2026; O'Colmain et al., 2016).

7.1.1.2 Productive use of waiting time in Ophthalmology clinics (Chapter 3)

Oermann (2003), in their study, used health education to occupy the patients while they waited to be seen. The study reported that patients attending the eye clinic in Midwest America who had a nurse show them a video about glaucoma care, go over key points, and answer individual questions during their waiting time were found to be significantly more satisfied with the education received compared to patients with no engagement (Oermann, 2003). However, this exercise had no impact on overall patient satisfaction. The study also reported that patients' satisfaction was negatively affected by longer visit durations and waiting times. The study also discussed and employed an efficiency-improvement method called lean analysis, a method increasingly adopted by health care settings to maximise resources and improve inefficiencies (Oermann, 2003). In this context, patient waiting time was a "non-value time add" as no clinical services were being provided, and it led to poorer patient satisfaction. Newman-Casey et al. applied lean analysis to identify pockets of usable wait time within glaucoma visits for patient engagement. Follow-up glaucoma patients spent an average of 102 ± 44.7 minutes in the clinic, comparable to the median time from my study in Chapter 3 (109 minutes {IQR = 83.5-153). The majority of the patients (87.5%) had at least one 10+ minutes of uninterrupted waiting time and suggested that the time be used for targeted patient education, such as teaching drop instillation techniques (Newman-Casey et al., 2019).

7.1.1.3 Head-mounted portable perimetry (Chapter 4)

Since the publication of the work on the portable head-mounted perimeter (Eyecatcher), several relevant studies have emerged. Bradley et al. (2024) used a virtual-reality headset (Radius), heavier in comparison to the Eyecatcher (Radius:170g; Eyecatcher: 107g), in 100 glaucoma patients of varying severity (Bradley et al., 2024). The study reported a better association with the HFA MD than Eyecatcher (r=0.94), though a direct comparison may be harder as the sample sizes differed significantly and the tests were performed in a supervised clinical setting, unlike the Eyecatcher, where tests were performed unsupervised and in a smaller clinical sample. Completion rates were also not reported, which could have provided further evidence of the instrument's feasibility. Shi et al. (2025) conducted a 24-month longitudinal study in 24 glaucoma patients using a VR-headset-based perimeter (Toronto Portable Perimeter) (Shi et al., 2025). While 72% of the cohort (n=18) independently performed one test per month for the first six months, adherence dropped significantly by the study's end, with only 11% (n=2) performing the test regularly, identifying how long-term adherence is a genuine challenge in glaucoma care. Completion rates for Eyecatcher were higher (100%), though this was measured over a much shorter duration (3 months). Unfamiliarity with technology and time constraints were the key barriers, both of which were also raised by the patients from my work in understanding patients' views on home-monitoring (Chapter 6), emphasising their importance. The study also reported better correlation with MD than the Eyecatcher ($r_{\text{Toronto Portable perimeter}}$>0.90 vs $r_{\text{Eyecatcher}}$=0.78 in glaucoma patients). Miyake et al. (2024) compared the performance of a head-mounted, button-free, gaze-analysing perimeter (GAP) against the HFA in a cross-sectional study (Miyake et al., 2024). The device had a comparable correlation coefficient to the Eyecatcher (r_{GAP}=0.81, $r_{\text{Eyecatcher}}$ =0.78) in 47 eyes with glaucoma, though performed in a supervised clinical setting. The Envision VR perimeter also reported high repeatability in their supervised clinical study (Tsamis et al., 2026). The perimeter showed better test-retest repeatability than the Eyecatcher; however, repeated longitudinal data were not collected.

Tan et al. (2026) further assessed Eyecatcher's utility in accelerating glaucoma clinical trials. The study concluded that home VF assessments may allow for a faster detection of glaucoma progression, despite reduced reliability compared to the HFA, due to the increased frequency of testing (Tan et al., 2026). Eyecatcher has also been evaluated as a part of a

portable test battery in a low-resource setting to explore its potential use in glaucoma case finding and monitoring (Garba et al., 2026). All participants (n=312) underwent both Eyecatcher and HFA tests. As a standalone test, the Eyecatcher showed a moderate accuracy of AUC=0.73; however, when combined with fundus photography, the accuracy improved to AUC=0.85, suggesting that combining structural and functional measures could help enhance the diagnostic abilities of portable testing equipment. This finding is consistent with the broader literature relevant to glaucoma diagnostics, which increasingly recognises how no single assessment/marker adequately captures disease damage across the full disease spectrum of glaucoma. A complementary combination of structural and functional biomarkers, rather than any individual measure in isolation, may be necessary to improve timely diagnosis and progression monitoring (Yap et al., 2018).

7.1.1.4 Other validating evidence on Spotchecks (Chapters 3 and 5)

Pardhan et al. compared the diagnostic efficacy of CamBlobs (the predecessor of Spotchecks against the Pelli-Robson CS test using a cross-sectional study approach in normally sighted and glaucoma patients. The study reported that CamBlobs (AUC=0.85, $P<0.001$) demonstrated comparable diagnostic accuracy to the Pelli-Robson test (AUC=0.88, $P<0.001$). The correlation coefficient between MD of the visual fields and CamBlobs chart logCS was r=0.59 ($P<0.001$), and this result was comparable to the correlation scores from glaucoma patients in the waiting room of our study (r=0.54, $P<0.001$, Chapter 3, Section 3.3.5).

7.1.1.5 Patient acceptability of home-monitoring (Chapter 6)

Since my earlier work on patient acceptability, the MONARCH study has examined patient acceptability of home-monitoring devices in older AMD patients as one of its outcomes (Hogg et al., 2024). This qualitative study was performed telephonically with patients participating in the long-term unsupervised clinical comparison of three home-monitoring devices. The results from the study highlighted that their older cohort required support to operate electronic devices, reinforcing our finding about concerns in patients around keeping up with the latest technology (Theme 1, Section 6.3.1). The patients from the MONARCH study also reported a strong preference for retaining face-to-face consultant contact, similar to the cohort in my study (Theme 5, Section 6.3.6). Based on these findings, the authors recommend reminder systems, clearer patient-facing instructions and triage pathways which align with the suggestions generated from the participants of my study.

7.2 Limitations and future work

7.2.1 Challenges in scaling new tests

Most of the work in this thesis focused on feasibility, the practical ability of a visual function test to generate clinically meaningful data in real-world patient populations. To a lesser extent, the work also addressed the accuracy and reliability of these testing methods. However, accuracy, reliability, and feasibility represent only three dimensions of a clinically useful test. Widespread use requires evidence of scalability, patient acceptability, and long-term cost-effectiveness.

In future, it would be valuable to determine whether portable assessment technologies such as PopCSF, Spotchecks, and Eyecatcher demonstrate comparable levels of acceptability and feasibility across different severities of glaucoma (mild, moderate, severe). A secondary objective of such a study would be to test whether the duration since diagnosis has any impact on the acceptability and feasibility of the monitoring device. I would execute this study in two parts. Firstly, by empirically evaluating acceptability across patients with different disease severities. I would conduct a comparison between the Eyecatcher and the HFA through a cross-sectional study in a tertiary eye care hospital when patients arrive for their routine perimetry assessment. This would allow patients to make a direct comparison between the two and provide their feedback.

The study in Chapter 3 also highlighted that the tests, in their current form, may not have provided sufficient evidence to support the integration of portable, rapid tests into routine testing. It would be valuable to assess the impact of other factors, such as the type of clinic (Consultant-led ophthalmology clinics versus technician-led virtual clinics), type of morbidity (glaucoma, cataract, etc.), stage of disease (mild/moderate/severe), availability of human resources to administer the test and review the data, patient waiting patterns, ambience of the waiting room, patient literacy and digital literacy rates, accessibility of the tests, patient's vision, sufficient patient waiting room space, patient's mood and willingness to engage, and the resilience of the test under pharmacological dilatation.

The studies in this thesis did not directly address the clinical relevance of contrast sensitivity, and while contrast sensitivity testing features throughout this thesis, it does so as a representative example of portable, self-administered visual function tests rather than as a

candidate diagnostic measure in its own right. It was selected for its portability, ease of administration, and capacity to generate data that correlate with disease status (Chapter 3). As such, no work presented here sought to establish the diagnostic accuracy of these tests in a large cohort. Formal validation against established clinical measures, alongside an assessment of what contrast sensitivity adds to the existing battery used to diagnose and monitor glaucoma, would be required to determine the long-term utility of such tests.

Sustained adherence was similarly beyond the scope of this PhD, and none of the work presented here explored long-term adherence or dropout rates. Both require detailed investigation before the techniques evaluated in this thesis can be considered for widespread use.

To assess the feasibility of home monitoring, I would recruit a subset of patients with different glaucoma severities and ask them to test themselves at home, unsupervised, using the device, similar to the approach adopted in Chapter 4. The outcome measures of this assessment would be unprompted engagement rates, reliability indices and test performance. Recruiting patients from the hospital services would also help address the limitation of relying solely on self-selecting volunteer participants in the study presented in Chapter 4.

7.2.2 The impact of supervision on data

In large parts of the work presented in this thesis, I have explored collecting clinical data from: a real unsupervised home environment, a simulated home-like environment, and a clinic waiting room. A key topic of interest throughout was how the absence of a clinician may impact the quality of the data. Results from Chapter 4 (Home-based VF testing) indicate that it is possible to collect VF data without supervision; however, the sample was quite small, and there are several factors (patient motivation, ease of use, quality of instructions, etc) that needed to be considered.

Supervision may also have an impact on the quality of the data. In Chapter 5 (Resilience of home-monitoring tests), participants who were briefed by the clinician completed the assessment slightly faster than those who were briefed by non-clinicians (check section 5.3.5). However, no difference was noted in the quality of data. A larger study comparing results with and without a clinician/technician could clarify the impact of instruction style

and quality. All participants would have to receive standardised training beforehand to minimise any influences of differences in learning. Primary outcome measures would include completion rates, variations in reliability indices, and statistically significant differences in MD that exceed the instrument's established repeatability limits. Participants would also complete a demographics questionnaire. These findings will help establish reliability thresholds for unsupervised use of home-monitoring devices.

7.2.3 The lack of consideration for practitioner feedback

Practitioner feedback has not been considered as part of this feasibility assessment, which represents a significant limitation. Without their input, there is a risk that additional remote data may increase, not reduce, the burden on stretched health services. Clinicians may be concerned about the barrage of data that may be produced as a result of administering these tests. Quality assurance protocols may also be needed in place to verify if the data obtained meets the standard necessary for informed clinical judgement. This step is crucial as poor-quality data would defeat the purpose of home monitoring and require re-testing.

Under the NHS, eye care professionals are not incentivised to perform additional tests or analyse supplementary data. Introducing new assessments without clearly defined use cases risks undermining the rationale for their adoption. If incorporated into mainstream clinical care, staff may need to take up further responsibility to review and interpret the data, adding a human resource cost to the NHS. Poor quality data may trigger additional testing, compounding the existing workload. Conversely, if the instrument lacks sufficient sensitivity to detect change, the patient may remain undetected until the damage worsens. Such scenarios could have catastrophic repercussions, which this thesis does not address.

To validate the concerns of the clinicians and to address some of the limitations mentioned above, a focus group discussion with clinicians, including ophthalmologists, optometrists, and technicians, could potentially address some of these limitations. The primary objective of this study would be to understand the views, expectations, hopes and concerns of eye care clinicians involved in the management of ophthalmology patients. Semi-structured interview-style questions exploring four themes could be used. The themes would include existing knowledge and attitudes, concerns about home-monitoring, willingness to engage with patient data, and long-term public benefit.

The study would benefit from gathering data from clinicians working across optometry subspecialty clinics that benefit from regular patient monitoring, including paediatric, cataract, macula, and glaucoma clinics. The rationale for adopting a focus group discussion approach is to allow for a qualitative exploration, which would provide targeted thematic understanding necessary for the development of a longer survey. If the qualitative study yields coherent and actionable themes, the findings will provide crucial insights into clinician acceptability that would be useful for future product development.

Chapter 8. Overall summary and conclusion of the thesis

In this thesis, I present evidence that there is a need for new vision testing strategies, prompted by a study assessing the impact of socio-economic deprivation on glaucoma care. To address this need, I explored the feasibility of administering new vision tests through a series of complementary studies involving patients primarily with glaucoma, followed by AMD. I have demonstrated that these novel tests are feasible to administer in non-clinical settings, including clinic waiting rooms, home environments, and simulated home-like environments. The findings also further indicate that these novel tests serve different purposes than traditional vision tests.

Overall, the rationale for pursuing this thesis using the previously discussed methodology is the PhD by prospective publication nature of this thesis, which allowed me to pursue a mix of both retrospective data analysis and prospective empirical feasibility assessments.

The rationale behind selecting these tests to address our hypotheses was based on pragmatism and the availability of resources. The tests were selected based on the following criteria: self-administrable without technical supervision, can be performed in less than five minutes, available in the UK and with some preliminary validation data that confirms their application for vision testing. The studies were inspired by existing work performed previously in the lab, and the availability of clinical spaces and patients.

To summarise briefly, the key conclusions of each of the studies in this thesis are:

1. Chapter 2: Individuals residing in neighbourhoods with higher deprivation levels are more likely to present to the clinic with advanced visual field loss than those residing in neighbourhoods with lower deprivation levels, and *vice versa*. The impact of neighbourhood deprivation was not observed to have a significant effect on the rate of progression of glaucoma once the individual is under the care of the HES.
2. Chapter 3: An investigation into the feasibility of utilising glaucoma patients' waiting time to test their visual function using simple self-assessable tests demonstrated that the approach was feasible in a glaucoma clinic setting. The results showed that both pen-and-paper and digital CS tests were quick to complete (2.5 to 3.0 mins), feasible for the majority of glaucoma patients (97.4% completion rate) and acceptable to

most patients (>80% feedback on all questions). The tests were resilient to anticipated variations in the environment (all P > 0.05) and correlated with clinical and demographic data.

3. Chapter 4: The Eyecatcher visual field glasses proved to be a feasible method to measure visual fields in glaucoma patients in their homes without supervision as well as in normally sighted individuals under simulated conditions. The test showed a 100% completion rate among patients with reasonable correlation with the HFA in terms of mean deviation (MD; r =0.85, P <0.001). The HFA demonstrated superior repeatability (CoR_{HFA} =2.9, CI: 2.1-4.1 dB, $CoR_{Eyecatcher}$ =3.9, CI: 2.1-6.1 dB), although the difference was not statistically significant. Some measurement errors were noted in Eyecatcher. Most patients and normally sighted individuals rated the Eyecatcher to be easy to use; however, some raised specific concerns about needing technical support.
4. Chapter 5: Home-monitoring tests such as Spotchecks and PopCSF demonstrate reasonable resilience to variations in environmental factors when evaluated in a simulated home-like environment. No significant effects of time of day, participant motivation, or seating type were observed (All P > 0.05). The test results were unaffected by illumination except when tests were conducted in extremely low lighting (<1lux, P=0.036). A smaller follow-up study further indicated that fingerprint-based screen smudges had no measurable impact on the test results of the tablet-based test (P = 0.573).
5. Chapter 6: Patients with mild to moderate glaucoma or AMD expressed the view that vision home-monitoring could potentially be beneficial; however, they have some significant concerns about its potential implementation. The participants made references to an increased sense of control and the potential for quicker detection of vision changes. However, some participants also criticised some aspects of the tests, particularly the design and reliability of the tests.

The findings of this thesis collectively demonstrate that novel visual function assessments can be feasibly administered outside traditional clinical settings, though not without some important limitations. Further research is required to establish their clinical validity,

diagnostic accuracy, scalability and long-term cost-effectiveness before such approaches are incorporated into routine eye care.

Chapter 9. Supplementary Material

9.1 Supplementary Material A (Relevant to Chapter 3)



Figure 9.1. Photographs of the waiting room with a capacity for approximately 70 patients

9.1.1 Patient acceptability questionnaire comprising nine questions for each participant.

Participant Unique Study Identification Number:

1. How was your experience with the Contrast Sensitivity Test done in the Waiting Room?

Spotchecks (Pen and paper test):

- Not applicable / I did not perform this test. ☐
- The test was enjoyable: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- The test was easy to perform: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- I understood the test well: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree

PopCSF (Digital tablet test):

- Not applicable / I did not perform this test. ☐
- The test was enjoyable: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- The test was easy to perform: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- I understood the test well: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree

2. How was your experience with the Pelli-Robson Test (Chart-based test) done in the Annex)?

- I was not able to perform this test. ☐
- The test was enjoyable: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- The test was easy to perform: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- I understood the test well: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree

Other Questions:

3. How would you rate your overall testing experience in the waiting room?

- I felt comfortable doing these tests in the waiting room: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- I felt supported doing these tests in the waiting room: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree
- I felt that it makes sense to utilise patients' time in the waiting room: Strongly disagree 1 - 2 - 3 - 4 - 5 Strongly agree

4. **Please provide any additional comments or feedback you may have.**

.....

.....

.....

Table 9.1. P-values of the pen-and-paper and digital tests comparing the impact of changes in environmental factors of illuminance, noise and crowd in the waiting room.

Environmental factors	P-value (Pen and Paper test) (N=77)	Relevant test statistic (Pen and Paper test) (N=77)	Degrees of freedom (N=77)	P-value (Digital test) (N=74)	Relevant test statistic (Digital test) (N=74)	Degrees of freedom (N=74)	Statistical test used
Illuminance	0.615	0.97	-	0.501	1.38	-	Kruskal Wallis-H test
Noise	0.529	77.50	-	0.402	70	-	Mann-Whitney-U test
Crowd	0.749	0.32	67	0.232	1.21	98	Unpaired-t test

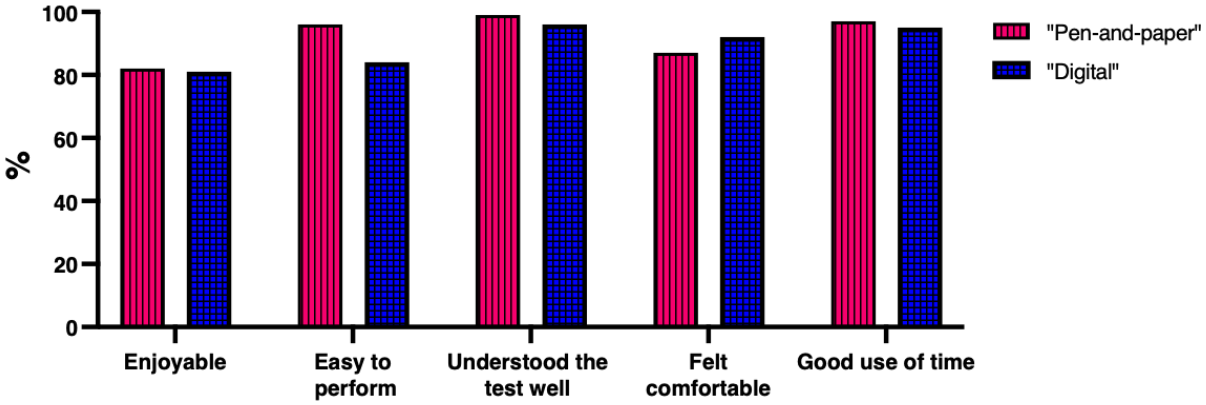


Figure 9.2.Patient Acceptability scores. The percentages of people who “agreed” or “strongly agreed” with the patient acceptability statements for the two CS tests, shown separately for the participants who were assigned the pen-and-paper Spotchecks test (pink, vertical lines) and the digital PopCSF test (blue, hatched lines), respectively.

Table 9.2. A breakdown of the costs involved in testing ophthalmology patients in the waiting room for a year. All calculations made here are for an assessment in both eyes and include the health care assistant's salary for a year, along with the estimated national insurance fees.

	Cost in Great British Pounds (£)
Digital Test	
Personnel costs (A year's salary to hire a research nurse and the associated national insurance costs)	27,514.00
Equipment costs (Two Apple iPad Pro devices)	1,998.00
Total costs (£)	29,512.00
Cost per patient (£): (29,512.00 / 15,080)	1.96
Pen-and-paper Test	
Personnel costs (A year's salary to hire a research nurse and the associated national insurance costs)	27,514.00
Equipment costs (A year's worth of Spotchecks supply to test 2 eyes [£1.48 per sheet for each eye])	44,526.00
Assumed subsidised costs (Assuming 30% discount, wholesale)	31,168.20
Total costs (£)	58,682.20
Cost per patient (£): (58,682.20 / 15,080)	3.89

9.2 Supplementary Material B (Relevant to Chapter 4)



Figure 9.3. Boxed version of Eyecatcher, as supplied to patients undergoing home monitoring. Including smartphone, smartglasses, Bluetooth response button, cleaning cloth, nose pieces, and magnetic lens inserts.

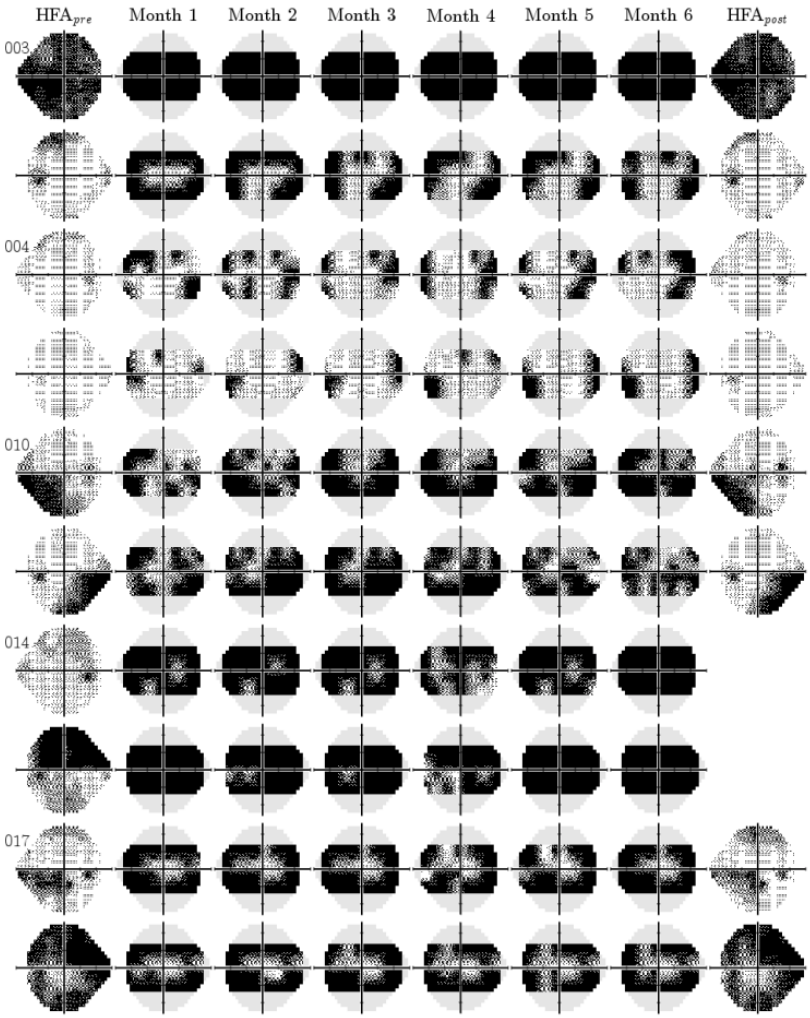


Figure 9.4. Alternative version of Figure 4.4 (main manuscript), showing the raw, unadulterated HFA data (first/last columns) without thresholding for equivalence with Eyecatcher.

Table 9.3. Breakdown of raw patient responses using the System Usability Scale (SUS). Individual questions are scored from 1 (strongly disagree) to 5 (strongly agree). The total score is computed by subtracting 1 from the odd rows (higher score = better), subtracting the even rows from 5 (lower scores = better), and multiplying the sum total by 2.5.

Eyecatcher's System Usability System (SUS) ratings

Question		Patient				
		IGA006	IGA010	IGA017	IGA003	IGA004
1	I think that I would like to use this system frequently	5	5	4	1	3
2	I found the system unnecessarily complex	1	1	1	4	4
3	I thought the system was easy to use	5	5	5	2	3
4	I think that I would need the support of a technical person to be able to use this system	1	1	1	1	2
5	I found the various functions in this system were well integrated	5	5	4	3	5
6	I thought there was too much inconsistency in this system	2	1	1	3	2
7	I would imagine that most people would learn to use this system very quickly	4	5	5	4	4
8	I found the system very cumbersome to use	1	1	1	5	3
9	I felt very confident using the system	5	5	5	2	5
10	I needed to learn a lot of things before I could get going with this system	2	1	2	1	2
	Total Score (out of 100):	92.5	100	92.5	45	67.5

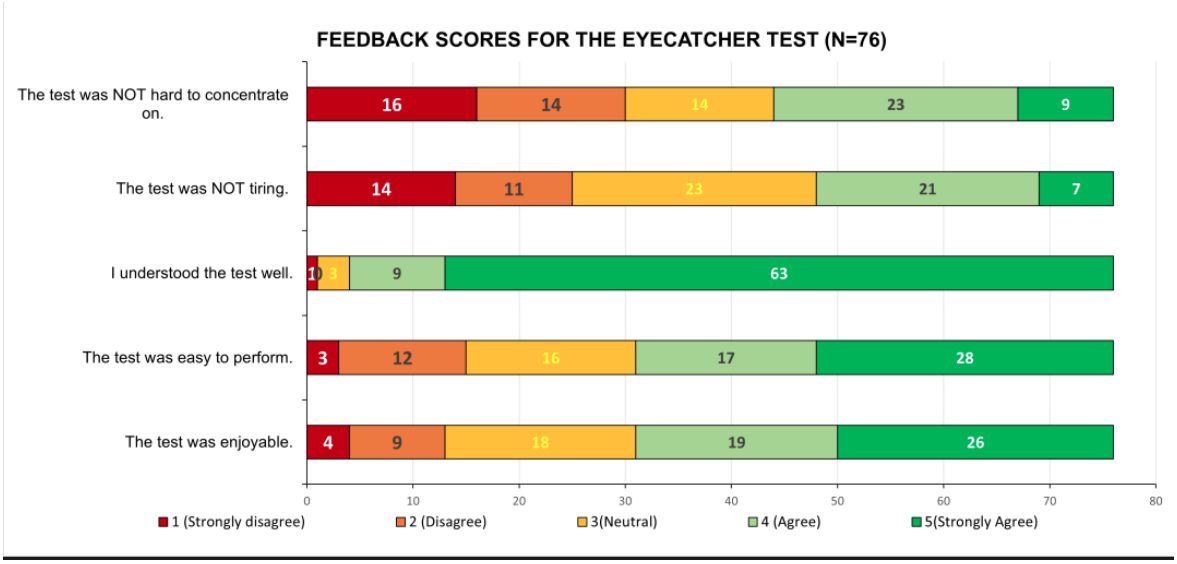


Figure 9.5. Eyecatcher usability ratings from normally sighted young adults. The bars in green shades and red shades represent favourable responses and unfavourable responses, respectively. For display purposes only, the first two statements have been inverted ("Not" added to the question and scores reversed) for ease of understanding.

9.3 Supplementary Material C (Relevant to Chapter 5)

9.3.1 Methods

9.3.1.1 Missing data

109 participants were recruited and screened for this study, of which 107 passed our screening procedure.

For analyses involving PopCSF, seven participants were excluded (*n*=100 included). For 5 participants, this was due to a technical error (a bug in the code that rendered the data unusable). An additional two participants were excluded, one because they did not press the screen a single time during the PopCSF test and one who did not wear their glasses for the PopCSF tests.

In addition, for analyses involving illumination levels, two participants were excluded as the illumination level was not recorded due to human error. While for the analyses of test duration, one participant was excluded as the test duration was not recorded due to human error.

9.3.2 Results

9.3.2.1 Repeatability of SpotChecks and PopCSF

In the main text, the test-retest variability (|test2 – test1|) was used to correlate those values with the investigated extraneous factors. However, to facilitate comparisons with previous literature using CoR_{95} we have added those values in this section. CoR_{95} values for each extraneous variable investigated (in the case of continuous variables, the variable was split on the median) can be found in **Supplementary Table 9.4**. Additionally, Bland-Altman plots of both SpotChecks and PopCSF can be found in **Supplementary Figure 9.6.**

Table 9.4 .CoR_{95} values of each investigated extraneous variable for both SpotChecks and PopCSF.

SpotChecks		PopCSF	
Splitting factor	CoR_{95} Repeatability (CI_{95}), *LogCS*	Splitting factor	CoR_{95} Repeatability (ci_{95}), *AUCSF*
Illumination (lux)			
< 606.5 *lux* (*n*=51)	0.14 (0.11 – 0.18)	<641 lux (*n*=50)	0.26 (0.21 – 0.31)
> 606.5 *lux* (*n*=51)	0.13 (0.11 – 0.15)	>641 lux (*n*=50)	0.26 (0.20 – 0.31)
Seating Type			
Sofa (*n*=51)	0.15 (0.12 – 0.17)	Sofa (*n*=48)	0.26 (0.22 – 0.31)
Table (*n*=53)	0.13 (0.10 – 0.16)	Table (*n*=52)	0.25 (0.20 – 0.31)
Time of Day (HH:MM)			
< 14:05 (*n*=52)	0.15 (0.12 – 0.18)	<14:30 (*n*=49)	0.26 (0.21 – 0.31)
> 14:05 (*n*=52)	0.12 (0.09 – 0.15)	>14:30 (*n*=43)	0.25 (0.19 – 0.32)
Feedback			
< 22 (*n*=42)	0.15 (0.12 – 0.19)	< 21 (*n*=47)	0.24 (0.20 – 0.29)
> 22 (*n*=47)	0.13 (0.10 – 0.16)	> 21 (*n*=42)	0.27 (0.21 – 0.33)
HVF Reliability (%)			
< 9.5 (*n*=52)	0.14 (0.11 – 0.16)	< 10 (*n*=49)	0.25 (0.19 – 0.31)
> 9.5 (*n*=52)	0.14 (0.11 – 0.17)	> 10 (*n*=43)	0.27 (0.22 – 0.32)
Administered by			
clinician (*n*=53)	0.14 (0.12 – 0.17)	clinician (*n*=48)	0.28 (0.23 – 0.34)
non-clinician (*n*=51)	0.13 (0.10 – 0.16)	non-clinician (*n*=52)	0.23 (0.18 – 0.28)
Total			

n=104	0.14 (0.12 – 0.16)	*n*=100	0.26 (0.22 – 0.29)

9.3.3 Repeatability plots of the CS tests.

Bland-Altman plots of SpotChecks (**Figure 9.6A)** and PopCSF (**Figure 9.6B).** Blue continuous central line shows the mean difference; the red dashed lines show the upper and lower limits of agreement. The numbers written close to the lines represent the values of the mean difference and limits of agreement. Shaded areas represent the 95% confidence intervals of the mean difference and limits of agreement.

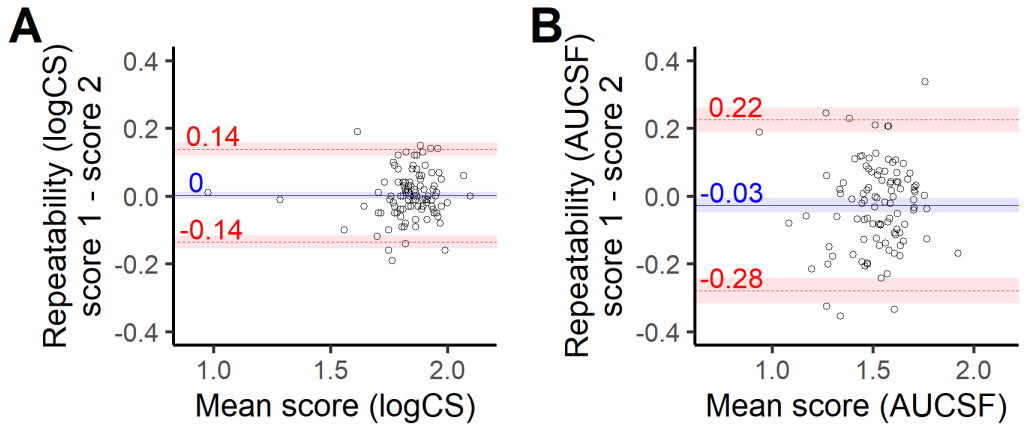


Figure 9.6. Repeatability plots (Bland-Altman) of the CS tests (SpotChecks **(A)** and PopCSF **(B)**).

9.3.4 Comparison to cataract patients

Here, we compare the data from the present study with previously collected data in older cataract patients (Bianchi et al., 2024). As shown in **Supplementary Figure 9.7**, the CS scores were considerably lower and more varied in cataract patients versus the healthy young adults in the present study, as one would expect.

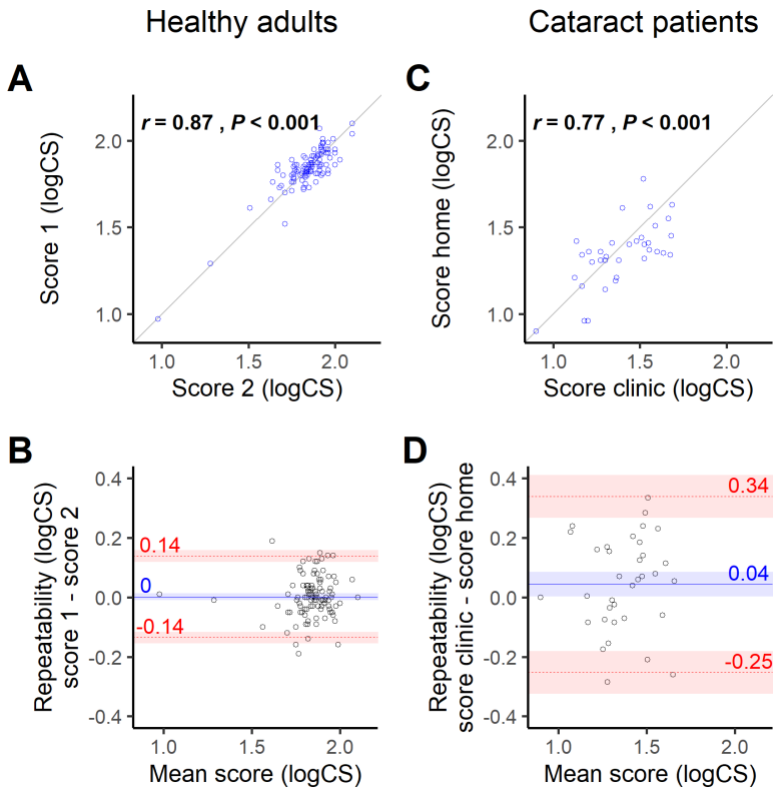


Figure 9.7. Figures comparing both tests to the reference standard. Scatterplots (**A&C**) and Bland-Altman plots (**B&D**) comparing the repeatability of SpotChecks done in young adults twice in the simulated apartment (**A&B**) and in cataract patients at home and in the clinic (**C&D**). The patient data was retrieved from the study by Bianchi et al. (2024).

9.3.5 Resilience to ambient illumination

To determine exactly what the minimum illuminance is required to perform the SpotChecks, we refitted the data in **Figure 5.3A** using piecewise linear regression. A linear regression on the SpotChecks data resulted in an R^2 of 0.063 and a Bayesian Information Criterion (BIC) of -119.8, which was a poor fit on the data. Applying a piecewise linear regression with one break resulted in the most ideal break at illumination of 11 lux, which resulted in a much better R^2 of 0.508 and BIC of -180.2, see **Supplementary Figure 9.8A**. This indicates that performing the test at conditions below 11 lux can have a detrimental effect on the test score.

To determine whether there was a maximum acceptably illuminance, we also applied a piecewise linear regression with two breaks on the data. The second break was at an illumination of 1395 lux. This extra break only had a very small effect on R^2 of 0.511, and the BIC slightly increased to -174.2, indicating overfitting. It does seem to indicate that performing the test around 1395 lux provides ideal conditions for performing SpotChecks, as can be seen in **Supplementary Figure 9.8B.** There was

a minor increase in score as illumination increased from 11 lux until 1395, after which it decreased again. Though only very few people were tested at more than 1395 lux (*n*=17), this result is possibly unreliable. Additionally, since the BIC increases from one to two breakpoints, the second breakpoint is likely overfitting on the data, so the model with one breakpoint (which has the lowest BIC) would be considered best.

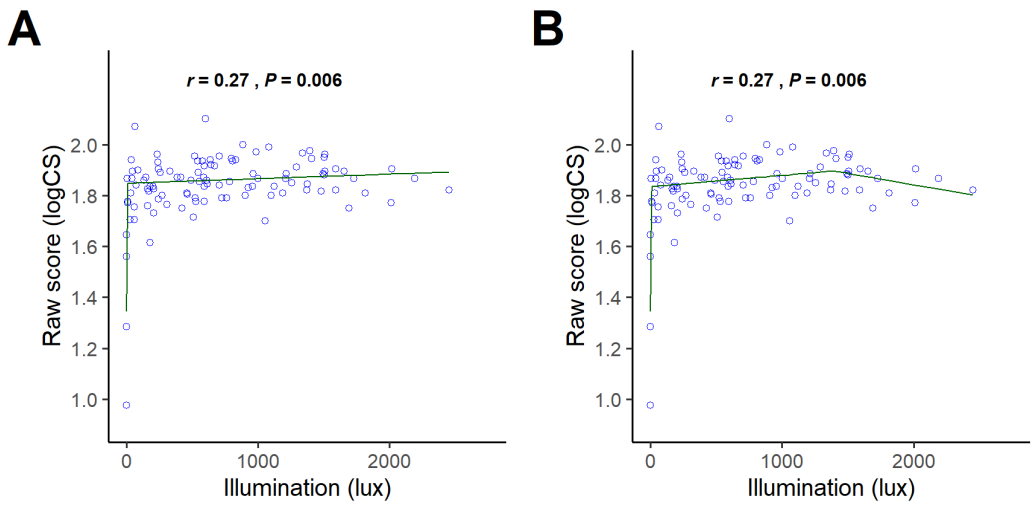


Figure 9.8. Figures of the piecewise regression for the resilience to illumination. **(A)** Scatterplot of the illumination vs the mean score on SpotChecks, the green line indicates the piecewise linear regression with breaks at 11 lux. **(B)** Scatterplot same as A, but with an additional break at 1395 lux. Numerical values indicate Pearson correlation coefficients.

9.3.6 Resilience to participant motivation

9.3.6.1 Participant feedback

This section is supplementary to section 5.3.5.1 in the main text and contains the figures of the resilience to the participant feedback. In brief, **Supplementary Figure 9.9** shows the effect of participant feedback (ranging from 5, extremely negative, to 25, extremely positive) on the raw score, repeatability, and duration of both CS tests.

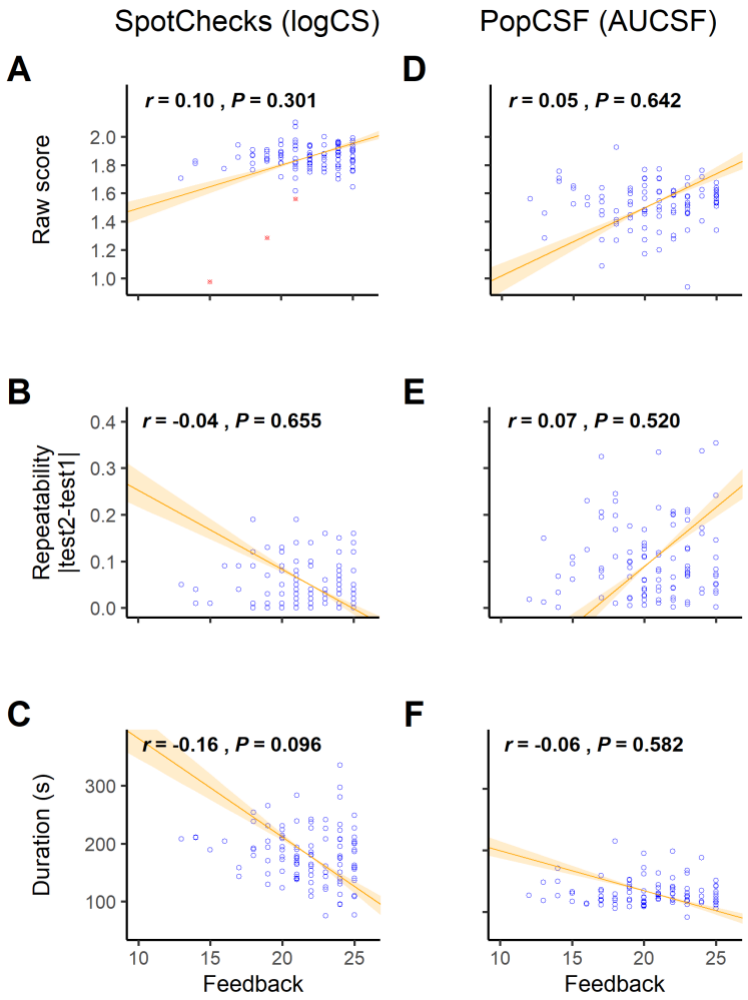


Figure 9.9. Figures of the resilience to participant feedback. **(A)** Scatterplots of the raw score vs the feedback score for Spotchecks. Note that in this figure, three participants (tested at ≤1lux; shown as a red crossed circle) were removed (outliers), **(D)** Scatterplots of the raw score vs the feedback score for PopCSF. **(B)** Scatterplots of the absolute difference between the second and first test vs the feedback score for Spotchecks and **(E)** Scatterplots of the absolute difference between the second and first test vs the feedback score for PopCSF. **(C)** Scatterplots of the duration of Spotchecks vs the feedback score for Spotchecks and **(F)** Scatterplots of the duration of Spotchecks vs the feedback score for POPCSF. Numerical values indicate the Pearson correlation coefficient. The line signifies the standard major axis regression, with shaded regions indicating the slope's 95% confidence interval.

9.3.6.2 HVF reliability

This section is supplementary to section 5.3.5.2 in the main text and contains the figures of the resilience to the HVF reliability score. In brief, **Supplementary Figure 9.10** shows the effect of the HVF reliability metric (the percentage of false positives, false negatives and fixation losses of a visual field test added together) on the raw score, repeatability, and duration of both CS tests.

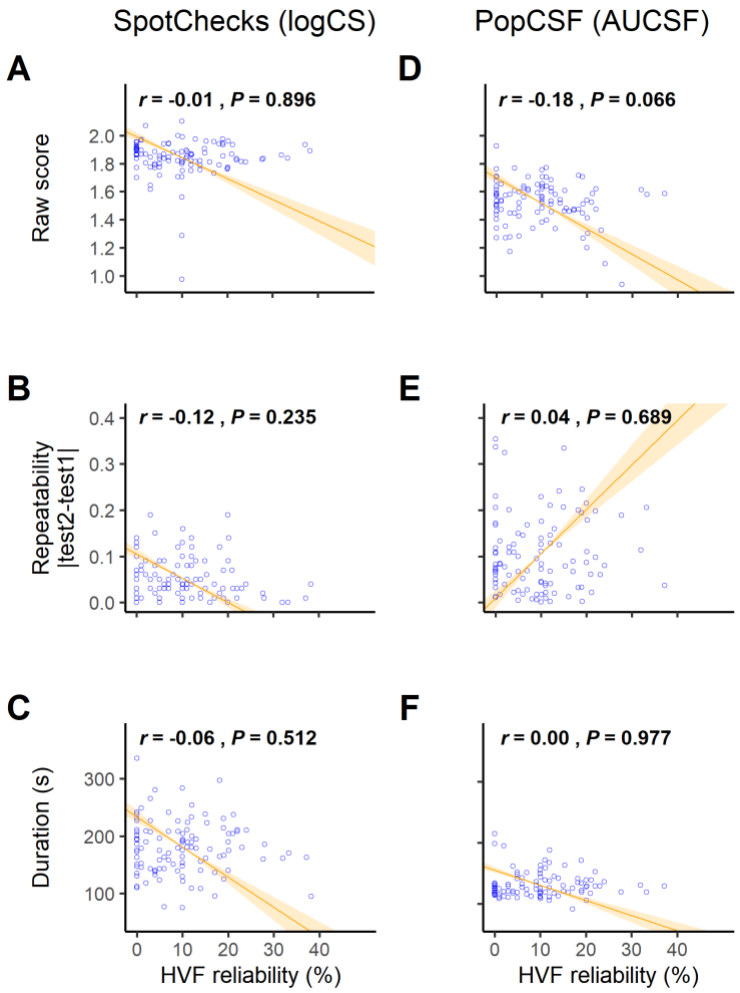


Figure 9.10. Figures of the resilience to the HVF reliability metric. **(A)** Scatterplot of the mean SpotChecks score with the HVF reliability score on the x-axis. **(D)** Scatterplot of the mean PopCSF score with the HVF reliability score on the x-axis. **(B)** Scatterplot of the absolute difference between the two SpotChecks scores with the HVF reliability score on the x-axis. **(E)** Scatterplot of the absolute difference between the two PopCSF scores with HVF reliability score on the x-axis. **(C)** Scatterplot of the duration of SpotChecks with the HVF reliability score on the x-axis. **(F)** Scatterplot of the duration of PopCSF with the HVF reliability score on the x-axis. Numerical values indicate Pearson correlation coefficients. The line signifies the standard major axis regression, with shaded regions indicating the slope's 95% confidence interval.

9.4 Supplementary Material D (Relevant to Chapter 6)

9.4.1 Explanation of the tests

Participants were given 3 tests to try, for a total of approximately 30 minutes. To avoid fatigue, participants were instructed that they did not necessarily have to finish each test on both eyes. In practice, for the tests of shorter duration, all participants completed a full test on at least one eye. For the longer tests, some participants completed the test on one eye, but others chose to stop the test earlier when they had established a clear idea of what the test involved.

9.4.2 Home-monitoring tests for glaucoma

The participants in the two glaucoma focus groups were given three different VF tests to experience, as shown in **Figure 6.1** of the main manuscript. The three tests were as follows:

Melbourne Rapid Fields (https://www.appviewmrf.com/), shown in **Figure 6.1A**, is an iPad-based static suprathreshold perimeter (Kumar & Thulasidas, 2020). Participants were asked to focus on a fixation point (that periodically shifts location) and to tap a red square at the bottom of the screen when they saw the stimulus, which is presented at varying luminance levels, appear on the screen. Tests are performed monocularly in a dimly lit room, and a full test for a single eye lasts approximately four minutes.

Eyecatcher v3 (https://www.eyecatchervision.com), shown in **Figure 6.1B,** is a portable static threshold perimeter that uses 'smartglasses' connected to a smartphone. The test is a new version of a tablet-based perimeter described previously (Jones et al., 2021), updated to take into account previous feedback from patients (Jones et al., 2021). As in Standard Automated Perimetry, participants were asked to fixate on a central cross and press a button whenever they saw a stimulus (200 msec Goldmann III dots of varying luminance). Tests are performed monocularly in a dimly lit room (both eyes interleaved). A full test generally lasts approximately seven minutes (for both eyes).

Visual Fields fast (https://visualfieldfast.com/), shown **in Figure 6.1C**, is a tablet-based white noise campimeter. Participants were asked to focus on a fixation point (that periodically shifts location) and to draw with their finger any areas of the screen that do not flicker or which otherwise look abnormal (e.g., scintillation). Tests are performed monocularly in a dim room, and a full test for a single eye generally lasts approximately five minutes.

9.4.2.1 Home-monitoring tests for AMD

The participants in the two AMD focus groups were given one hyperacuity test and two contrast sensitivity tests to experience, as shown in **Figure 6.1D-F** of the main manuscript. The three tests were as follows:

AllEye (https://alleye.io/), shown in **Figure 6.1D**, is a tablet-or smartphone-based test of near-vision hyperacuity. Participants were asked to align the three dots on their screen by pressing the arrows on the screen. Participants were presented with three dots at different angles and alignments a total of 12 times. Tests are performed monocularly in a dimly lit room. For a full test, a single eye test generally lasts five minutes.

PopCSF, shown in **Figure 6.1E**, is an iPad-based task measure of the contrast sensitivity function (i.e., contrast sensitivity and acuity) (Crossland et al., 2024). Participants were asked to 'pop' bubbles (i.e. Gabor patches of varying contrast and spatial frequency) by pressing them as they bounce around the screen. Infrared head-tracking (using the iPad's TrueDepth camera) is used to scale the stimuli based on viewing distance. Tests are performed monocularly in a dim room, with a full test for a single eye lasting approximately five minutes.

Spotchecks (https://www.precision-vision.com/products/contrast-sensitivity-tests/peakcontrast-sensitivity/spotchecks/spotchecks/), shown in **Figure 6.1F**, is a single-use pen-and-paper contrast sensitivity test (the outcome of which is similar to that of the Pelli-Robson letter chart (Anderson et al., 2023; Vu et al., 2024). Participants were asked to mark with an 'x' any dark spots (the contrast of which progressively decreases down the page). Tests are performed monocularly in a dim room, and a full test for a single eye lasts between one and ten minutes, depending on the participant.

9.4.3 Focus group conversation topic guide used by the focus group facilitators

Table 9.5. Focus group conversation topic guide used by the focus group facilitators.

1	What are your overall thoughts on the system? (Prompts: did you think the system was user friendly? Would you recommend this to a friend? Would you use it?)
2	What do you think about the idea of telemedicine ? (Prompts: Do you like the idea of being able to do the tests at home? What do you think are the advantages/disadvantages of telemedicine?)
3	This app is recommended to be used once every two weeks, would you be likely to do this?
4	What would make you stop using them? What would discourage you from using them?
5	How often would you use these apps/systems? (Prompts: Every week? Twice a week? Never? What would motivate you to maintain your use of them?)

Table 9.6. Table listing the statements presented to participants during the focus group session. Participants were asked to rate these statements from most to least important.

Features
I would like the app/device to send me text reminders to do the test
I would like the app to read the instructions out loud
I would like to see my results at the end of the test
I would like the app to tell me if there has been a change in my score and if I need to see my practitioner
I would like to receive confirmation that my results have been seen by my practitioner
I would like to be supervised doing the test by my practitioner

Table 9.7. Table showing participant demographic and diagnosis information. Glaucoma participant 3 was unable to be contacted again to verify their age.

Participant number	Age	Diagnosis
AMD P1	80	Unilateral wet AMD
AMD P2	73	Bilateral dry AMD
AMD P3	84	Bilateral wet AMD
AMD P4	93	Unilateral wet AMD
AMD P5	77	Bilateral dry AMD
AMD P6	49	Bilateral dry AMD
AMD P7	77	Bilateral dry AMD
Glaucoma P1	79	Primary open angle glaucoma
Glaucoma P2	85	Normal tension glaucoma
Glaucoma P3		Primary angle closure glaucoma
Glaucoma P4	77	Normal tension glaucoma
Glaucoma P5	65	Primary angle closure glaucoma
Glaucoma P6	70	Normal tension glaucoma
Glaucoma P7	68	Primary open angle glaucoma
Glaucoma P8	50	Primary angle closure glaucoma

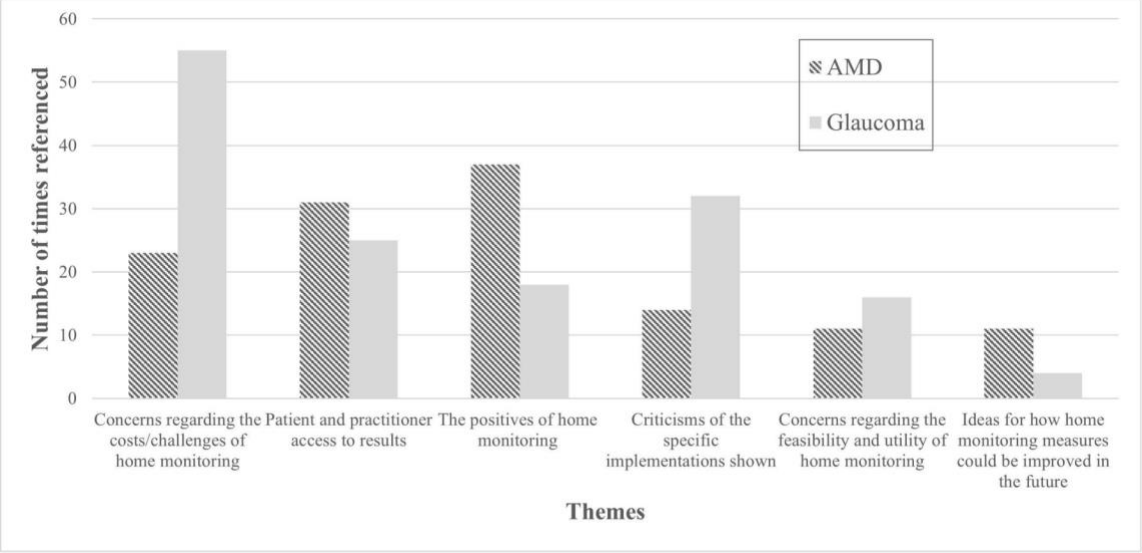


Figure 9.11. Bar chart showing the frequency of the themes discussed by AMD and glaucoma patients.

Chapter 10. References

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